D-D FUSION NEUTRONS FROM A STRONG SPHERICAL SHOCK WAVE FOCUSED ON A DEUTERIUM BUBBLE IN WATER

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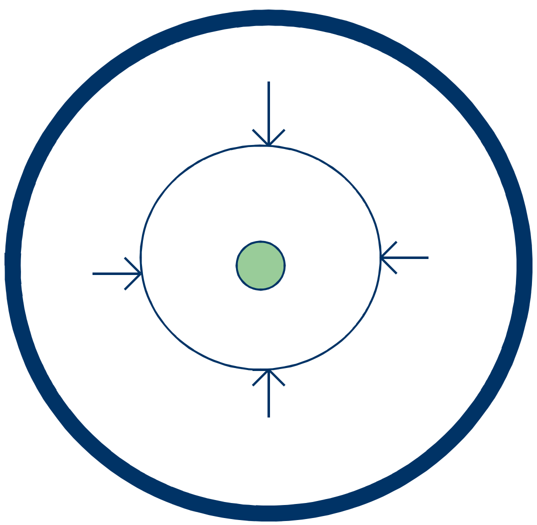
SONOFUSION

- Sonofusion is making some noise
- A bit short in energy, ~mJ in bubble
- Concentration of energy in a collapsing cavity in a liquid is interesting
- 1/r velocity, pressure and temperature
- Worth considering

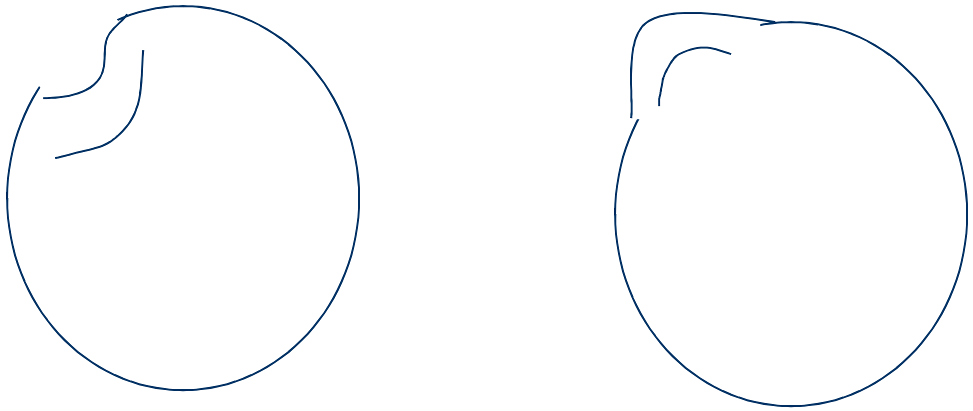
Spherically focused shock wave

- More energy required than the small ultrasound transducer
- More powerful sound wave becomes shock wave



Advantages of shock wave

- Focusing shock is stable



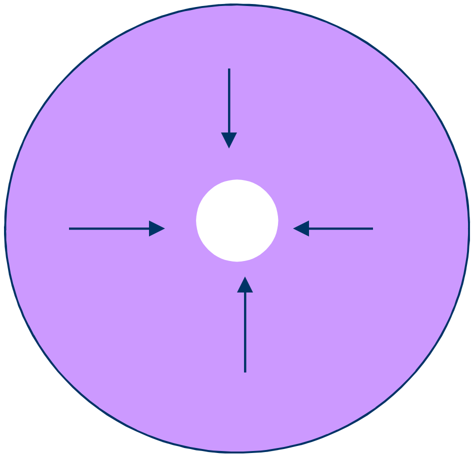
Defocus, slow down   Focus, speed up

Advantages of shock wave

- All pictures of shocks from our experiment or from other work are very smooth, no bumps or jets. Shocks look nice and stable.
- Shocks can have extreme material velocity
- Super Nova explosion
- Nuclear explosion
- Shocks are cheaper to produce than laser or particle beam
- If atomic liquid (liquid metal), the liquid is not damaged

Stable cavity collapse?

- Pressure in shock accelerates the dense liquid pushing against the lower density target.
- RT stable?



Final crunch of cavity

- At the final crunch, the less dense target slows the denser liquid.
- RT unstable for very short time at max compression.
- No worse than laser ICF

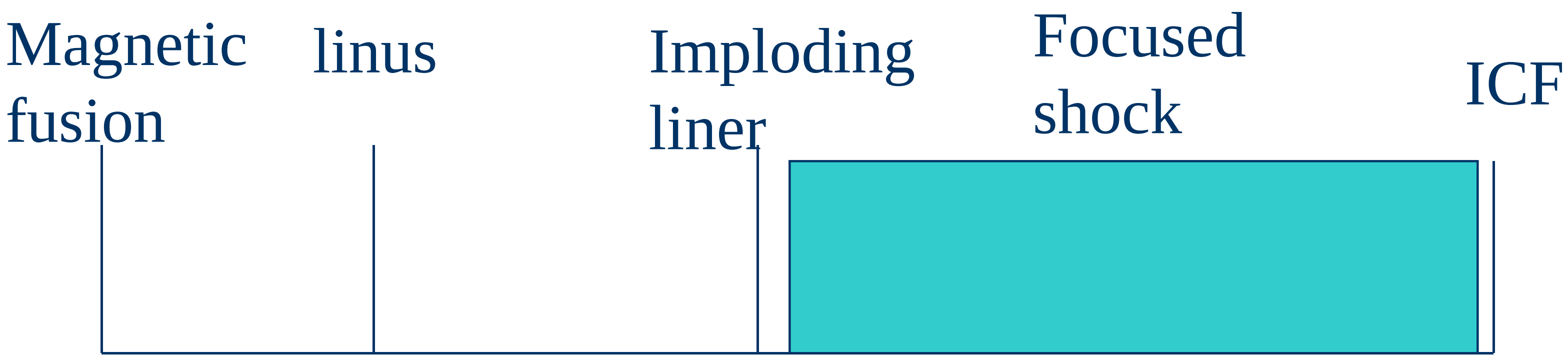
Target

- Target could be inertial confined (ICF)
- Target could be a pre-formed magnetized plasma (MTF)
- Simpler is a D-T bubble, but more complex multi-layered targets could be designed for a higher yield, like laser targets
- A compact torus (spheromak, FRC) could be used for MTF

MF to MTF to ICF

Heat losses
due to instability

Extreme power
density

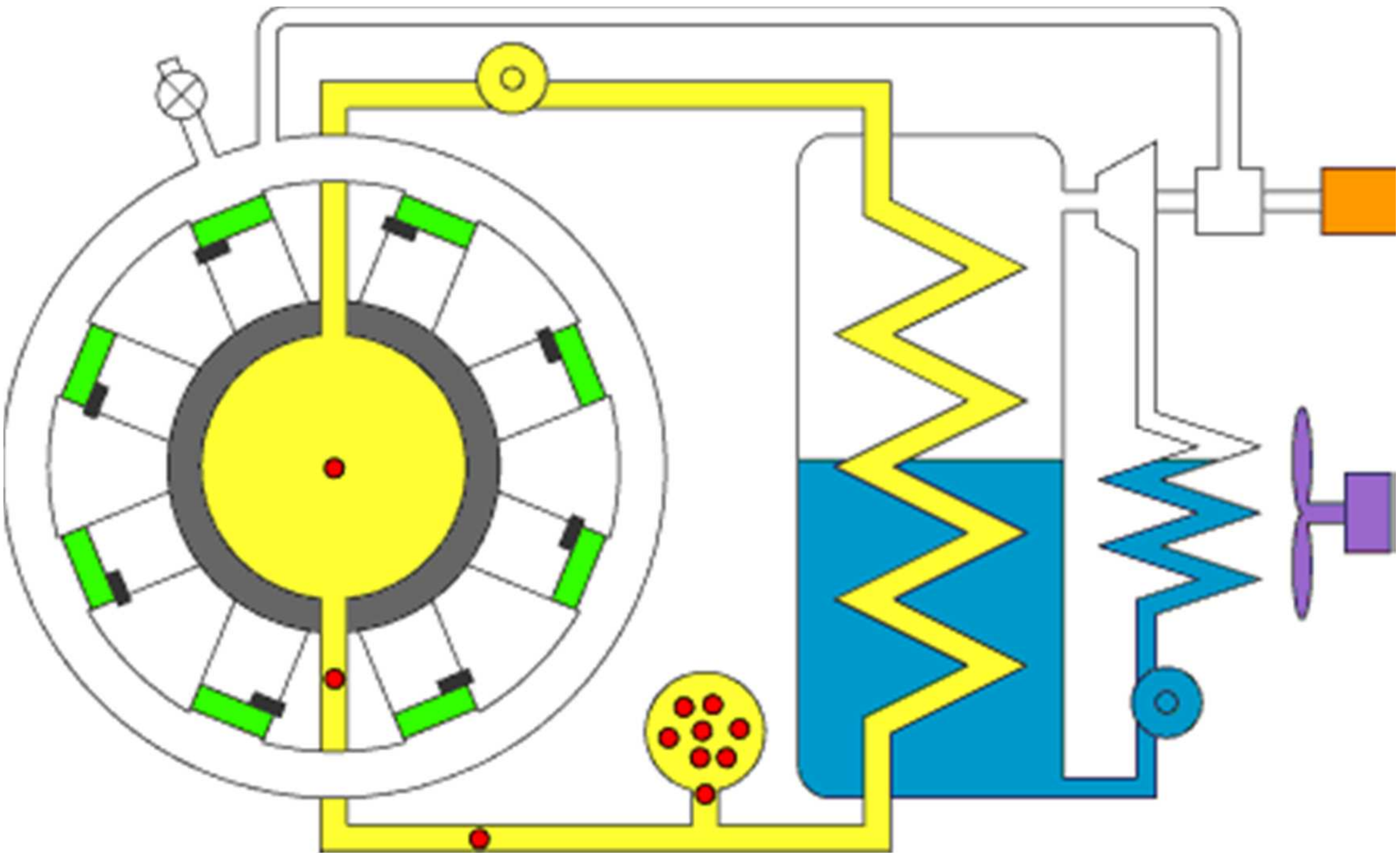


n=1E14	n=1E17	n=1E20	n=1E25
P=1 Bar	P=1 kBar	P=1 Mbar	P=100 Gbar
v=0 km/s	v=0.5 km/s	v=5 km/s	v=500 km/s
t=1 s	t= 1 ms	t=1 us	t=10 ps

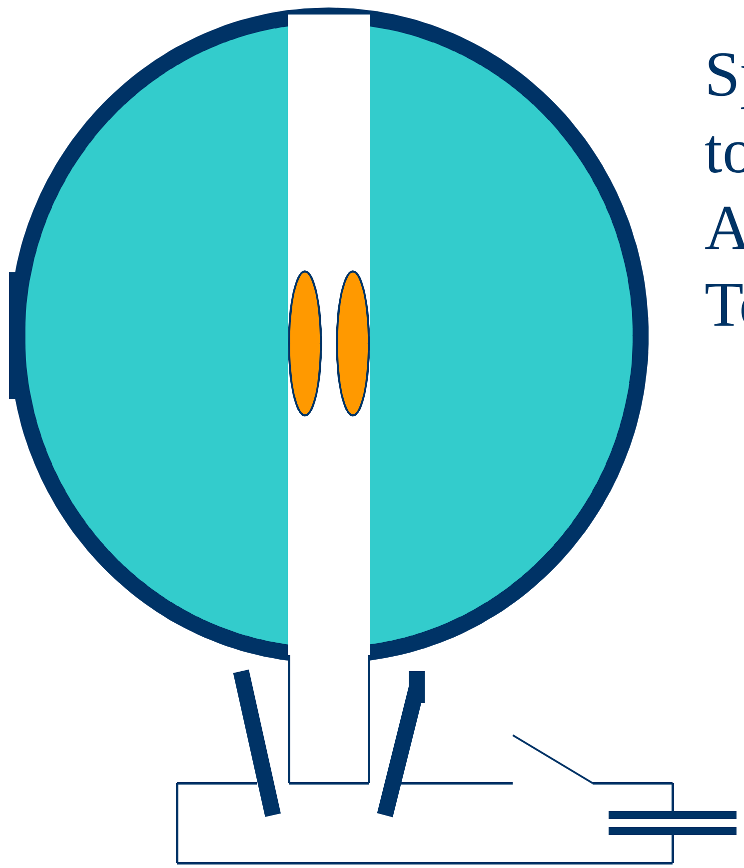
Shock generation

- Electric (electromagnetic, electrothermal)
- Cost of pulse power technology is ~2$/J
- Rep rate ~1Hz, power supply only is ~2$/W
- Max cost for power plan with negligible fuel cost is ~2$/W to be economical
- Piston impact delivers energy in 10 us
- Compressed air or steam accelerates pistons
- Very low cost, 10 MJ of compressed air 100 k$

Focused shock driven fusion plant



Focused shock driven MTF



Spin the liquid
to form a vortex
And inject a compact
Torus (FRC, spheromak)

Engineering advantages

- All neutrons and other radiation stopped in the liquid
- The liquid re-breeds tritium (lead-lithium liquid alloy for example)
- Low neutron load on reactor structure
- Very low cost drivers, low tech reactor
- If (big if) the physics works out, could rapidly lead to economical power generation

Possible pitfalls

- Symmetry requirements are high, especially for ICF
- Shock losses
- Shock losses are deadly for spherical pinch, but losses in low compressibility liquid metal may be lower than in a compressible plasma
- EOS of materials is not very well known, will make hydro simulations questionable.

Hydrodynamic simulation

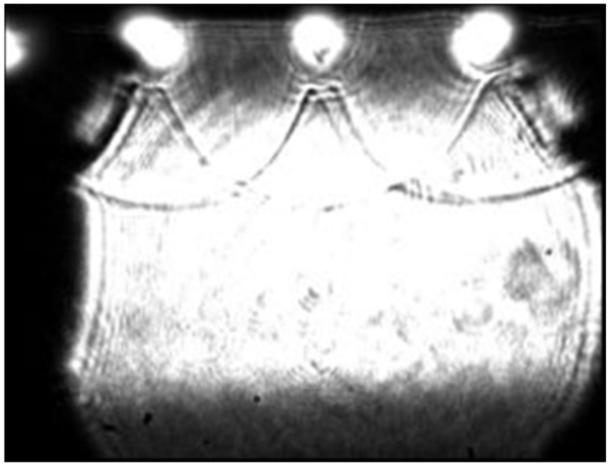
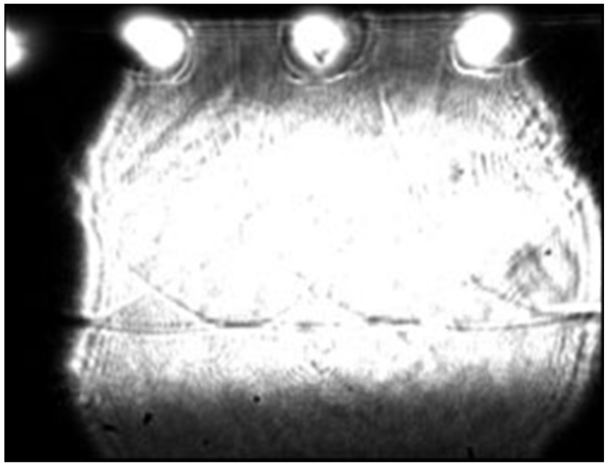
- A small hydro simulation with HYADES to estimate possible fusion yields of small scale demonstration experiments predicts 1E-5 to 1E7 neutrons depending on the water EOS table used.
- Definitively need more simulation both for ICF and MTF.
- Any hydro simulation scientists interested???

Experiment

- Develop a shock generator
- Piston impact will require fancy servo control system to have suitably small time jitter
- Not enough resources now
- Electric discharges are easier to time right
- First try spark-array igniting explosive gas mixture

Experiment

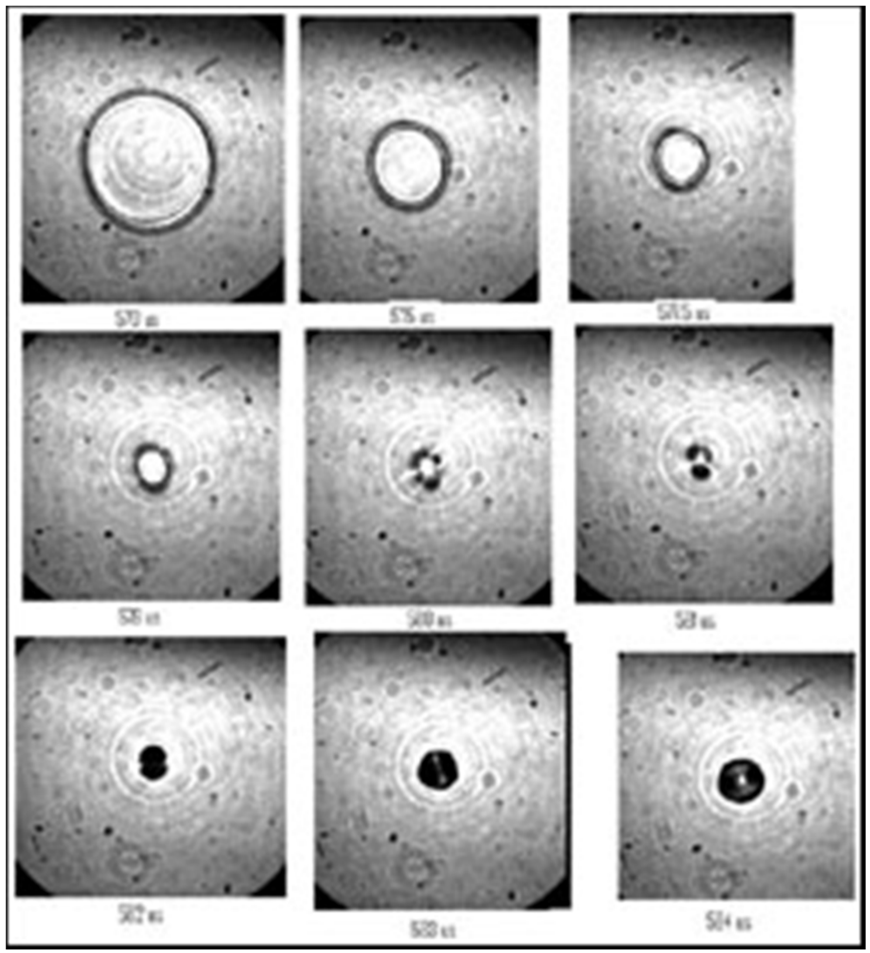
- Acoustic impedance mismatch between exploding gas and liquid is too high
- Spark-array itself makes a nice shock in air

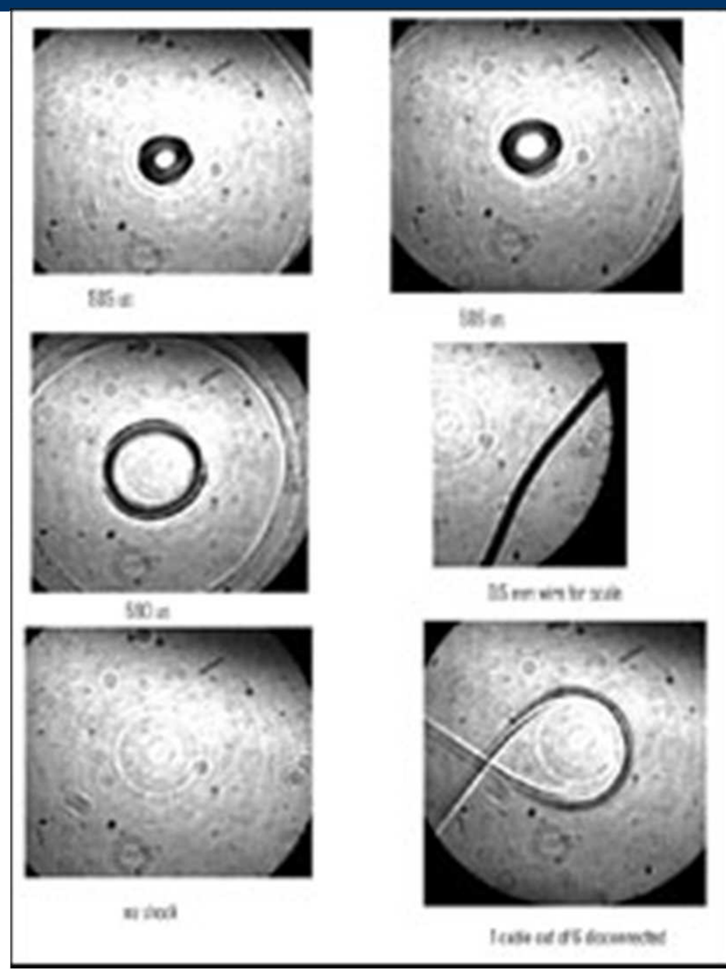
Cylindrical set-up

Cylindrical machine power supply

Cylindrical shock in air



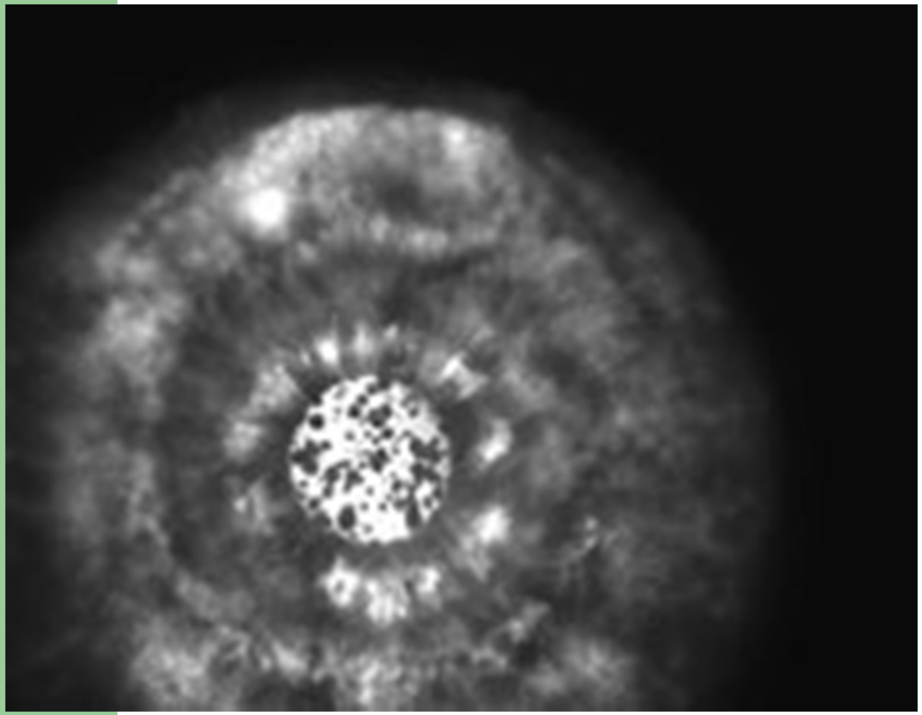
Cylindrical shock in air

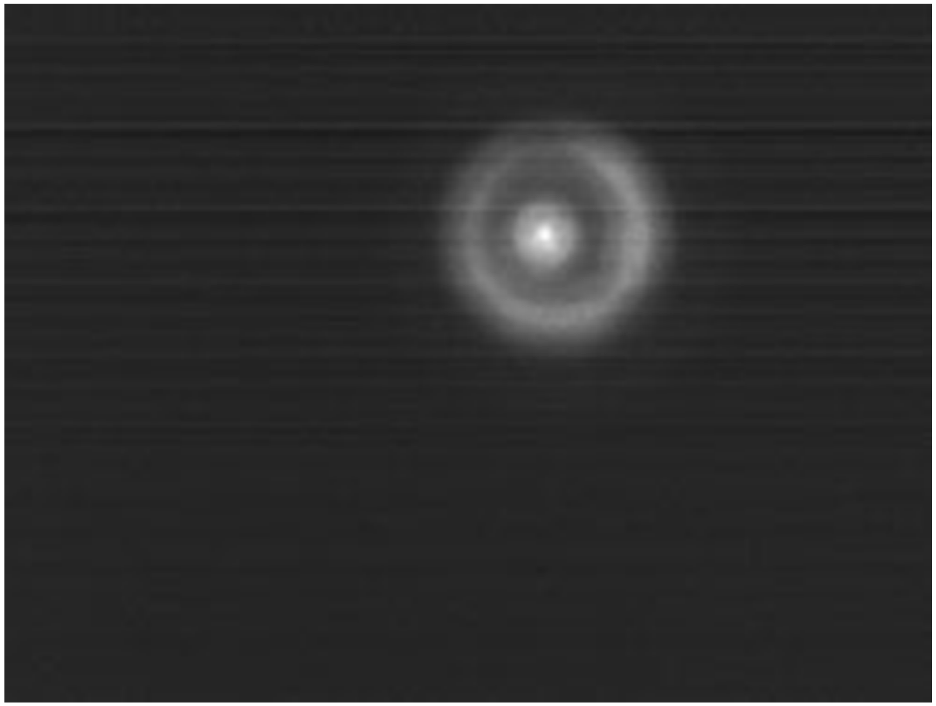


Cylindrical shock in water

- Spark-array did not work in water. Only one array fired and took all the energy.
- Changed to exploding aluminum foils by passing high current in them
- Worked well

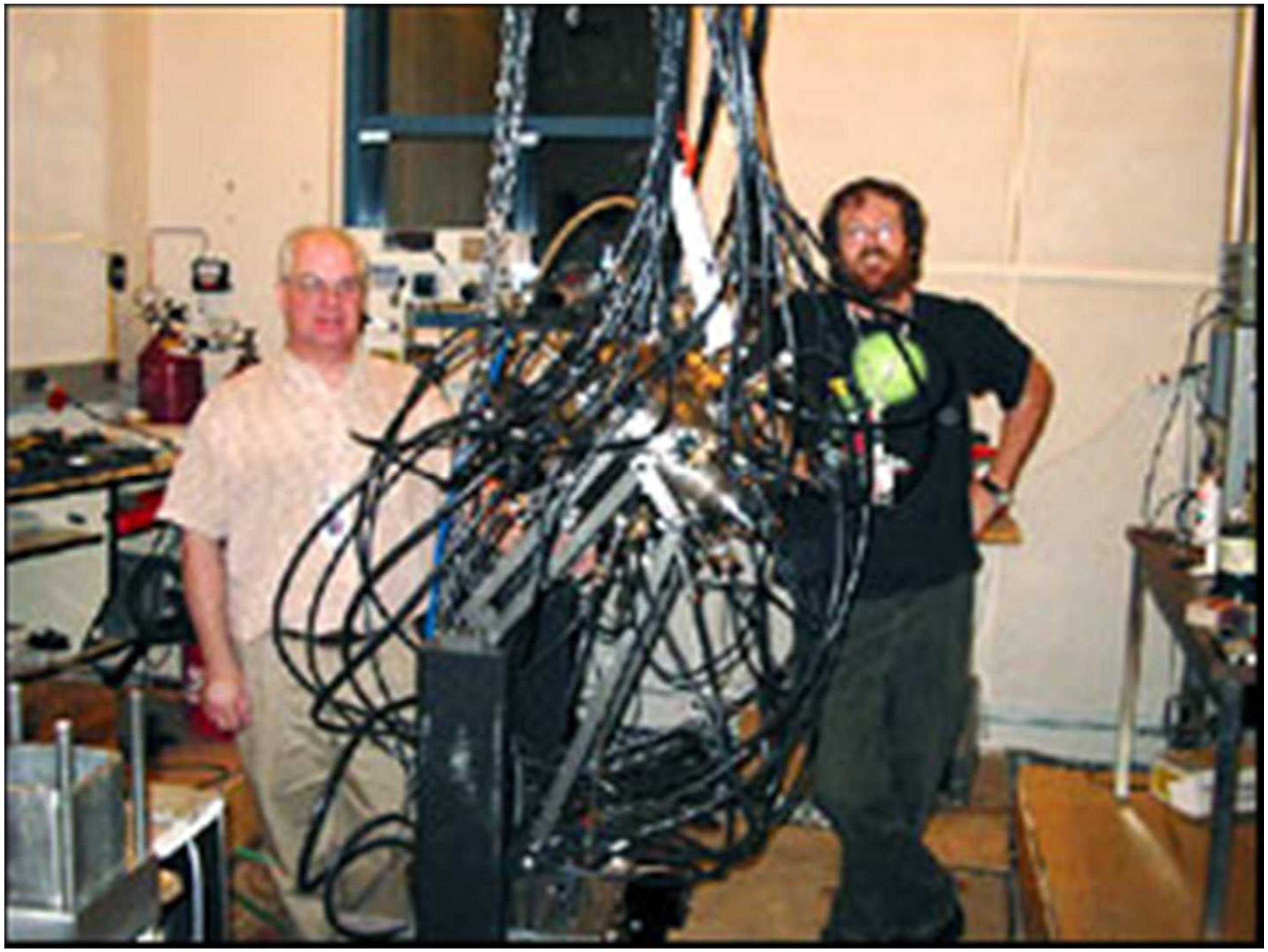
Cylindrical shock and plasma





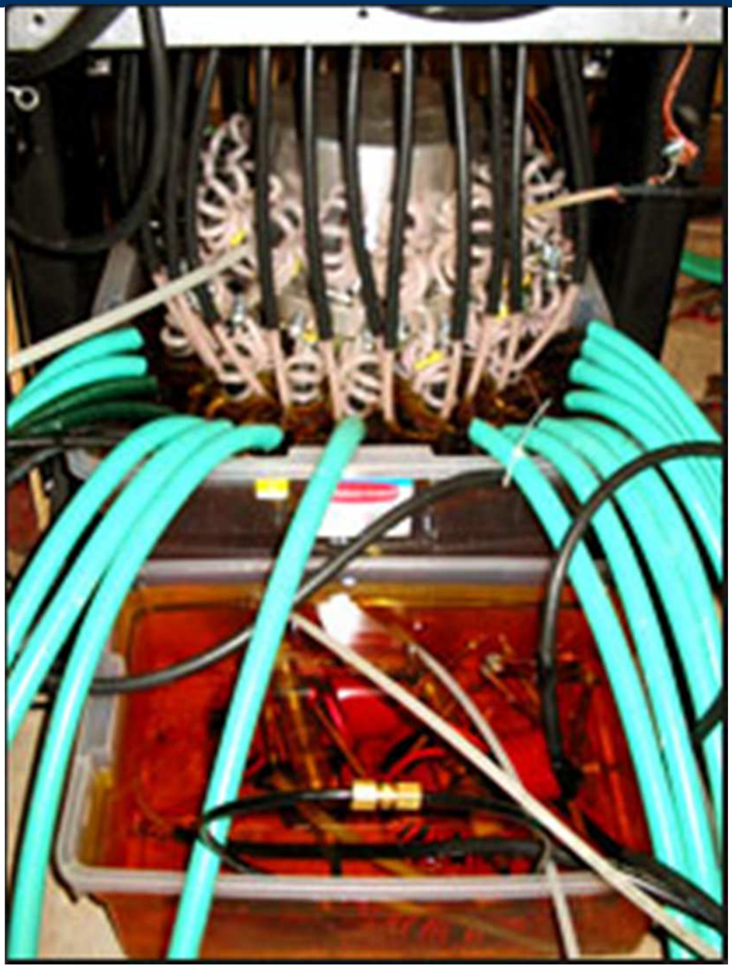
Naked sphere

Sphere

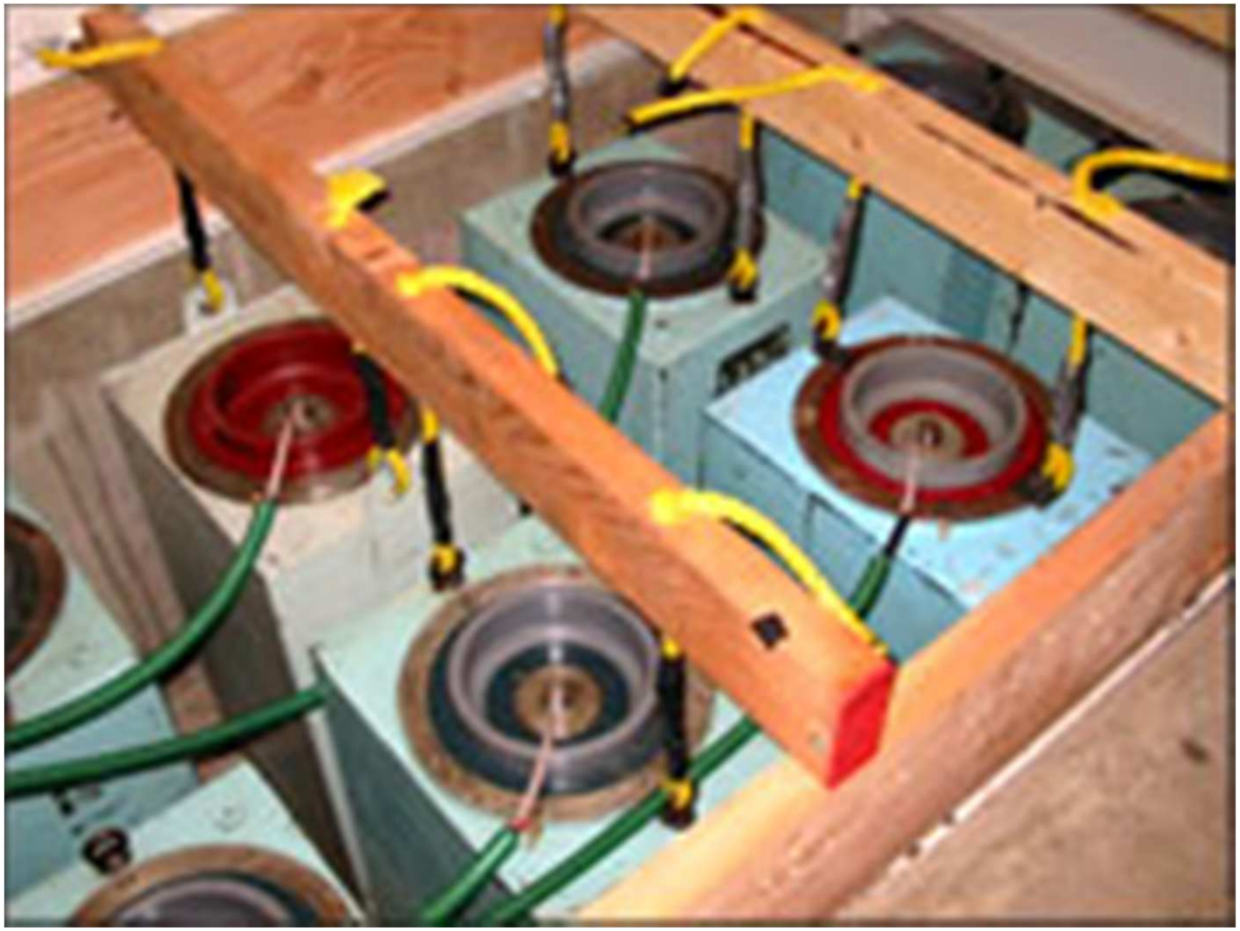


Sphere open

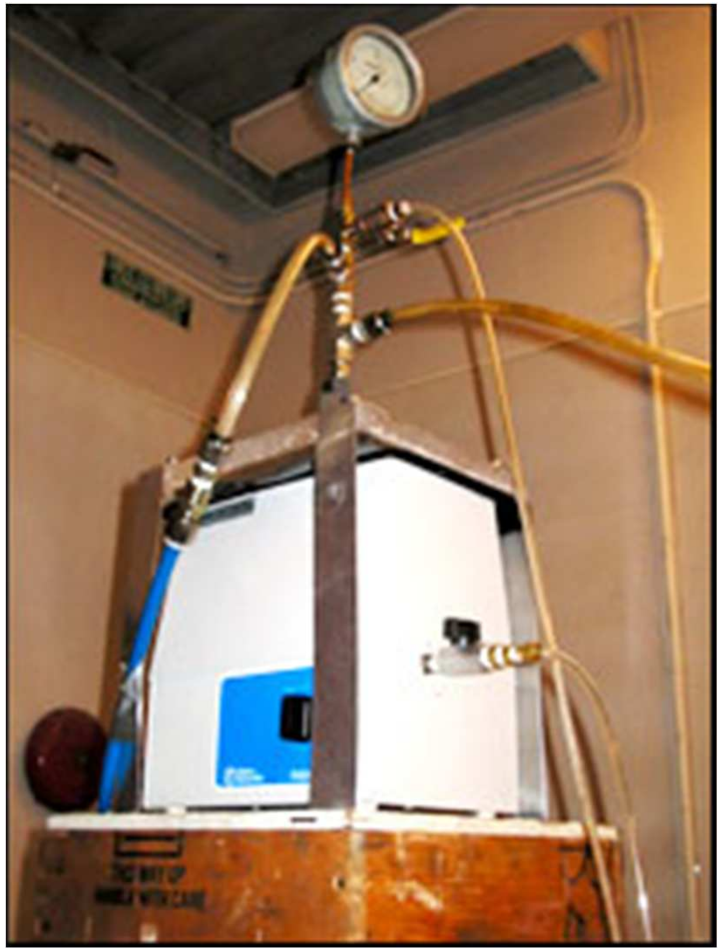
Spark gap switch



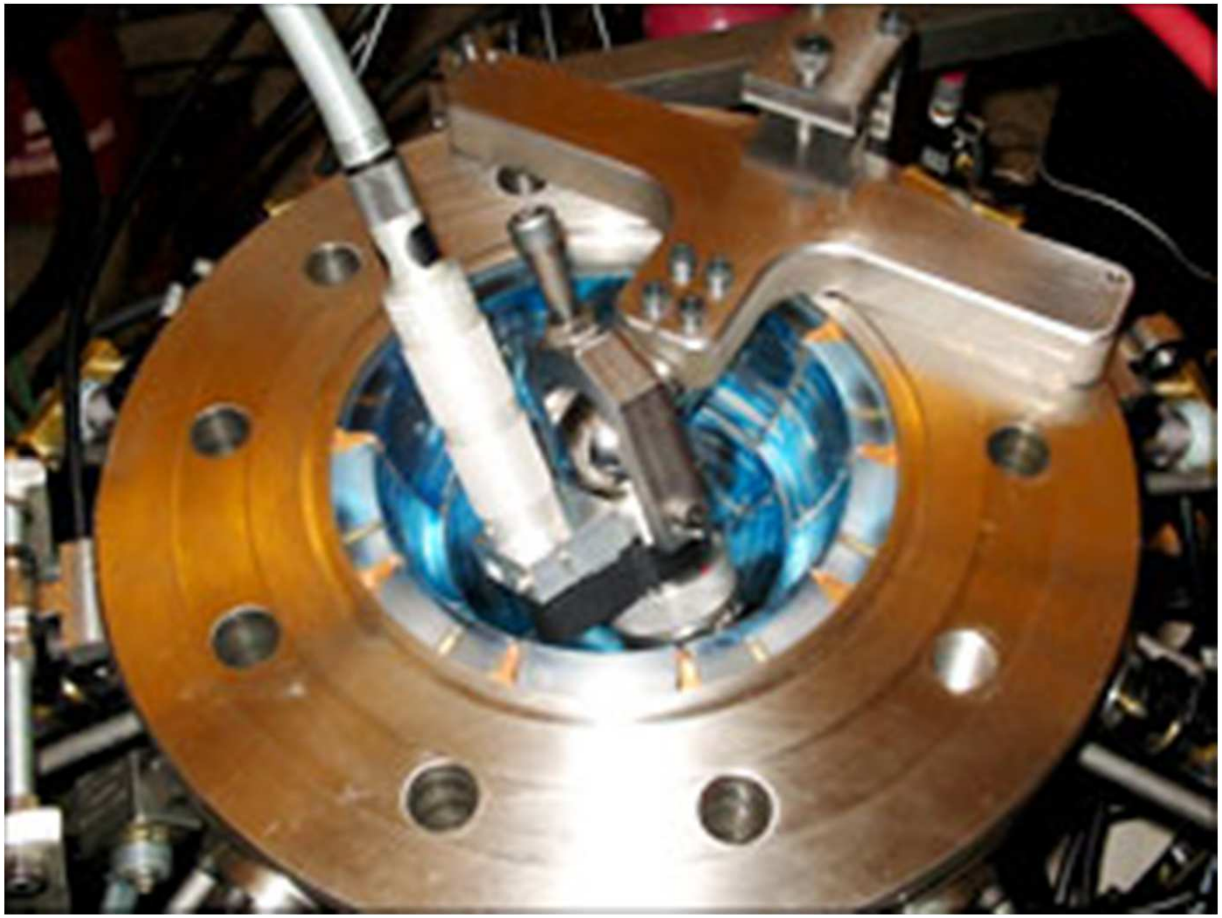
Capacitor bank



Ultrasound water degassing

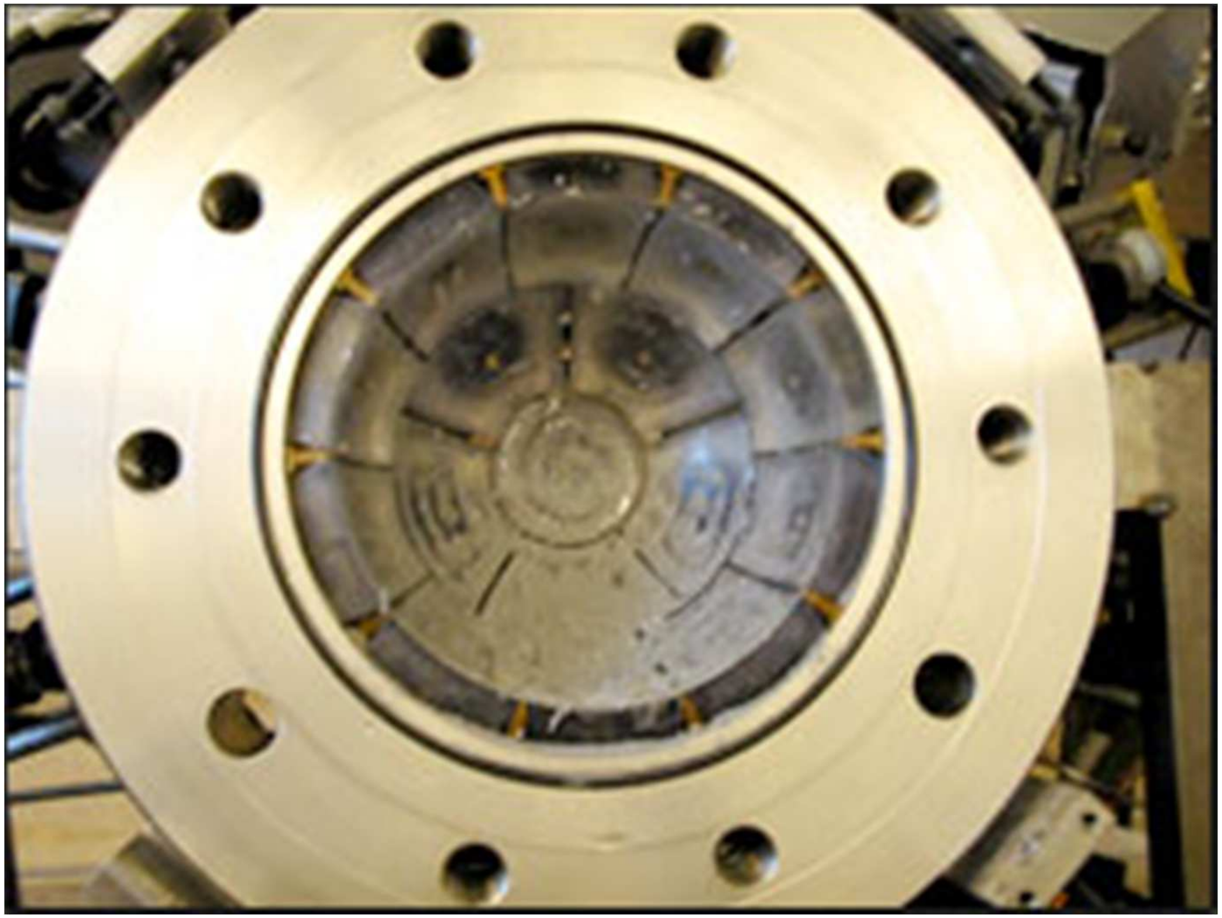


Spherical mill

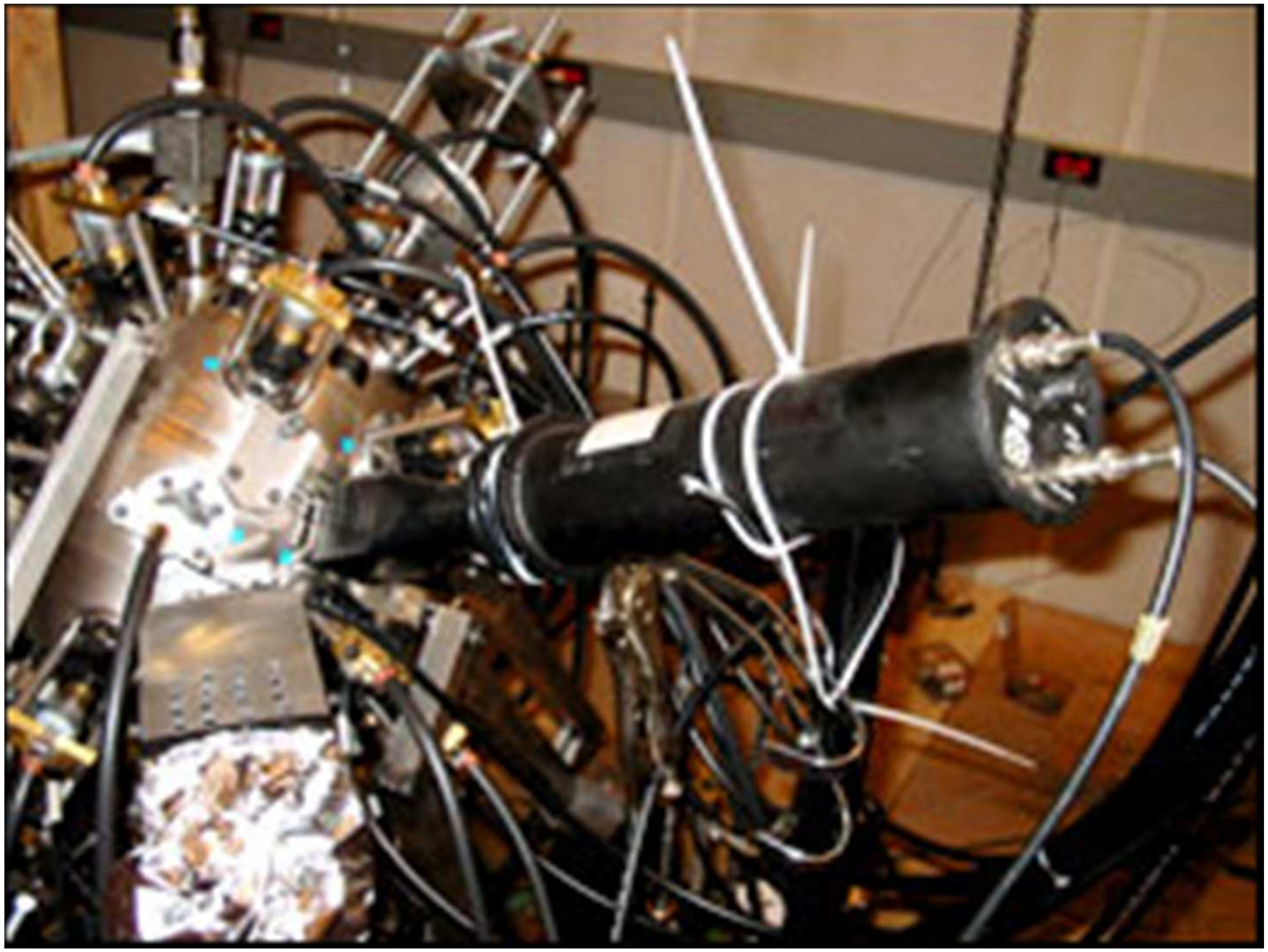


Aluminum foil spirals

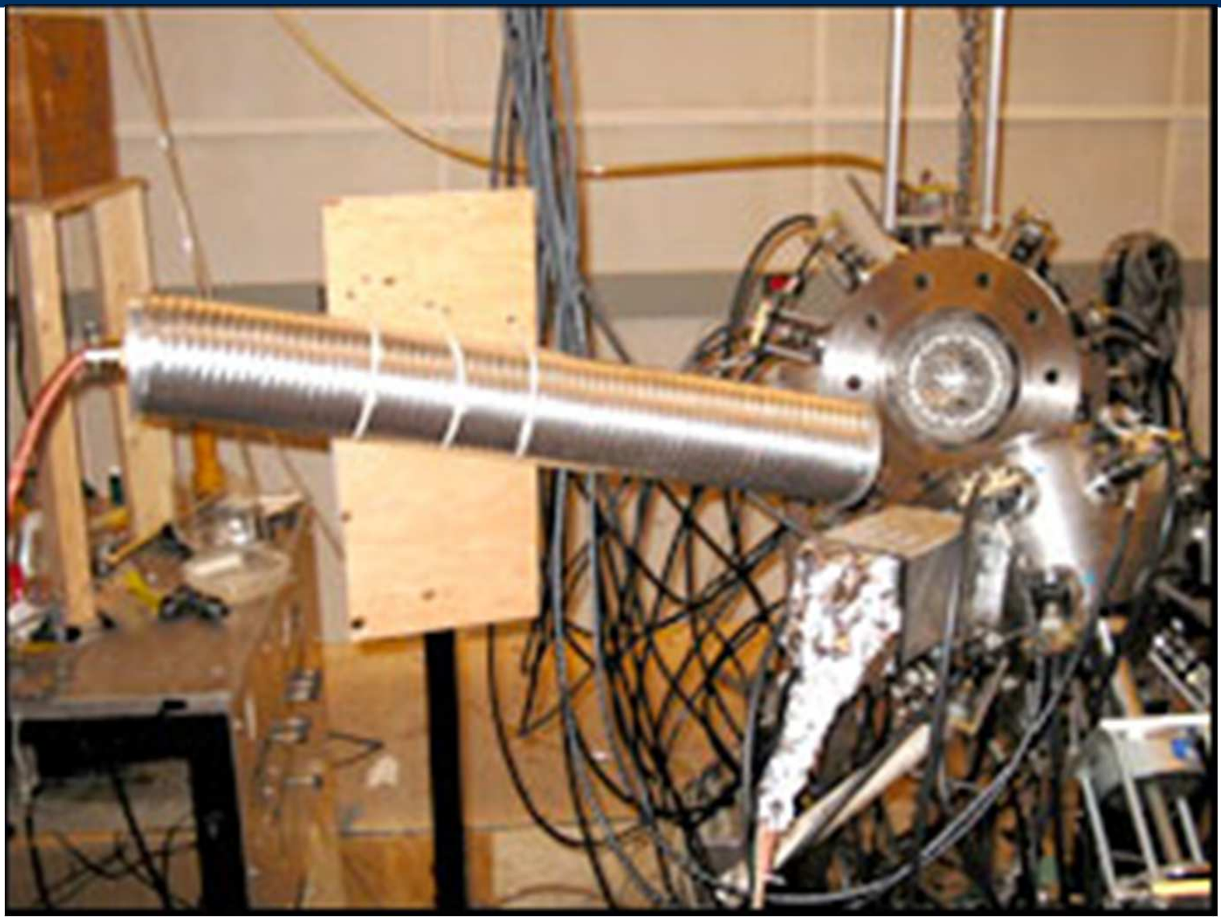
Blown foil



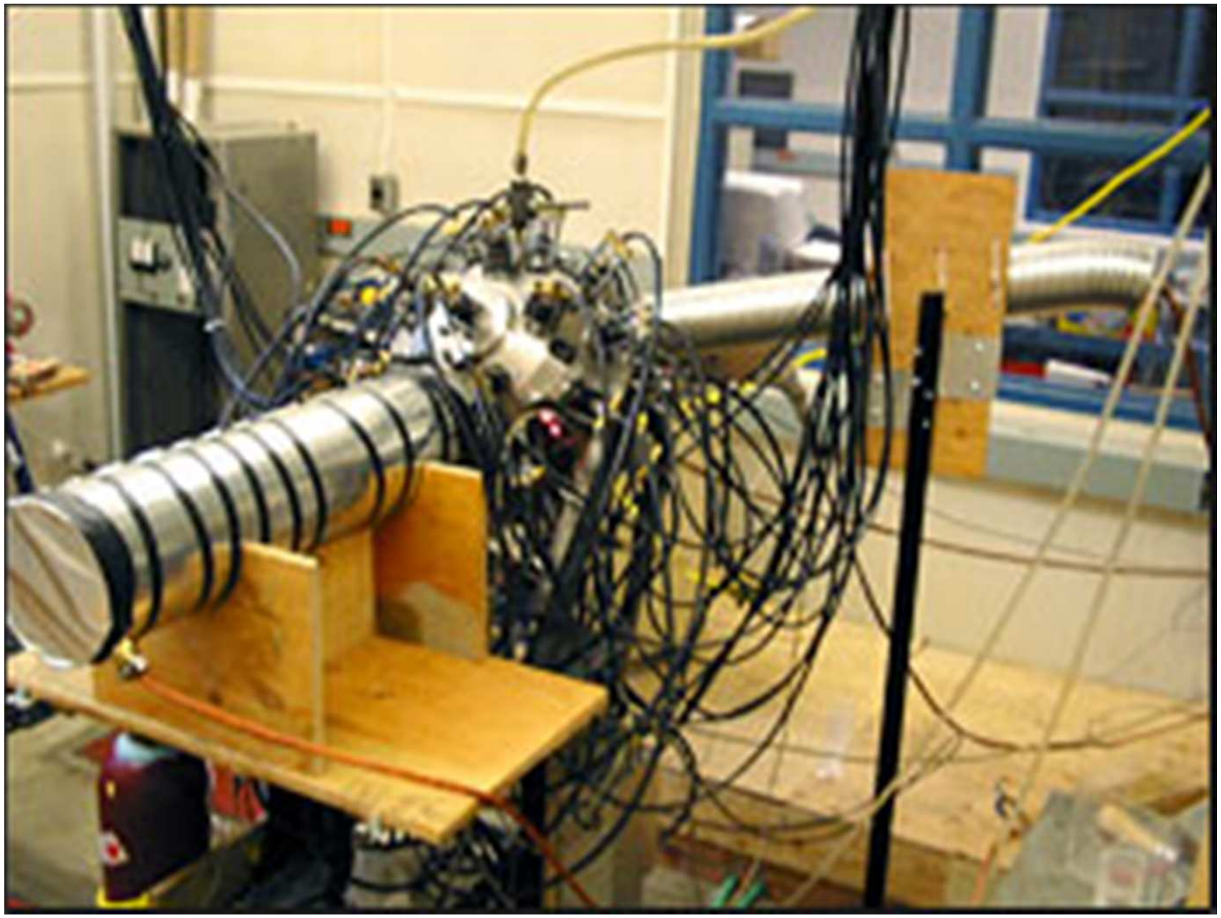
Plastic scintillator



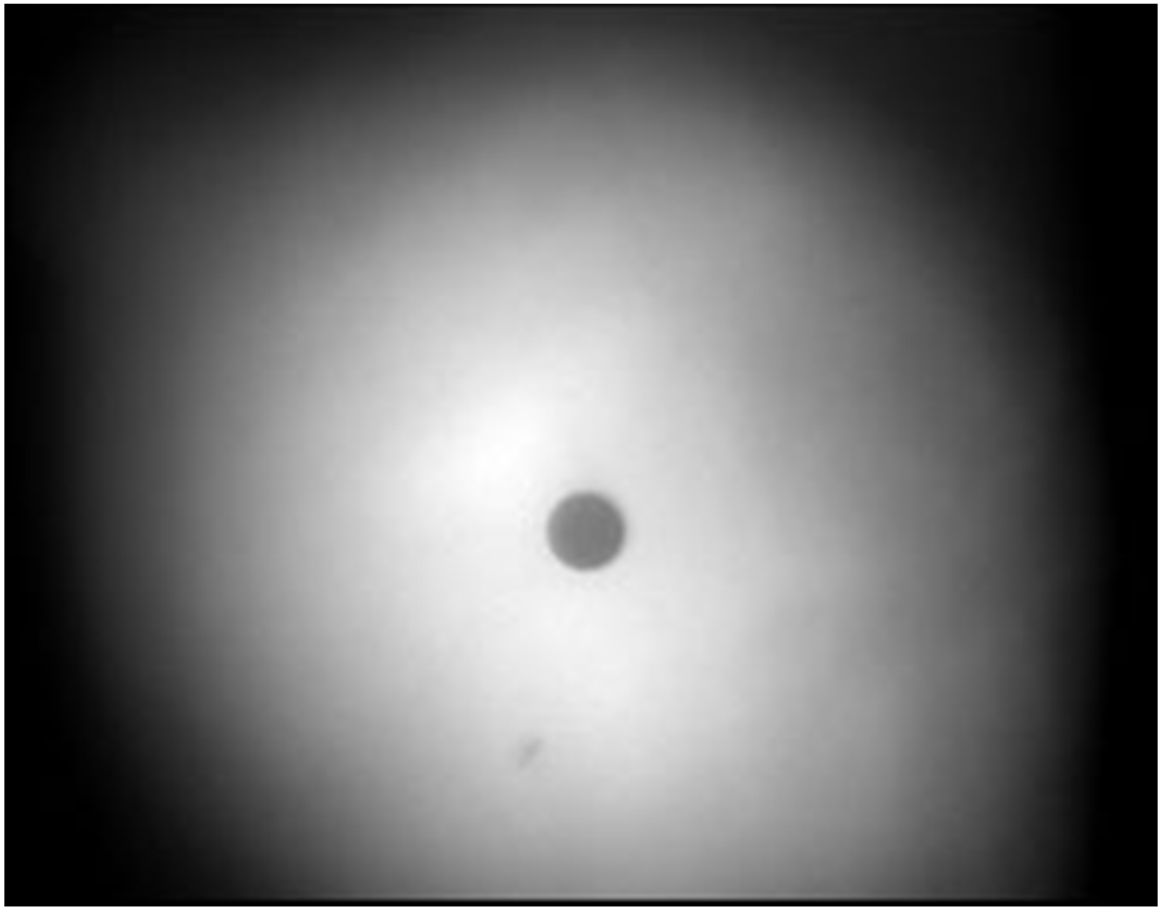
Shielded plastic scintillator



Shielded liquid scintillator



Bubble tracked by two cameras



Sphere specification

- Diameter: 16 cm
- Surface accuracy: 20 um
- Capacitor: 32 X 1.9 uF=60.8 uF
- Max voltage: 60 kV
- Max energy: 100 kJ
- Timing accuracy between 32 foils: <5 ns
- Ringing time: 11 us

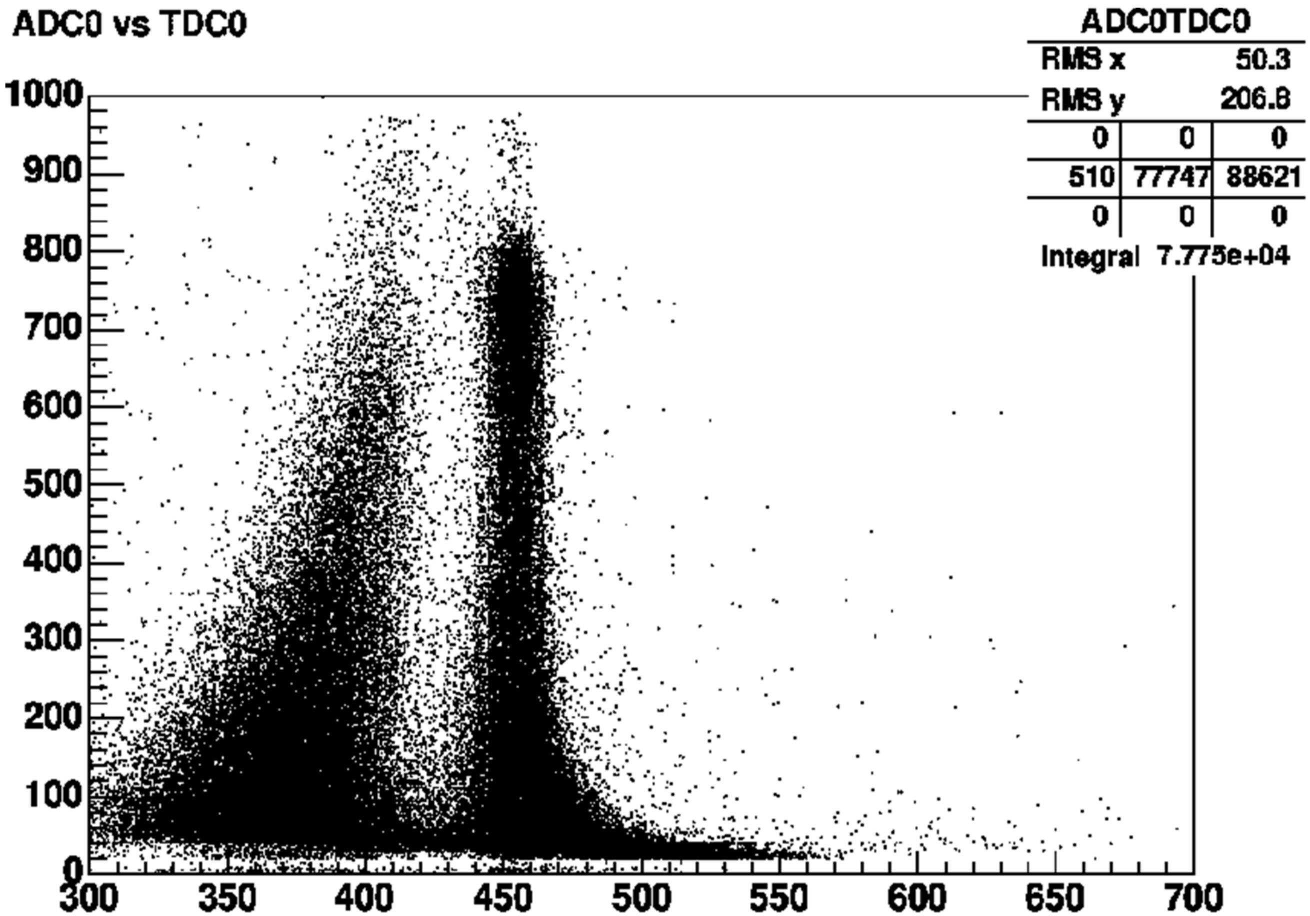
Sphere specification

- Energy transfer time: 90% of energy in 5 us
- Max Power, current: 20 GW, 700 kA
- Experiment so far ran at: 38 kV, 9 GW, 400 kA
- Deuterium bubble diameter: 100 um<D<6 mm
- Bubble pressure: 0.4 psi to 160 psi
- Bubble centering: +/- 30 um
- Bubble spherical to better than 7 um

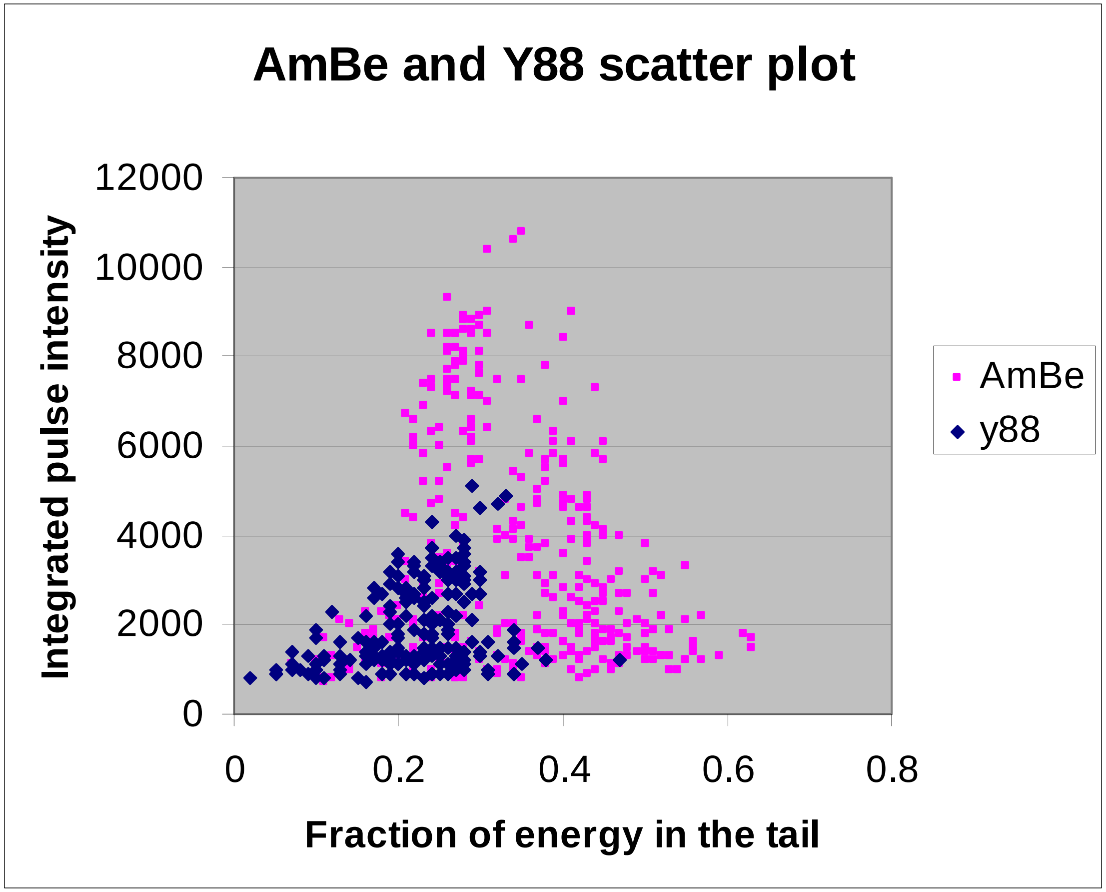
Detectors

- 5 x 5 x 7.5 = 187 cm3 plastic scintillator
- 1.8 MeV gamma Compton edge at 150 mV
- D=12.5 cm, L=7.5 cm, 920 cm3 NE213 liquid scintillator
- 1.8 MeV gamma Compton edge at 840 mV
- Liquid scintillator can do pulse shape discrimination (PSD). Neutrons produce longer pulses than gamma rays

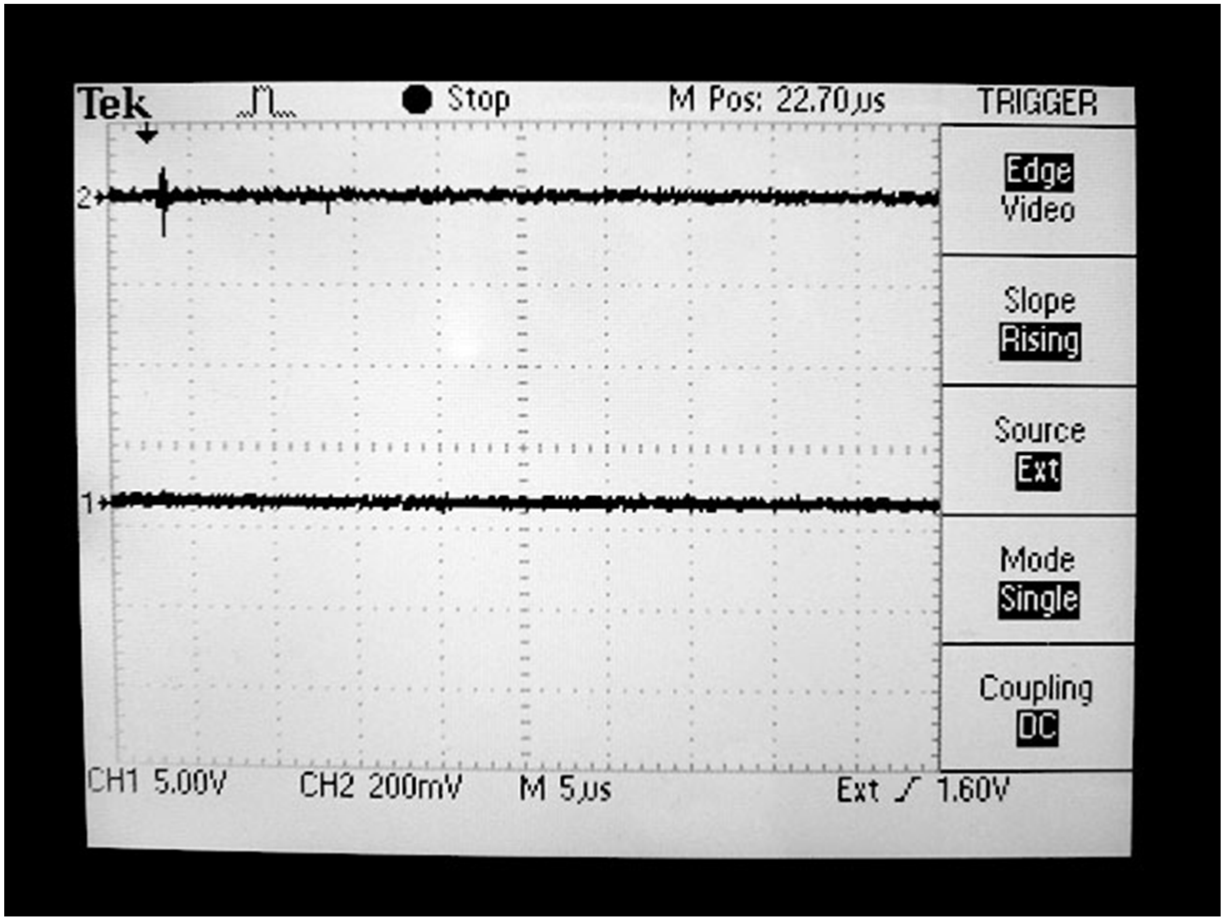
AmBe PSD with analogue NIM



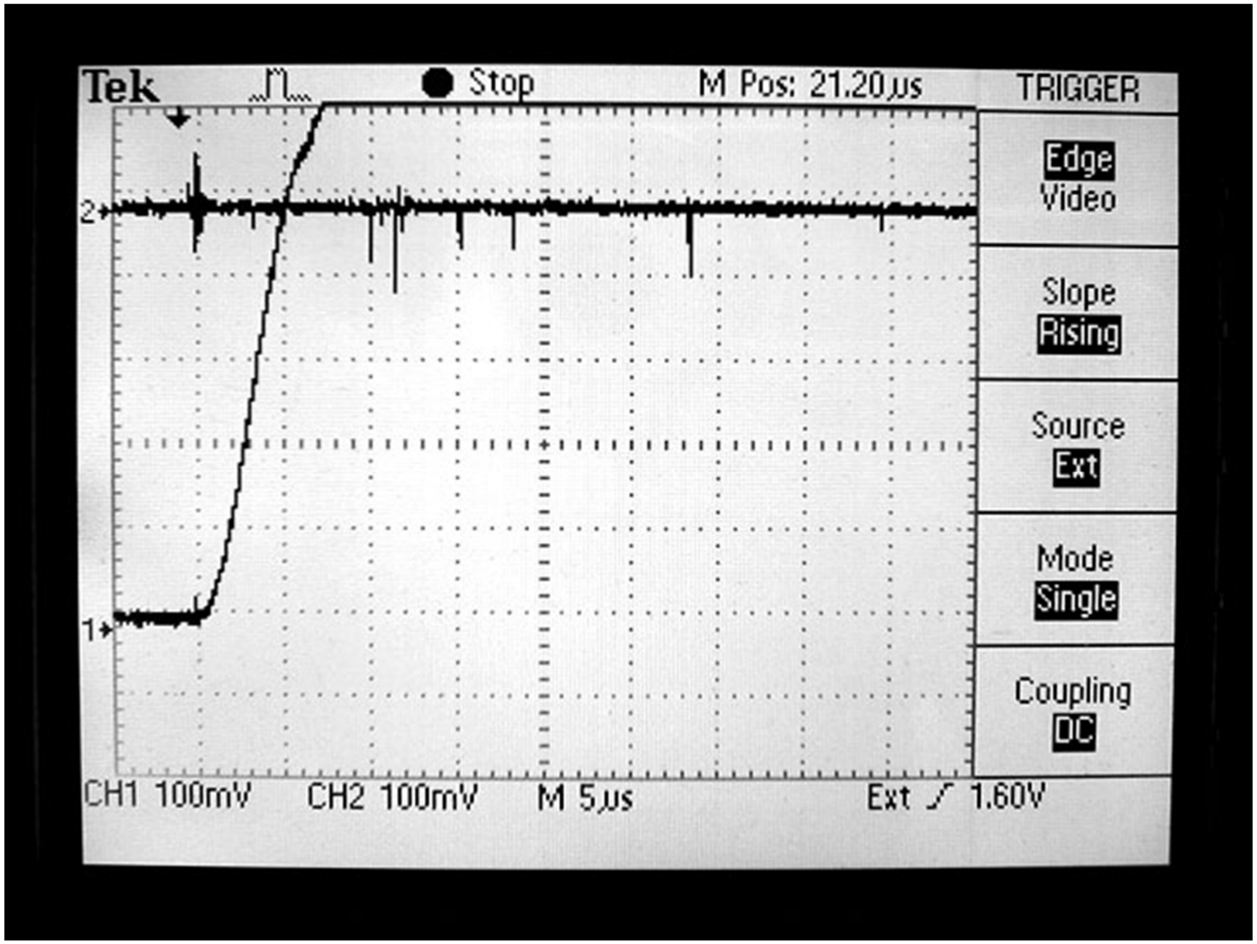
AmBe and Y88 PSD from digital traces from oscilloscope



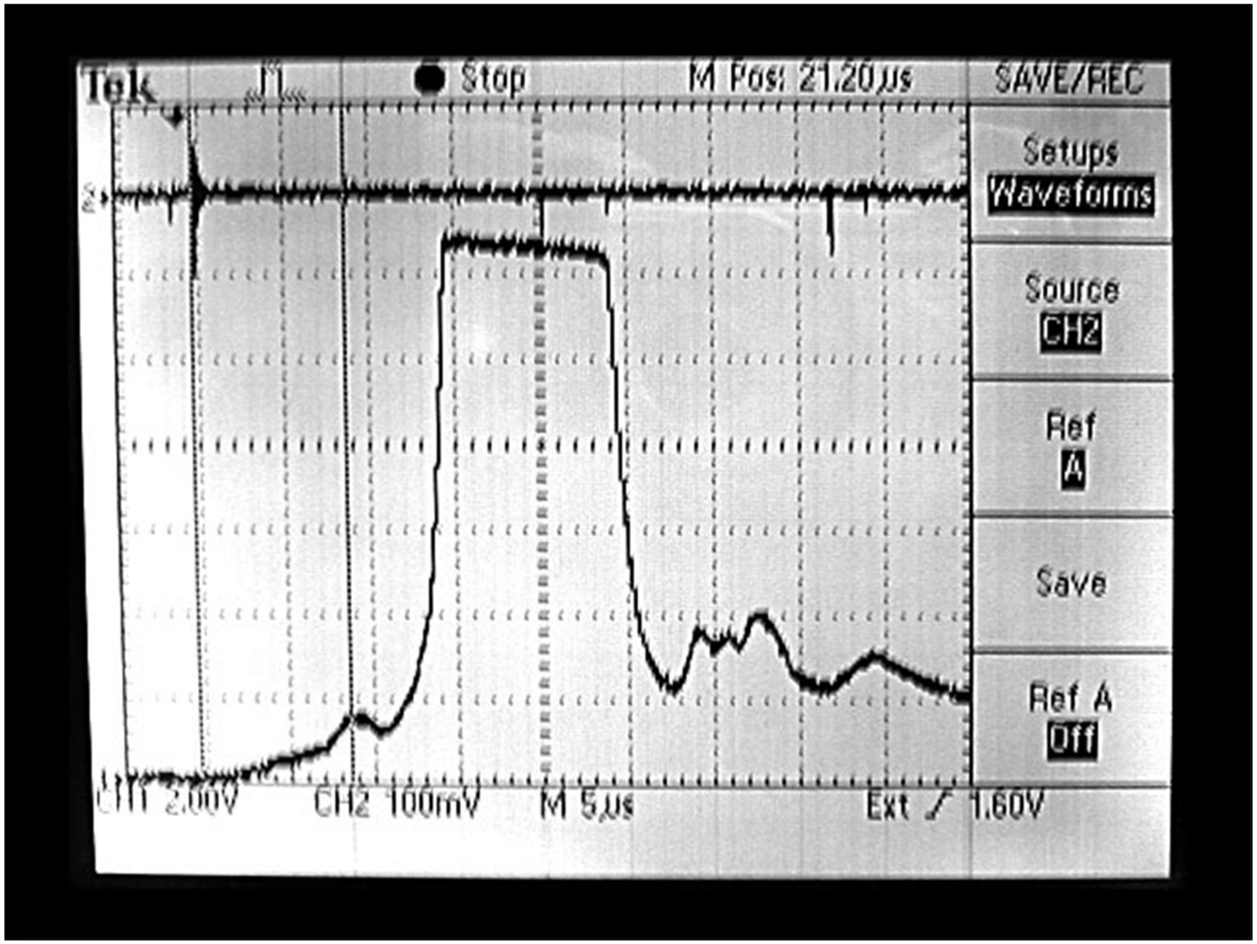
Results, 5 out of 8 shots in Deuterium gave a signal



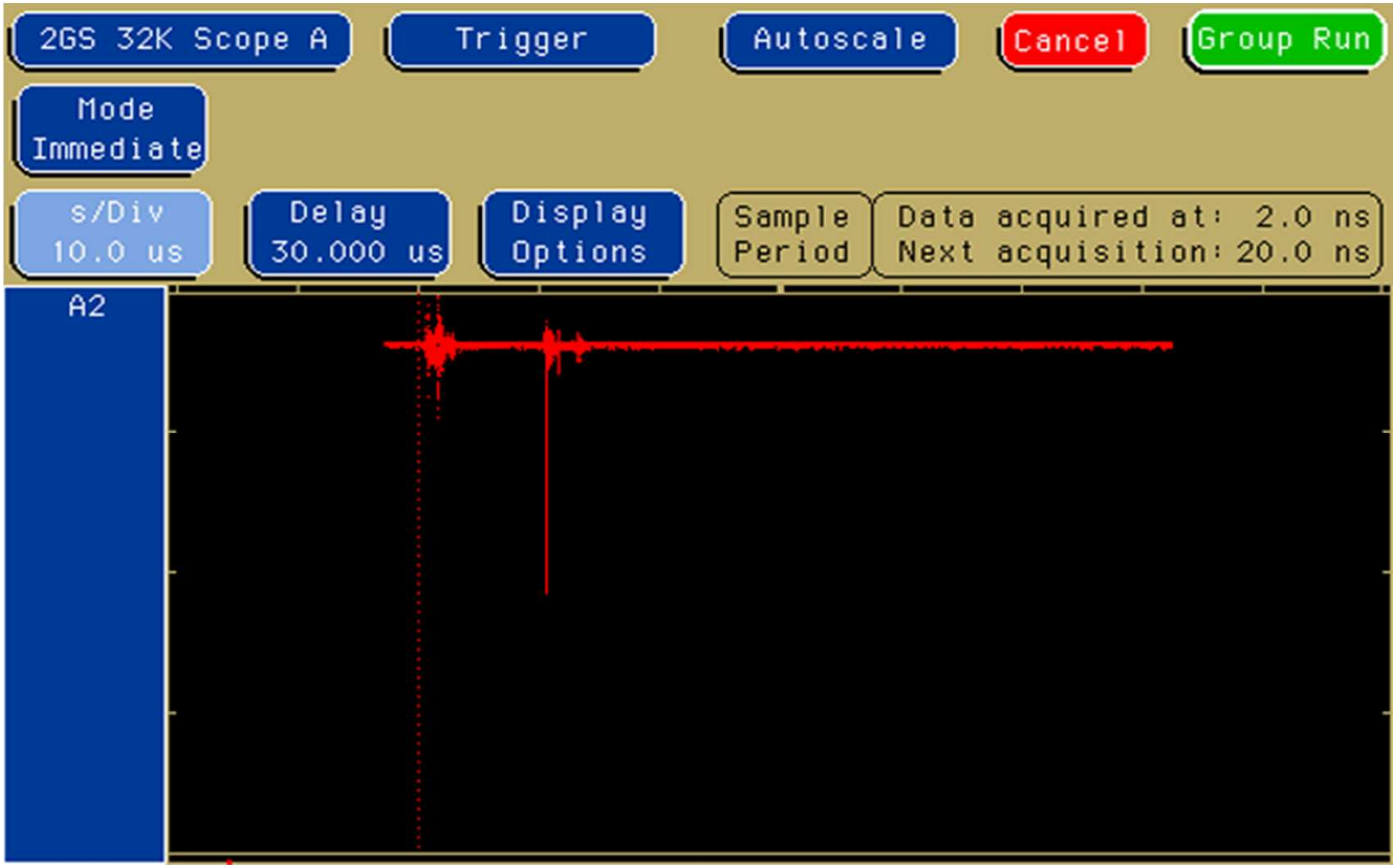
Deuterium results



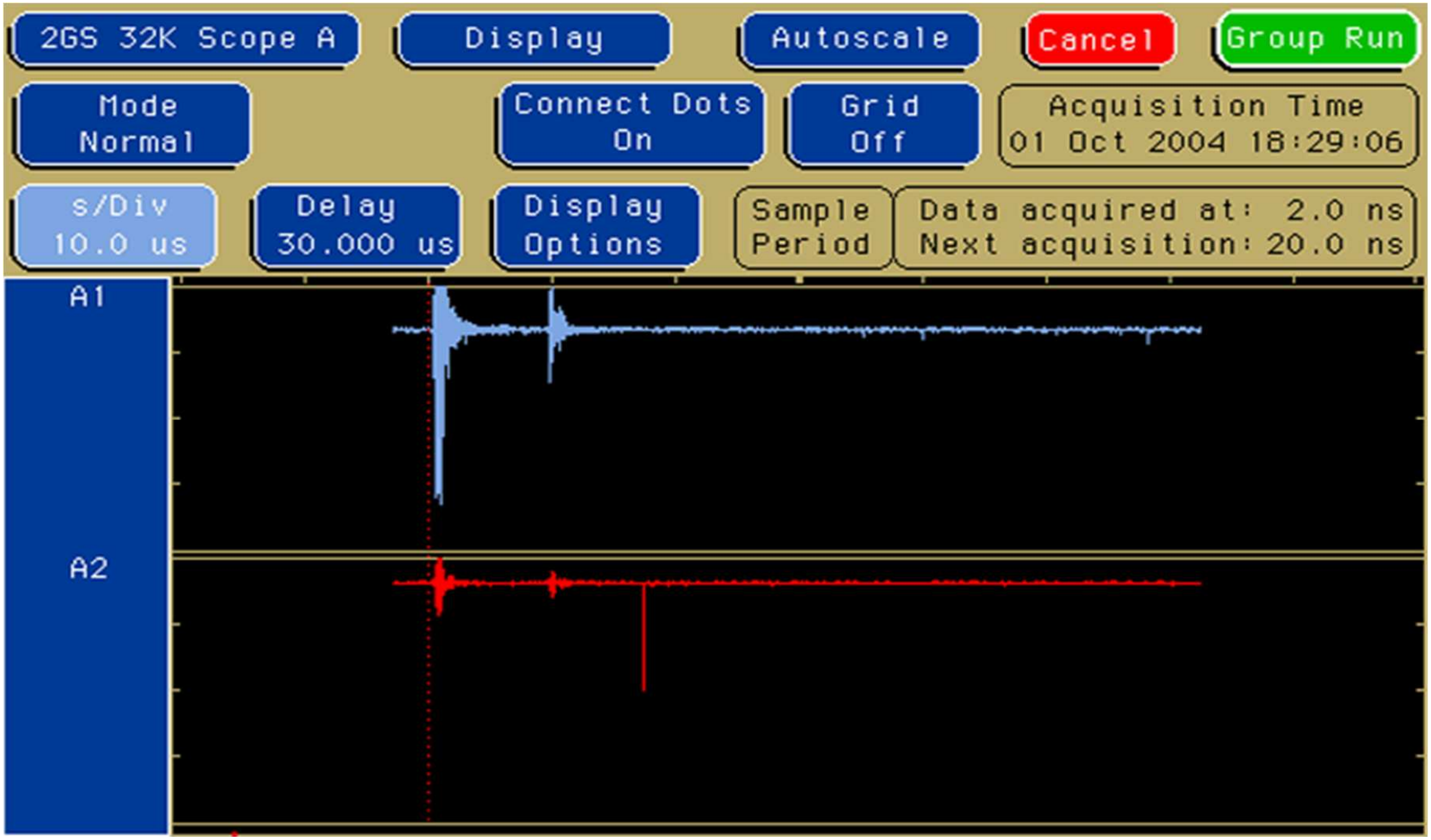
Deuterium results



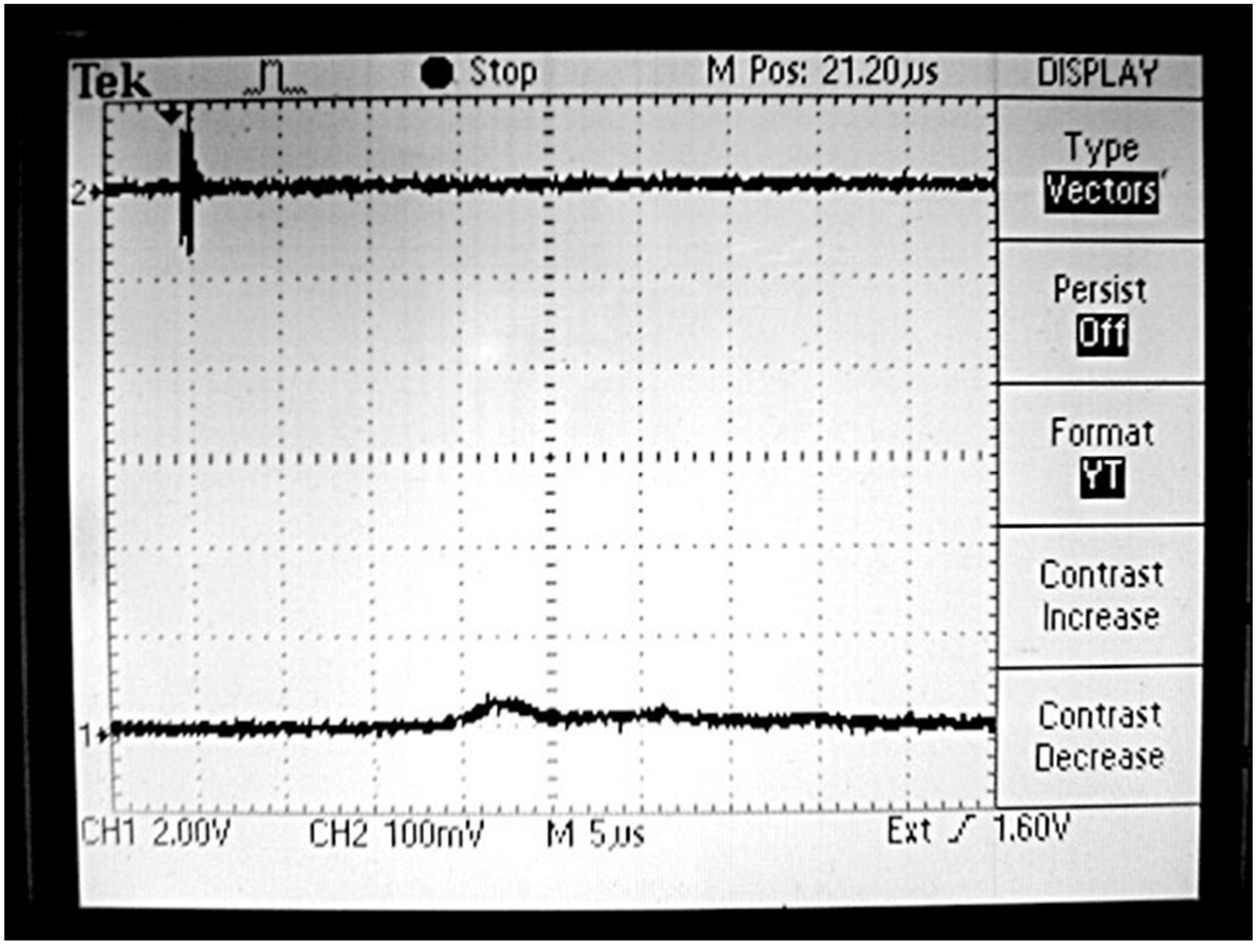
Deuterium results



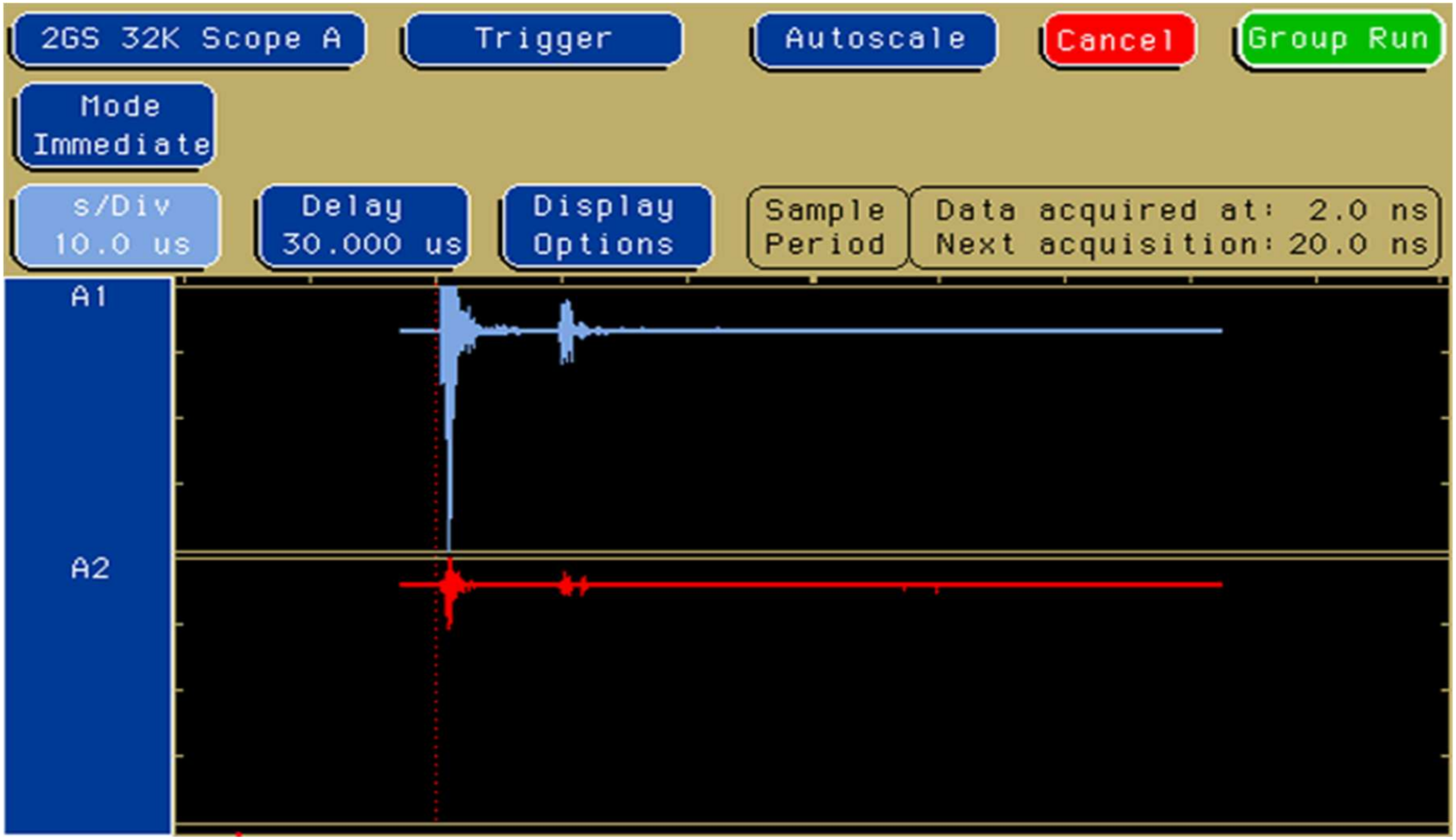
Deuterium results



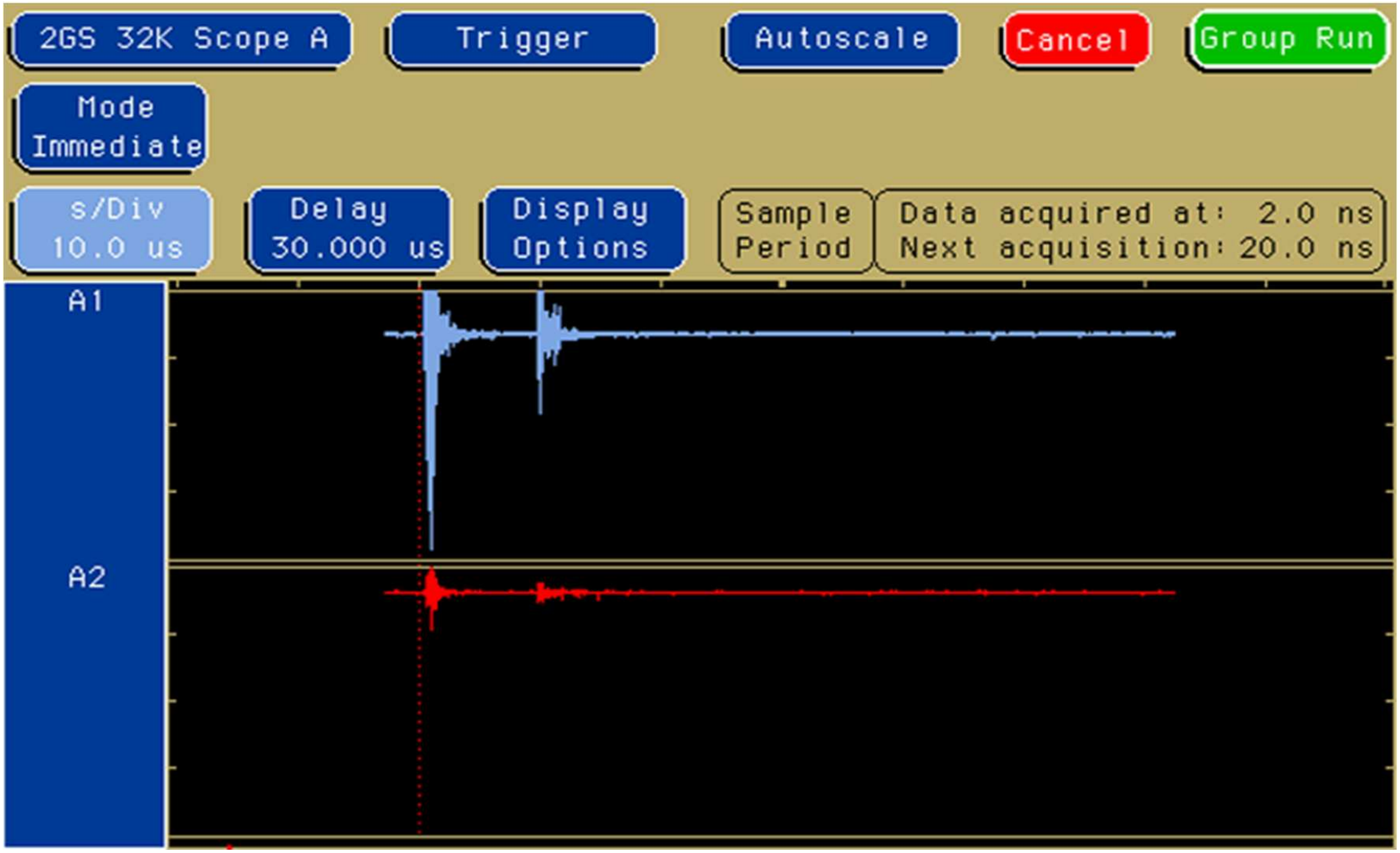
4 out 4 shots with hydrogen gave no signal



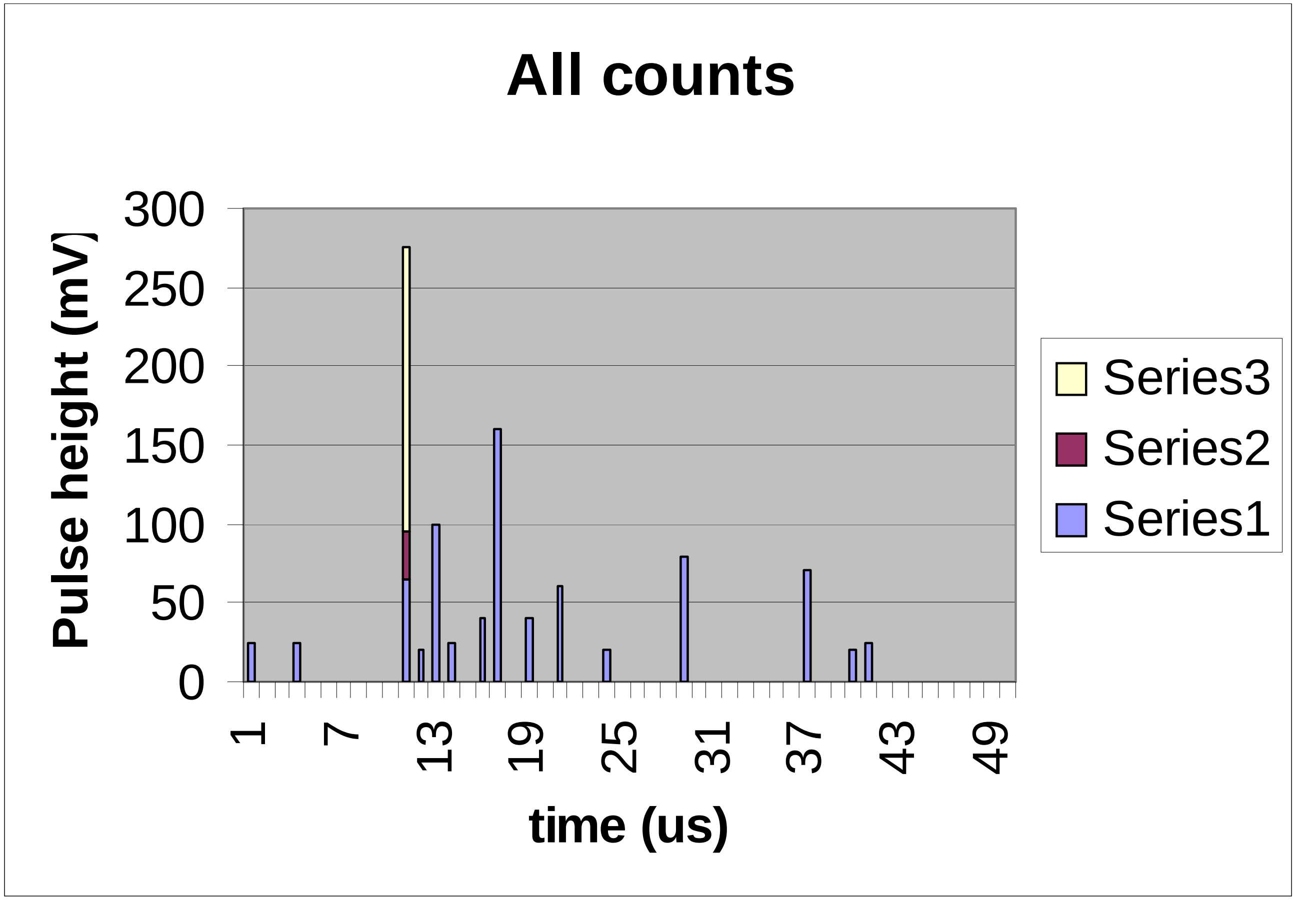
Hydrogen results



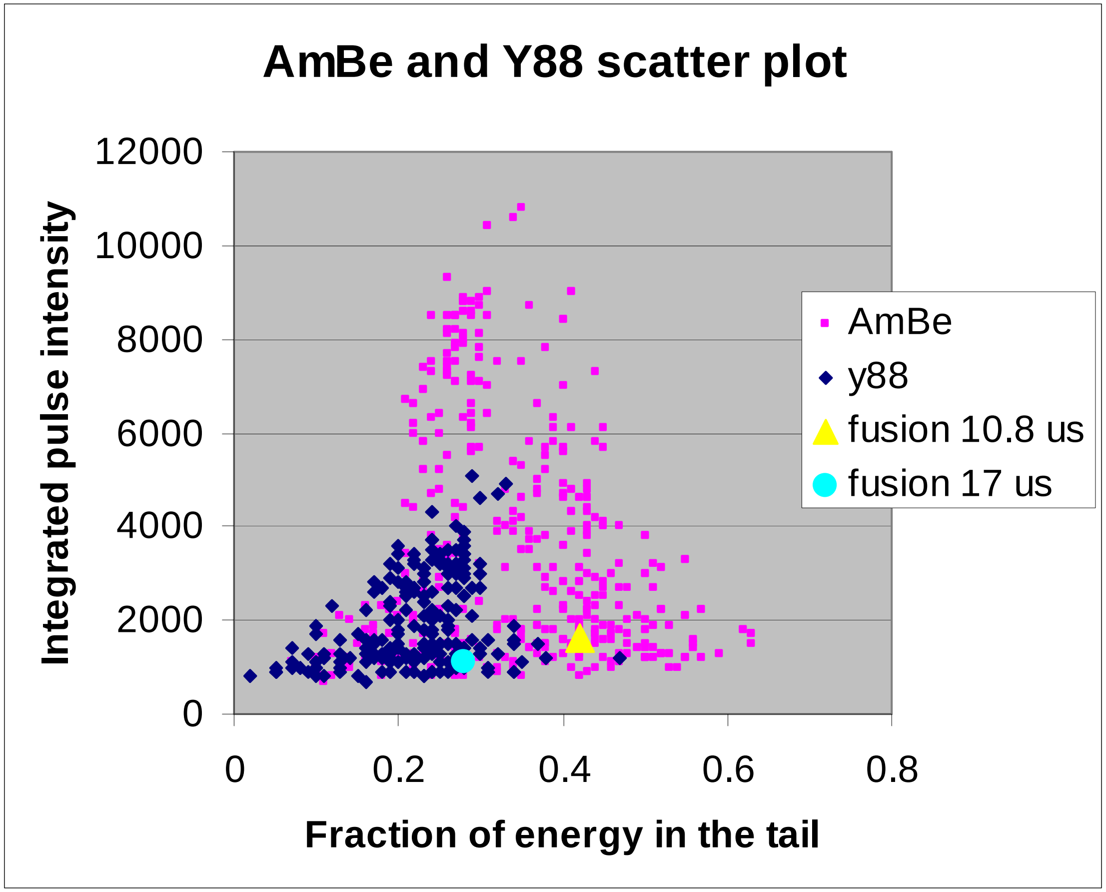
Hydrogen results



All signals on a plot



PSD of fusion results



Results

- Signal above background
- Particularly 3 signals at 10.7 +/- 0.1 us is very unlikely
- One would expect a quick neutrons peak, what are the later counts?
- Water thermalizes some neutrons, they diffuse for many us, they are absorbed by water and steel and emit delayed gamma rays

Monte Carlo Simulation

- The delayed gammas are predicted by a neutrons and gammas transport code (MCNP)
- It predicts more neutrons than gammas, we seem to see more gammas than neutrons
- All fast neutrons arrive simultaneously, average neutron count is small. So our neutron peak may be many neutrons at the same time
- From this code and assumption, our best shot gave a fusion yield of 5E4

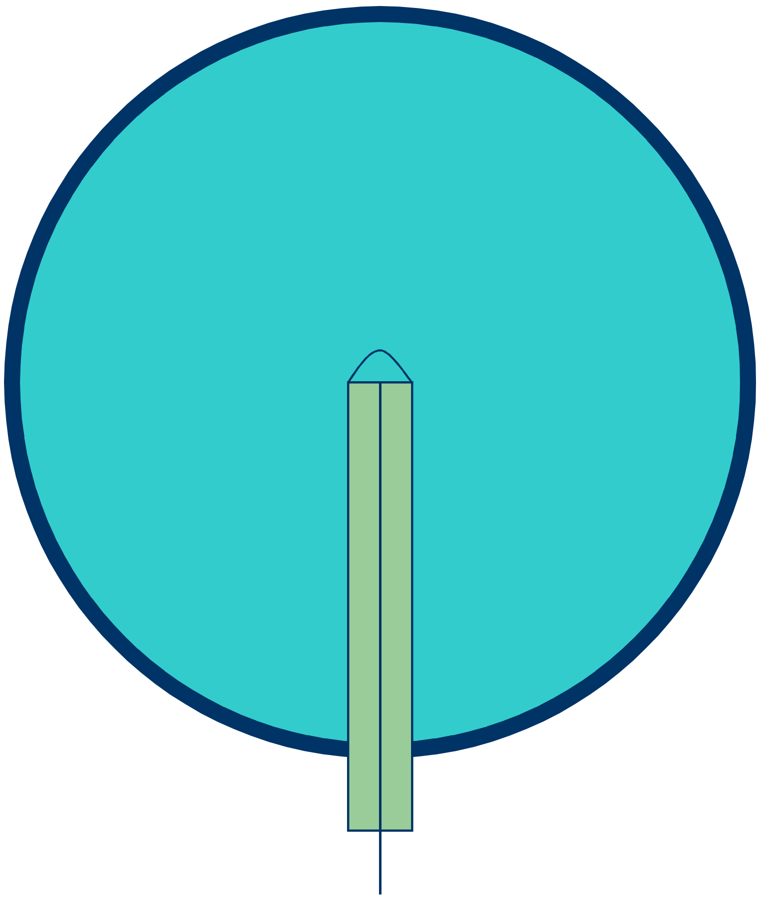
Interpretation

- The signal at 10.7 us is many neutrons at the same time from D-D fusion
- The later signals are gammas from thermal neutron absorption
- 10.7 us correspond to an average shock speed of Mach 5.

Review of the data

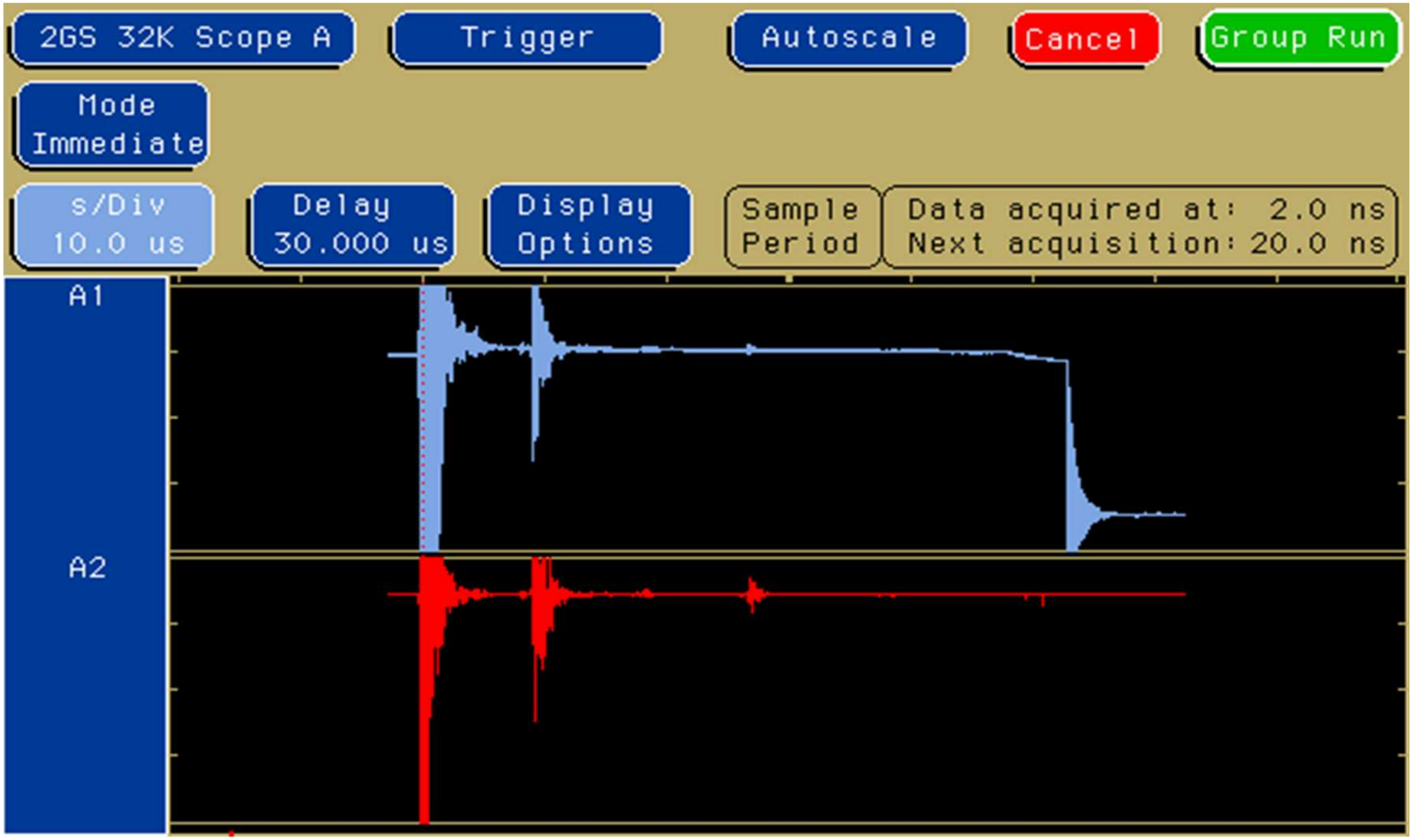
- We sent out the data to be reviewed by experienced scientists
- They were not convinced
- One proposed to try to measure shock arrival time in center, it should be 10.7 us if interpretation of the signal is correct

Shock arrival time measurement



Coaxial cable with small aluminum foil just above center conductor. Shock closes the contact.

Shock timing



Shock arrival time

- The shock seems to arrive at 52.8 us, that is within experimental error Mach 1
- Not compatible with fusion signal at 10.7 us
- Possible problem with the shock damaging the cable and switch before the shock arrives giving the wrong timing
- Possibly correct, therefore no fusion signal

Future plan

- Try to detect neutrons in present set-up
- Hydro simulation (anybody interested??)
- If promising, build a bigger experiment
- Cost ~5 M$
- Energy 10 MJ
- Time to build 2-3 years