High Gradient Research at NRL

Steven H. Gold
Naval Research Laboratory

US High Gradient Research Collaboration Meeting
SLAC National Accelerator Laboratory
9–10 February 2011

Activities

- **Dielectric-Loaded Accelerating (DLA) Structures**
  (with ANL, Euclid, SLAC)
  - Multipactor and breakdown in DLA structures
    — 16 experiments since 2002 (plus one at SLAC)
  - Compact X-Band Test Accelerator—work in progress
- **High Power RF Pulse Compressors**
  - Active Pulse Compressor with plasma switch tubes (with Omega-P, IAP) — 8 tests (2002–2008), then transitioned to SLAC for active SLED experiments
  - Active Pulse Compressor with e-beam switching (with Omega-P, IAP) — first test January–March 2011
  - Active Pulse Compressor with ferroelectric switching (with Omega-P, Yale, Euclid) — first test later this year

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Dielectric-Loaded Accelerating Structures

DLA (Dielectric-Loaded Accelerator)

- Low-loss dielectric liner, instead of irises, used to reduce v_{ph} to *c*.

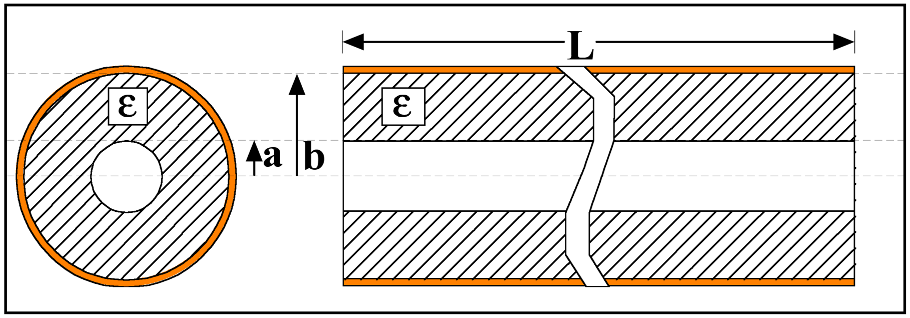
Principle Advantages

- Simple geometry
- No field enhancements on irises
- High gradient potential

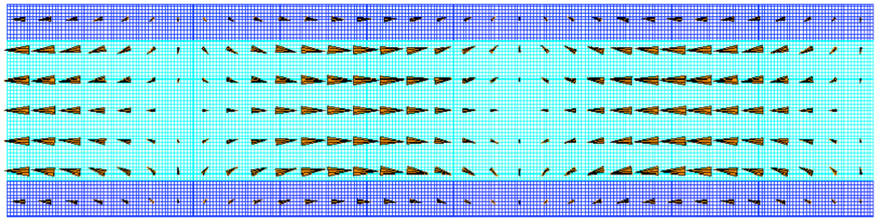
Major Issues

- Multipactor
- Breakdown at dielectric joints

Geometry



Electric Field Vectors

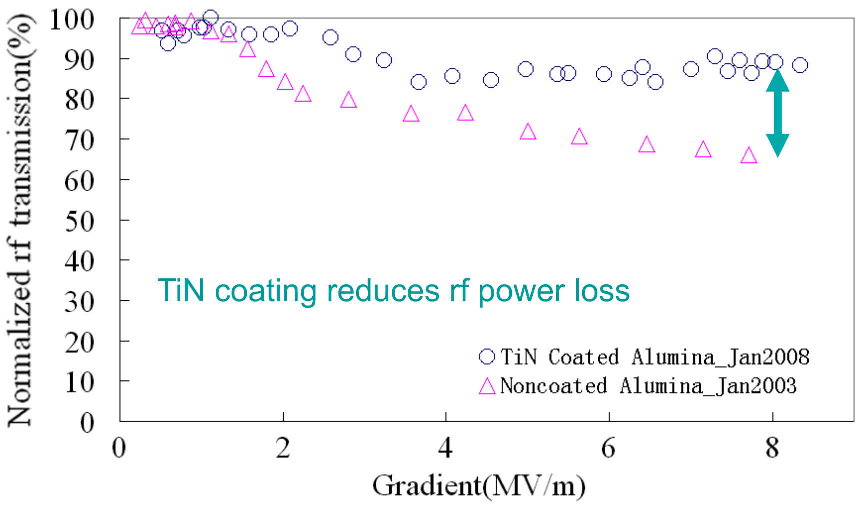


Summary of DLA Test Structures

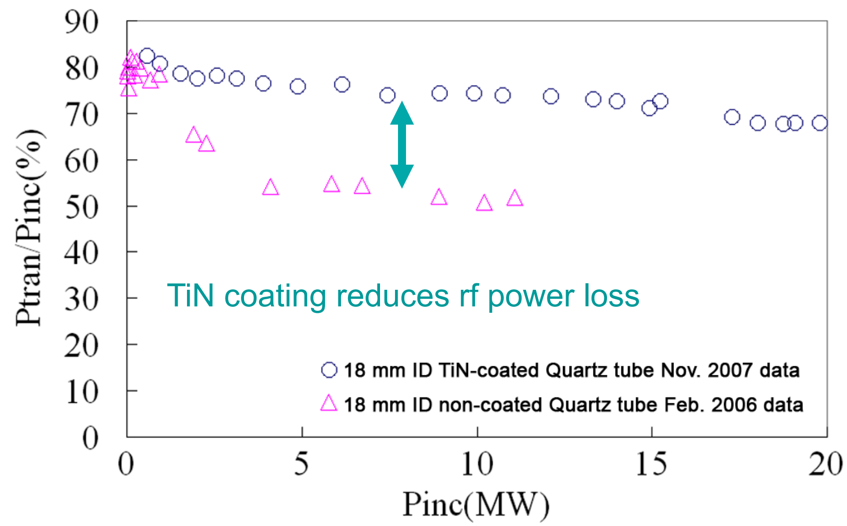
Material	Al_2O_3 [±TiN]	$Mg_xCa_{1-x}TiO_3$	SiO_2[±TiN]	SiO_2	SiO_2
Dielectric constant	9.4	20	3.78	3.78	3.8
Loss tangent	$2x10^{-4}$	$3x10^{-4}$	$2x10^{-5}$	$2x10^{-5}$	$2x10^{-5}$
Inner radius	5 mm	3 mm	8.971 mm	1.5 mm	3 mm
Outer radius	7.185 mm	4.567 mm	12.079 mm	6.45 mm	7.37 mm
R/Q	6.9 kΩ/m	8.8 kΩ/m	3.6 kΩ/m	15 kΩ/m	10.8 kΩ/m
Group velocity	0.134 c	0.057 c	0.38 c	0.265 c	0.27 c
RF power for 1MV/m gradient	80 kW	27 kW	439 kW	73.4 kW	105 kW
Demonstrated Gradient @ 200ns	8 MV/m	6 MV/m	5 MV/m (9 MV/m@ 50ns)	15 MV/m	12 MV/m

Past DLA Results

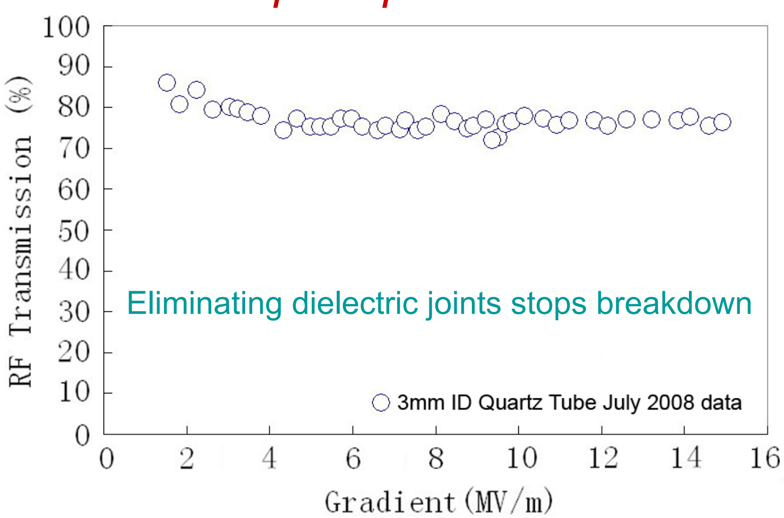
Effect of TiN coating on Alumina DLA



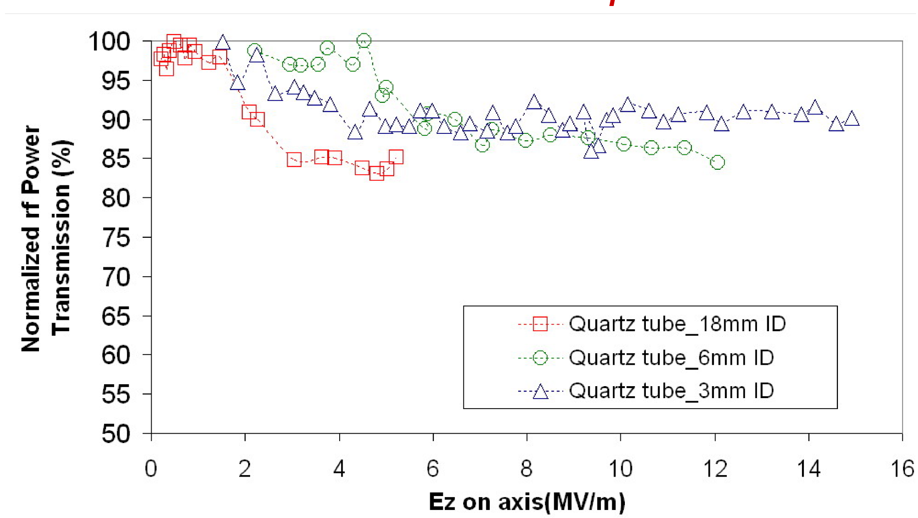
Effect of TiN coating on Quartz DLA



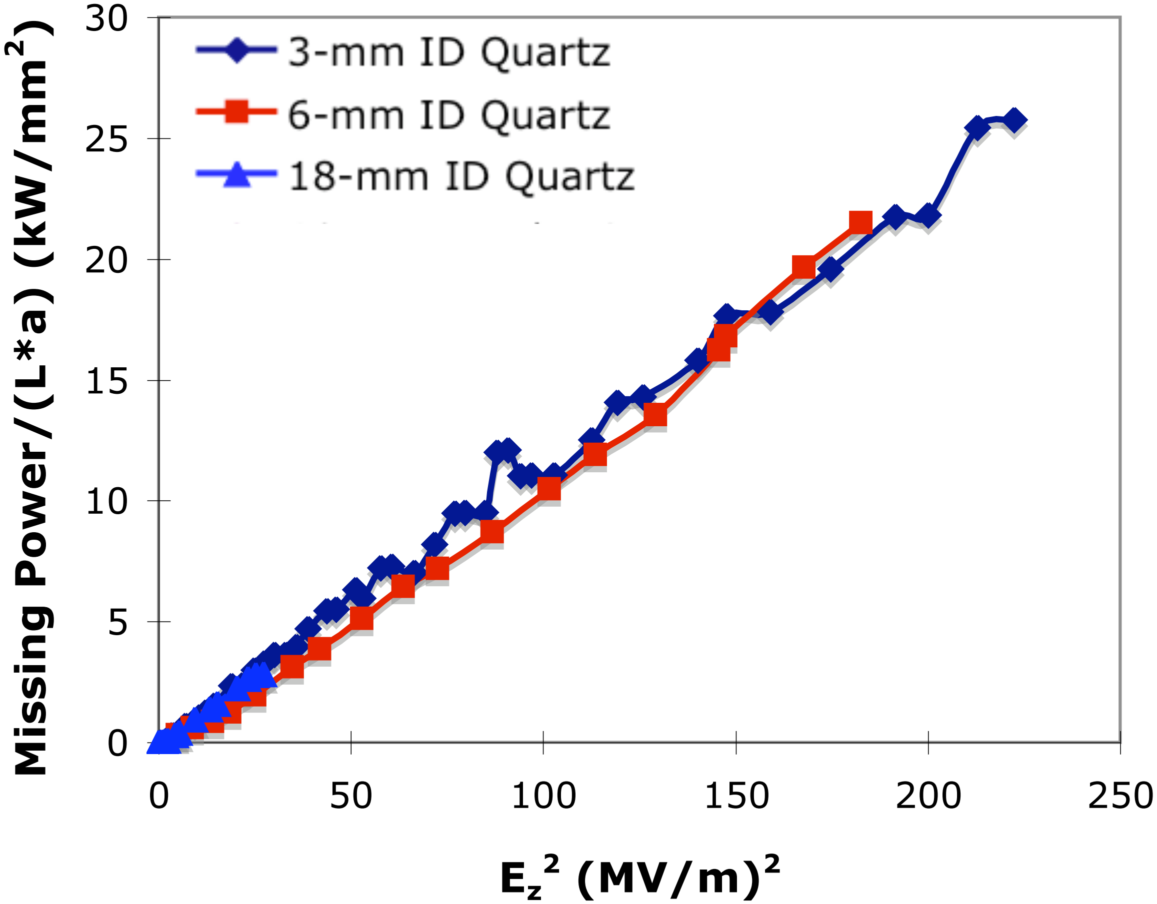
Test of clamped quartz DLA structure



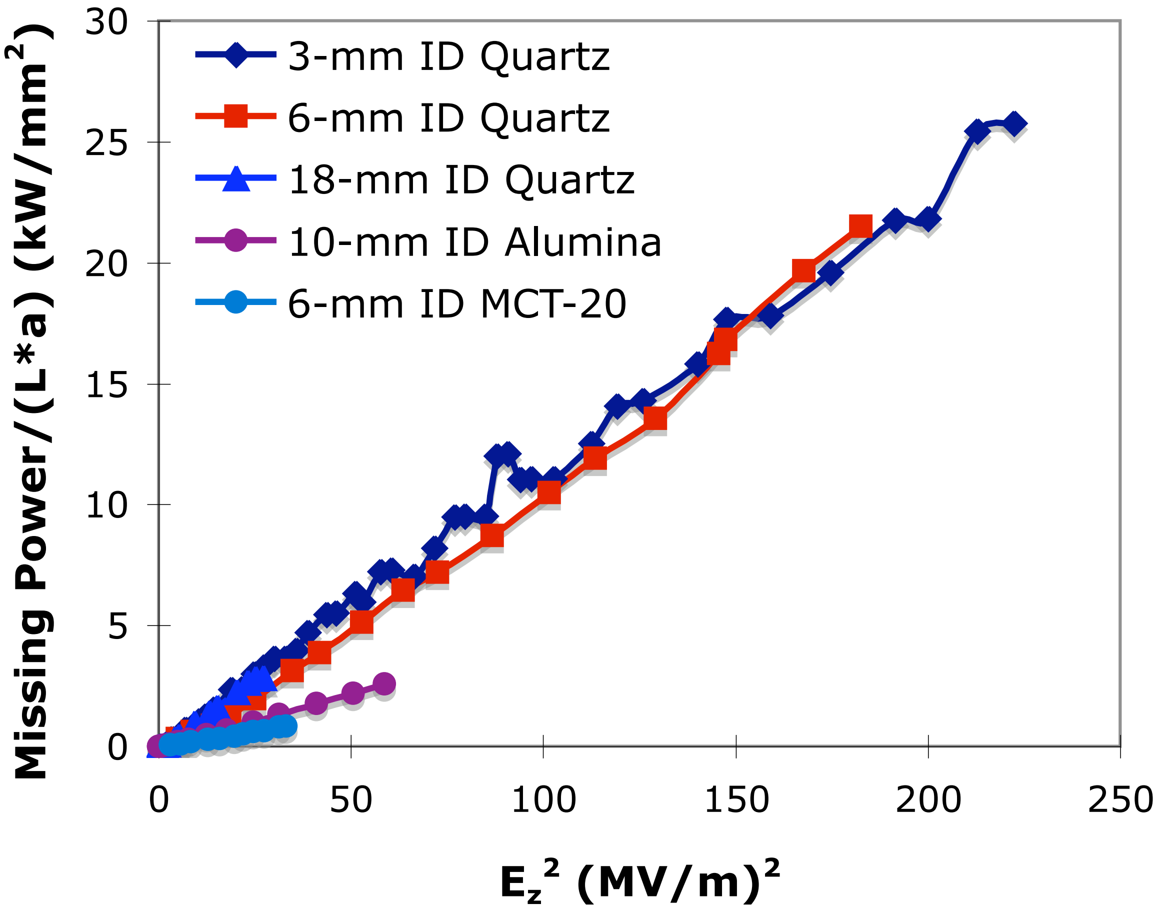
Effect of radius on quartz DLA



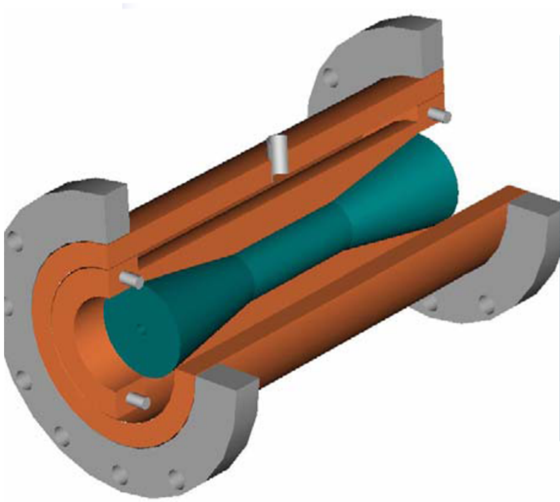
Effect of Radius on Quartz DLA

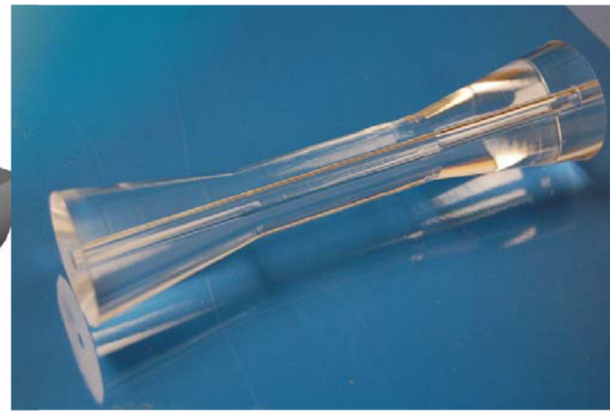


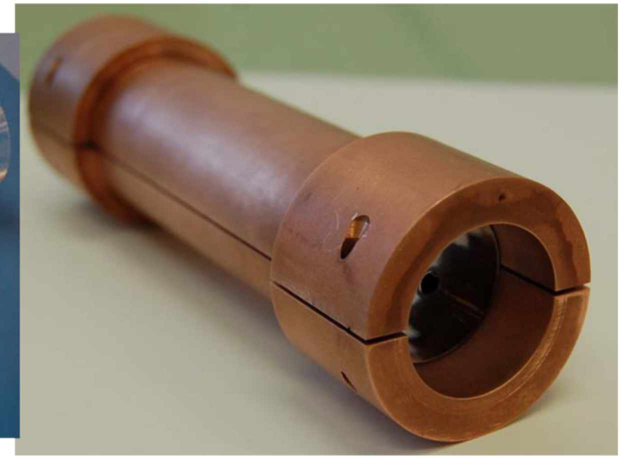
Effect of Radius on Quartz DLA

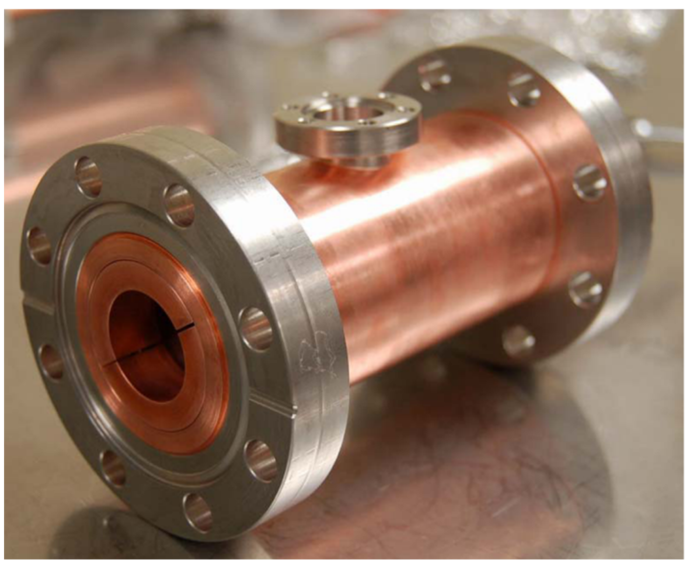


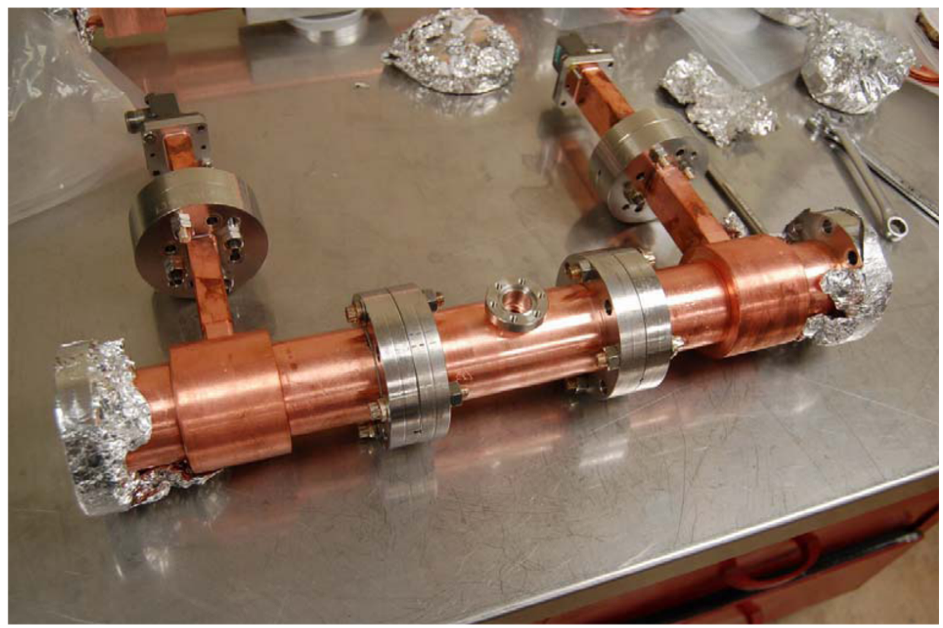
Clamped Quartz Structure





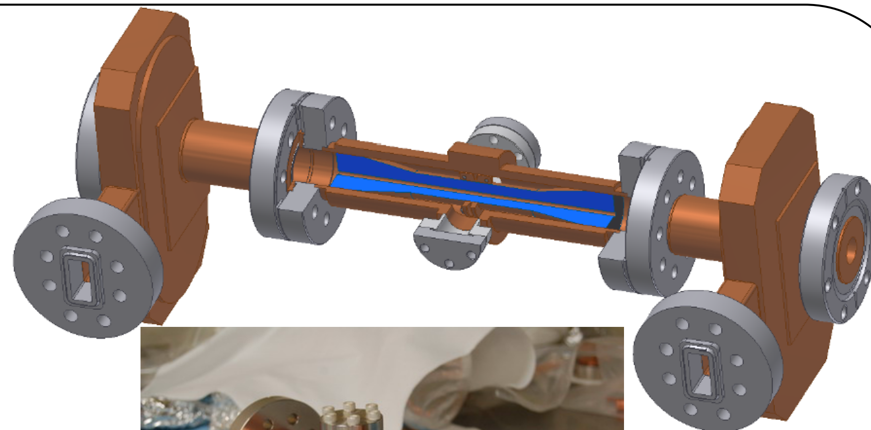


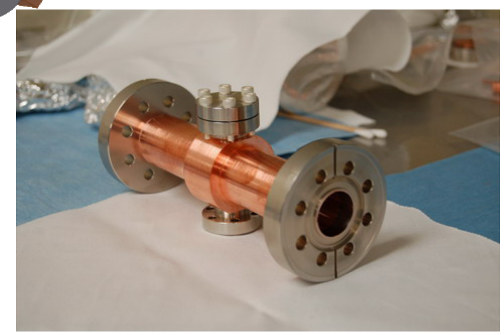




DLA Experiments @NRL in a year

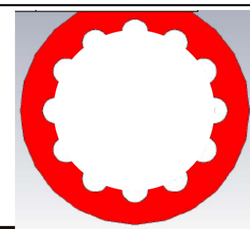
1. The 1st metalized quartz DLA structure, has been built and will be tested at NRL in a few months.

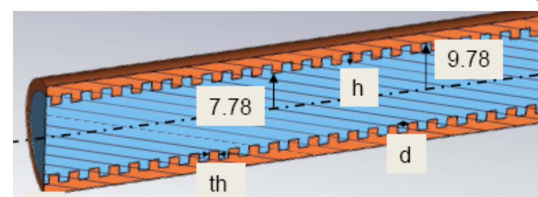




Thanks Sami to support with two SLAC type high power couplers.

2. The 1st azimuthally and axially grooved quartz DLA structures, which are targeted to mitigate the multipactor, are under construction. They will be tested at NRL in a year.





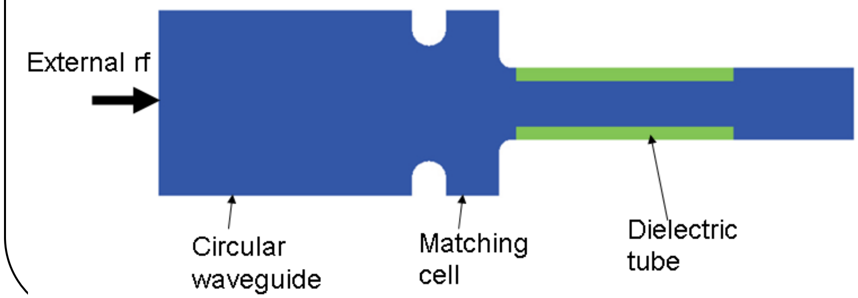
Structures Aiming for High Gradient

Travelling wave DLA Structure

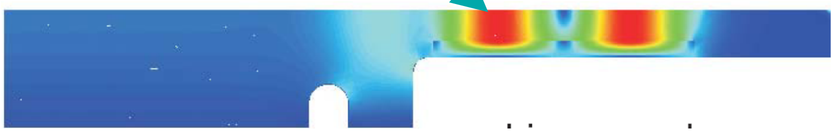
ε_r (MCT)	ID/OD	r/Q	V_g	Gradient per 20MW input	Gradient per 500MW input
15.7	5mm/8.67mm	10.9kΩ/m	0.0665c	28.1MV/m	140.4MV/m

Dielectric tube has been developed.

Standing wave DLA Structure (submitted to SBIR 2011)



170MV/m per 20MW input



DLA Summary

- Goal is to understand multipactor and breakdown in DLA structures
- Rf breakdown generally occurs at discontinuities–couplers and dielectric joints—and can be eliminated by joint-free structures
- Multipactor appears to be universal, even at modest accelerating gradients, but has a finite risetime, and isn’t seen in short-pulse experiments (e.g., AWA). Low SEE coatings reduce, but don’t eliminate it. The high power scaling still isn’t understood.
- New experiments in preparation:
  - Metallized structures to eliminate dielectric gaps
  - Grooved structures to suppress multipactor
  - High gradient TW and SW structures

Two-channel active RF pulse compressor using electron beam switching

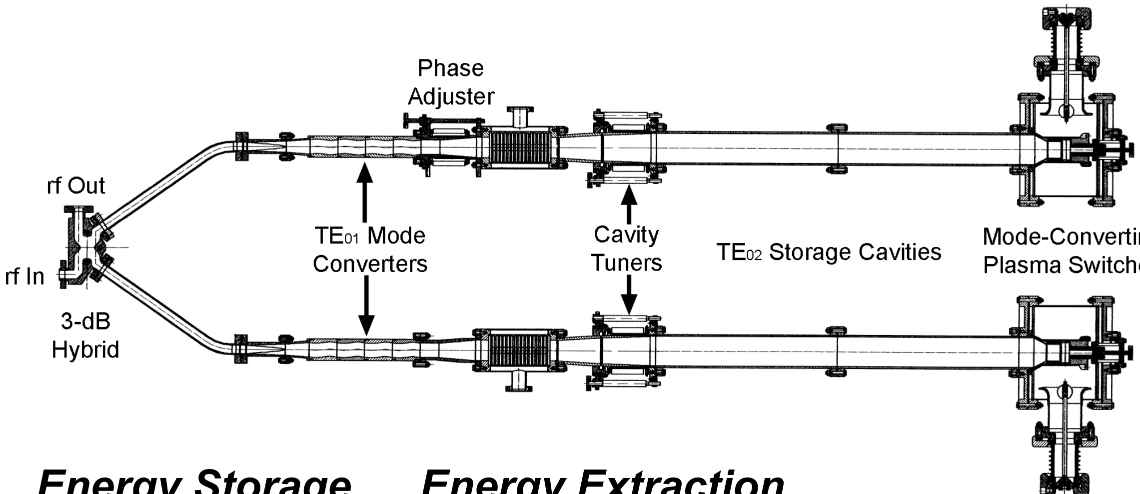
A.L. Vikharev,[1,2] O.A. Ivanov,[1,2] A.M. Gorbachev,[1,2]
V.A. Isaev,[1] M.A. Lobaev,[1,2] J.L. Hirshfield,[2,3] S. H. Gold,[4] and A.K. Kinkead [5]

[1] Institute of Applied Physics RAS, Nizhny Novgorod, Russia
[2] Omega-P, Inc., New Haven, CT, USA
[3] Department of Physics, Yale University, New Haven, CT, USA
[4] Plasma Physics Division, Naval Research Laboratory, Washington, DC, USA
[5] Icarus Research, Bethesda, MD, USA

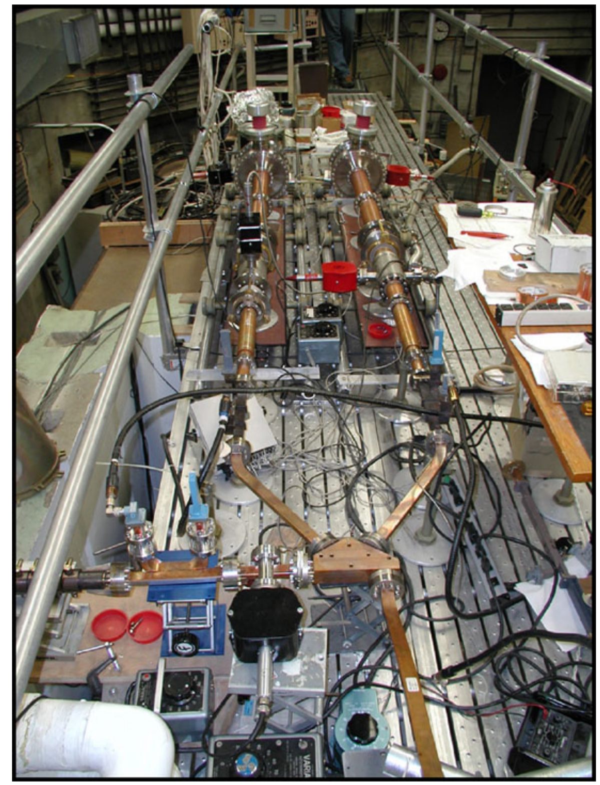
Background

- Active microwave pulse compressors offer improved compression ratios and efficiencies compared to passive compressors such as SLED 2
- A series of experiments were carried out on pulse compressors switched by triggered breakdown of low-pressure gas-filled quartz tubes, using both transmission and reflection configurations
- The highest output power was ~70 MW in ~40-ns pulses at ~8x compression from a two-channel, dual-mode compressor in the reflection configuration
- Performance was limited by multipactor and self-breakdown of the quartz switch tubes, as well as by transient switching effects caused by the inability to control the electron density during the switching process.

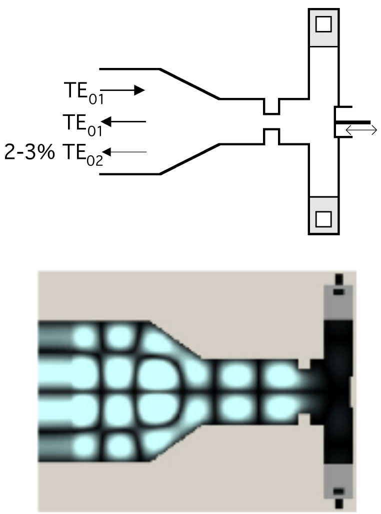
Two-Channel Dual-Mode Pulse Compressor Based on $TE_{01} \rightarrow TE_{02}$ Mode Conversion*



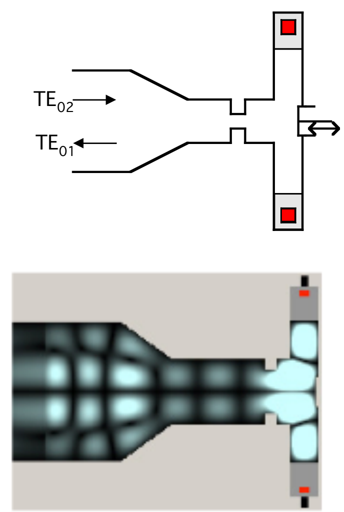
Experimental Setup



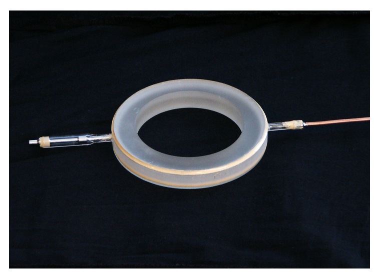
Energy Storage



Energy Extraction

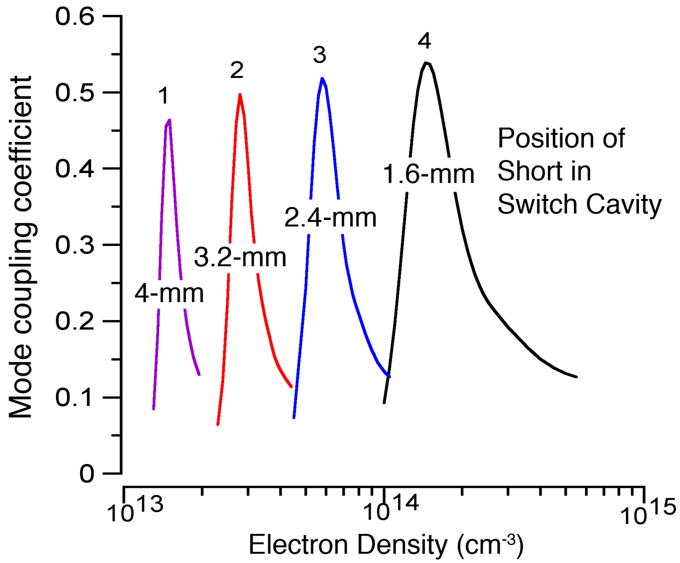


Design of Gas Discharge Tube



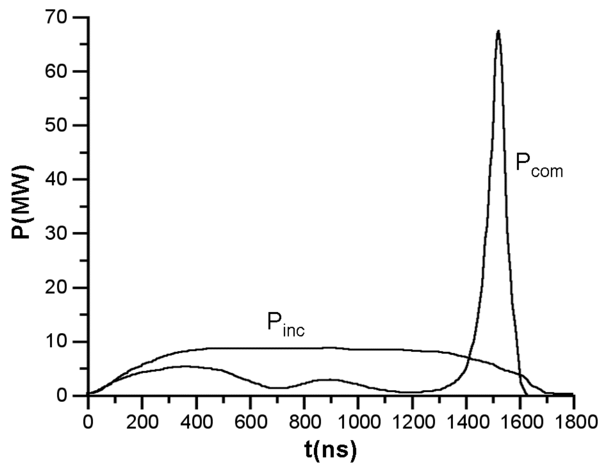
*A.L. Vikharev *et al.*, *Phys. Rev. ST Accel. Beams* **12**, 062003 (2009).

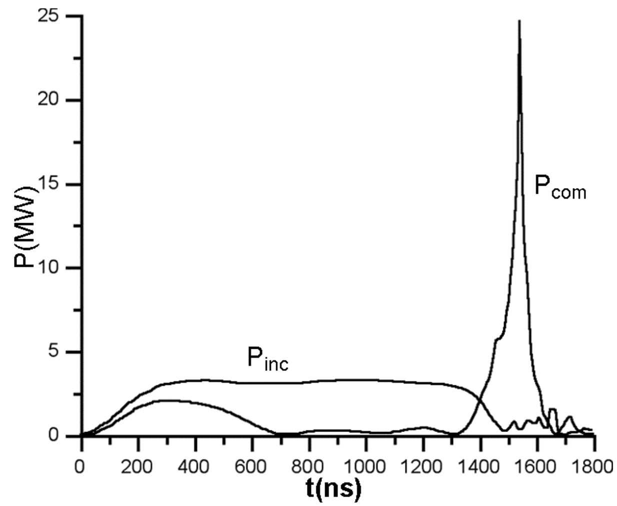
Principle of Switch Operation



- Switch cavity is initially tuned below resonance, determining the resonant value of n_e
- HVPG ionizes the switch tube, creating an initial n_e that tunes the switch towards resonance
- Cavity RF fields increase, further increasing n_e
- Effective switching requires raising n_e to the resonant value, and keeping it there throughout the switching process
- There are two main adjustments
  – Adjustable short: affects "resonant" value of n_e as well as initial rf fields in the cavity
  – Gas fill pressure: affects self-breakdown threshold (lower pressure is better); and n_e produced by HVPG and by RF fields as the switch tunes into resonance

Incident and Compressed Pulses





<u>Untriggered Switching</u>

Switch setting: ~3

Pressure: 0.02–0.05 Torr

Input power: ~8.5 MW

Output power: ~68 MW

Output pulse length: ~70 ns

Power gain: ~8x

Efficiency: ~60%

<u>Triggered Switching</u>

Switch setting: <1

Pressure: 0.02–0.05 Torr

Input power: ~3 MW

Output power: ~25 MW

Output pulse length: ~35 ns

Power gain: ~8x

Efficiency: ~45%

Pulse Compressor Summary

(from March, 2009)

- Two-channel TE_{02}-mode energy storage cavities with plasma switches are a promising candidate for high-power active RF pulse compression
- The final experiment demonstrated 65–70 MW, 40–70 ns compressed pulses using untriggered switching. The power gain was 7.4–8.2 with energy efficiency of 55–63%.
- The highest power in triggered switching was 25 MW in a 34-ns pulse, limited by self-breakdown and the difficulty of controlling electron density during the switching process. Possible solutions include
  - Redesigning switch cavity to reduce rf electric fields at the quartz switch tube
  - Changing the switching mode to detune the switch out of resonance, instead of tuning into resonance. This might be done with an e-beam instead of a gas discharge tube.

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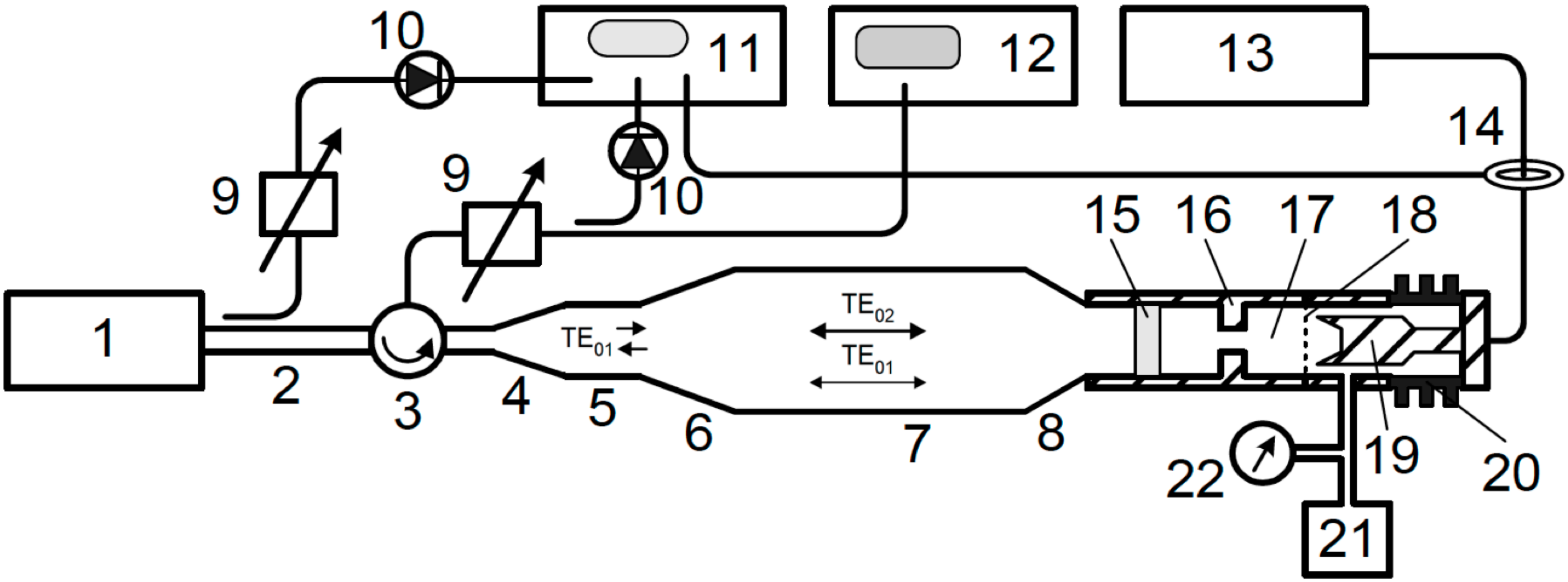
Diagram of Single-Channel Pulse Compressor using e-Beam Switching*



1 – microwave generator, 2 – directional coupler, 3 – circulator, 4 – $TE_{10} \rightarrow TE_{01}$ mode converter, 5 - cylindrical waveguide, 6 – input-output taper, 7 – storage resonator, 8 – taper, 9 - attenuator, 10 – microwave detector, 11 - oscilloscope, 12 - scalar network analyzer, 13 - HV pulser, 14 - Rogowski coil; 15 - microwave window, 16 - movable diaphragm, 17 – switch resonator, 18 – anode, 19 – cathode, 20 – isolator, 21 - pumping, 22 - vacuum meter.

*O.A. Ivanov *et al*., in *Proc. 14th Adv. Accel. Concepts Workshop*, 2010, p. 292.

Principle of Operation of e-Beam Switch

The reflection coefficient at frequency ω from a cavity tuned to ω_0 is

$$R = 1 - \frac{2\beta}{(1+\beta)\left(1 + 2 \cdot i \cdot Q_L \dfrac{\omega - \omega_0}{\omega_0}\right)}$$

where $\beta = Q_0/Q_e$, Q_0 is the intrinsic *Q*-factor of the cavity, Q_e is the coupling *Q*-factor, and $Q_L = Q_0 Q_e/(Q_0 + Q_e)$ is the loaded Q-factor.

For $\beta >> 1$, and $\omega = \omega_0$, $R \approx -1$.

For $\beta >> 1$, and $|\omega - \omega_0| >> \omega_0/2Q_L$, $R \approx 1$.

Therefore , if an overcoupled cavity is rapidly driven out of resonance, the phase of the reflected wave will change by $\Delta\varphi \approx \pi$ while $|R|$ remains ≈1.

This will change the $TE_{02} \leftrightarrow TE_{01}$ coupling coefficient from ~3% to ~40%.

The transition time is $\tau_p \sim Q_L/\omega_0$. For $Q_L \sim 200$ and f_0 = 11.4 GHz, $\tau_p \approx$ 3-5 ns.

Principle of Operation of e-Beam Switch (continued)

Shifting the resonant frequency of the switch cavity by f_0/Q_L with an electron beam requires:

$N_e \geq 2\, n_c\, V_R\, A\, /\, Q_L \approx 10^{11}$ electrons, where

$Q_L \approx 200$

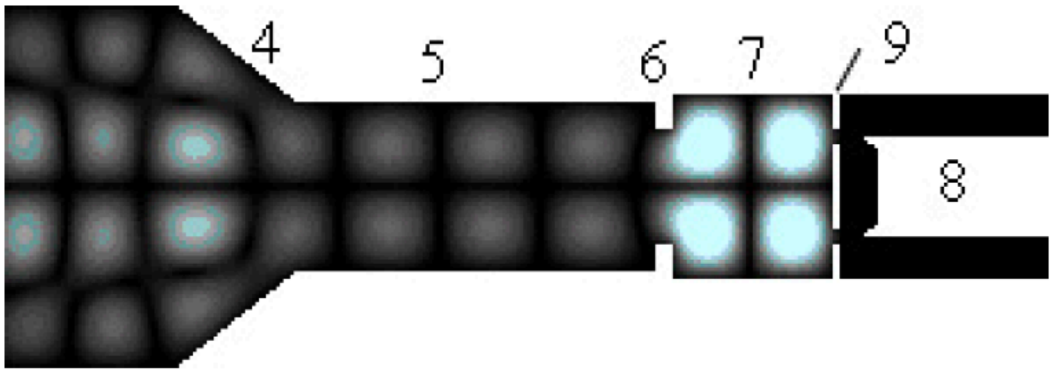
$n_c = 1.6\times10^{12}$ cm^{-3}

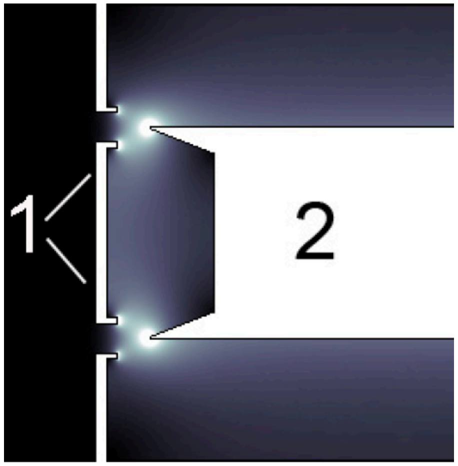
$A \approx 0.5$ for TE_{01} mode

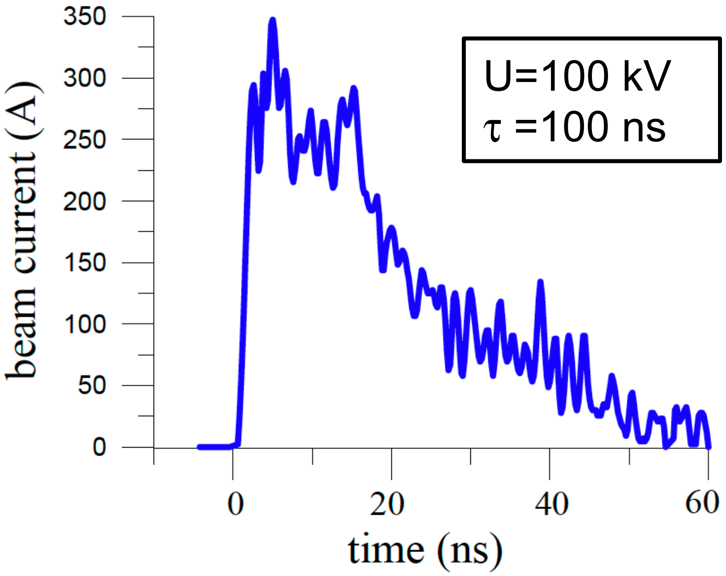
$V_R \approx 50$ cm^3

$\Rightarrow \quad I \geq 250$ A

e-Beam Switch







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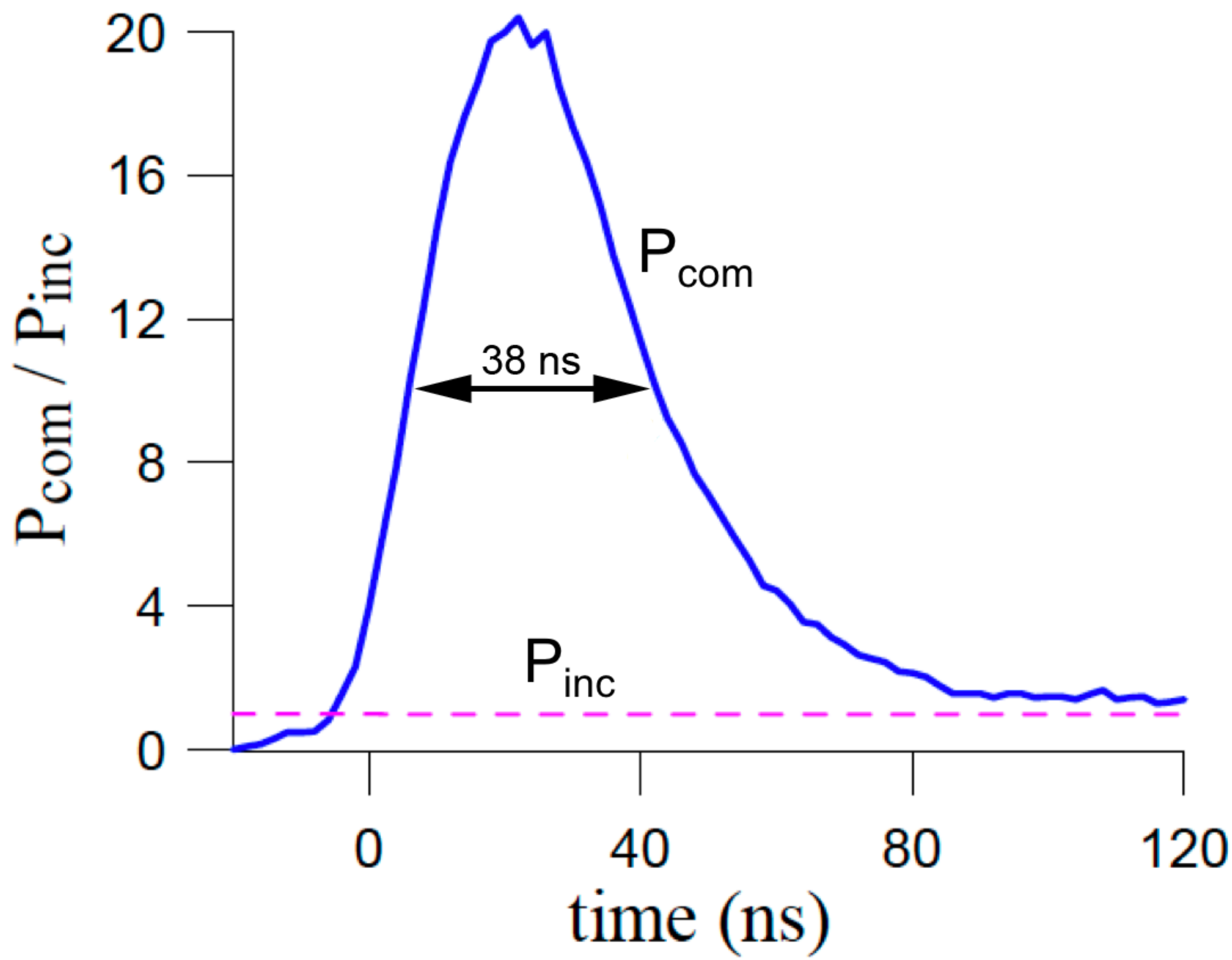
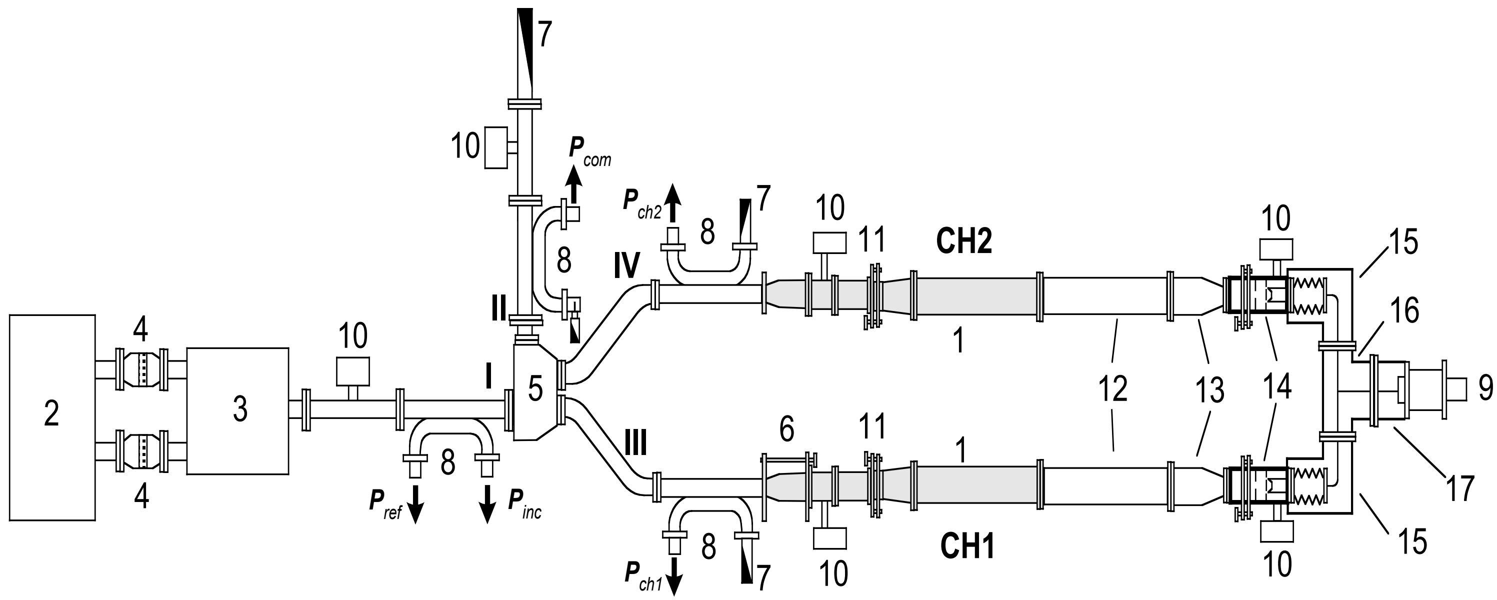
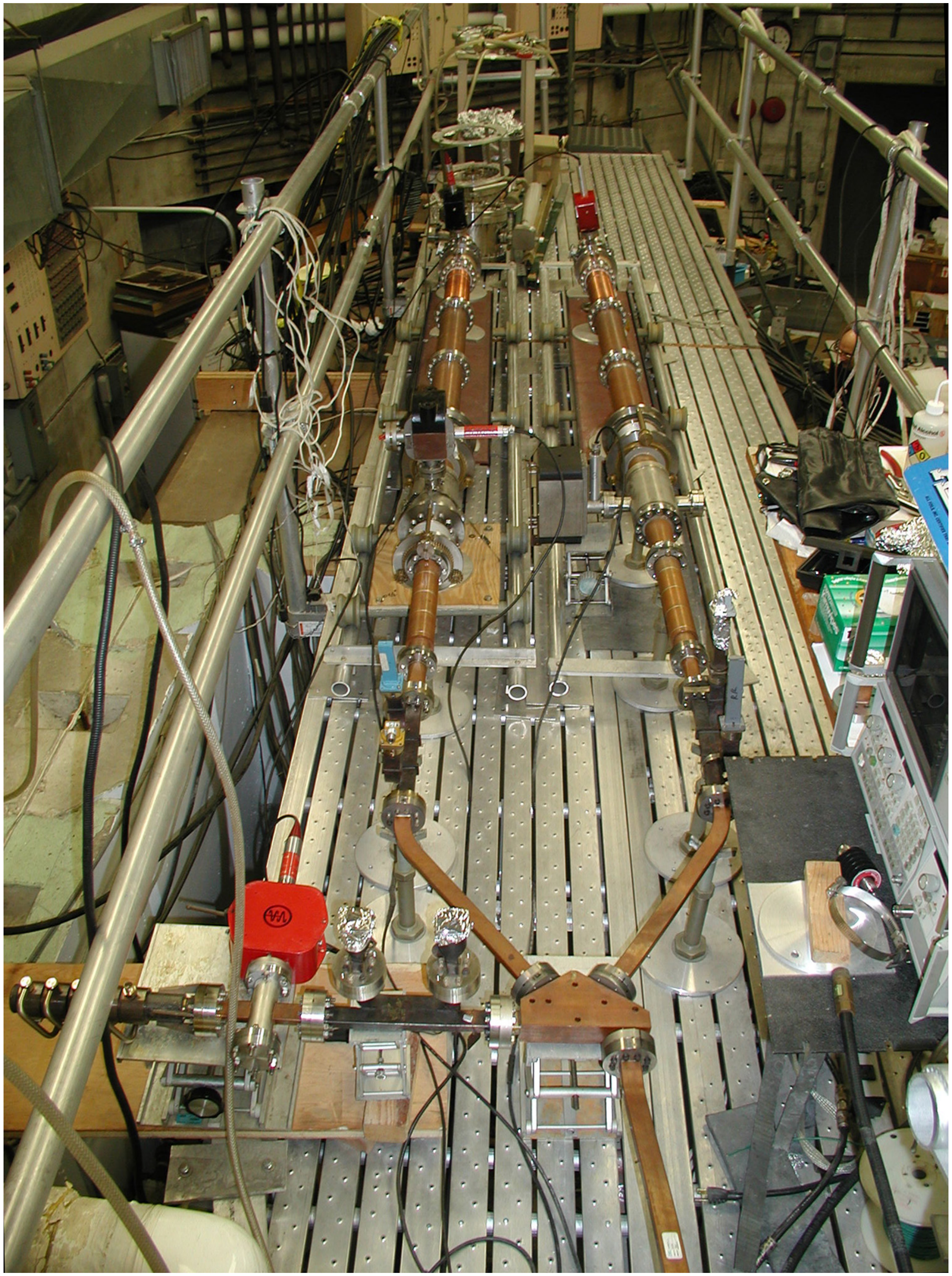
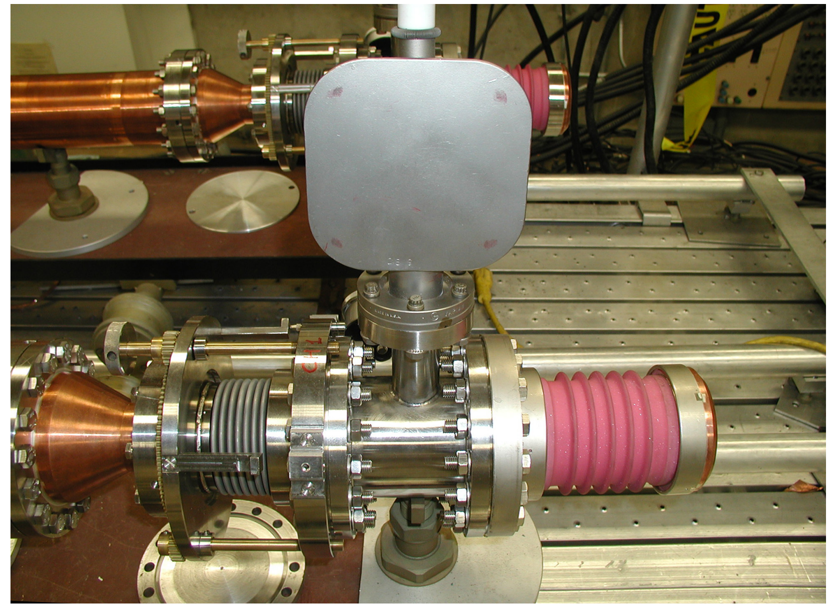


Two-Channel Dual-Mode Pulse Compressor with e-Beam Switching

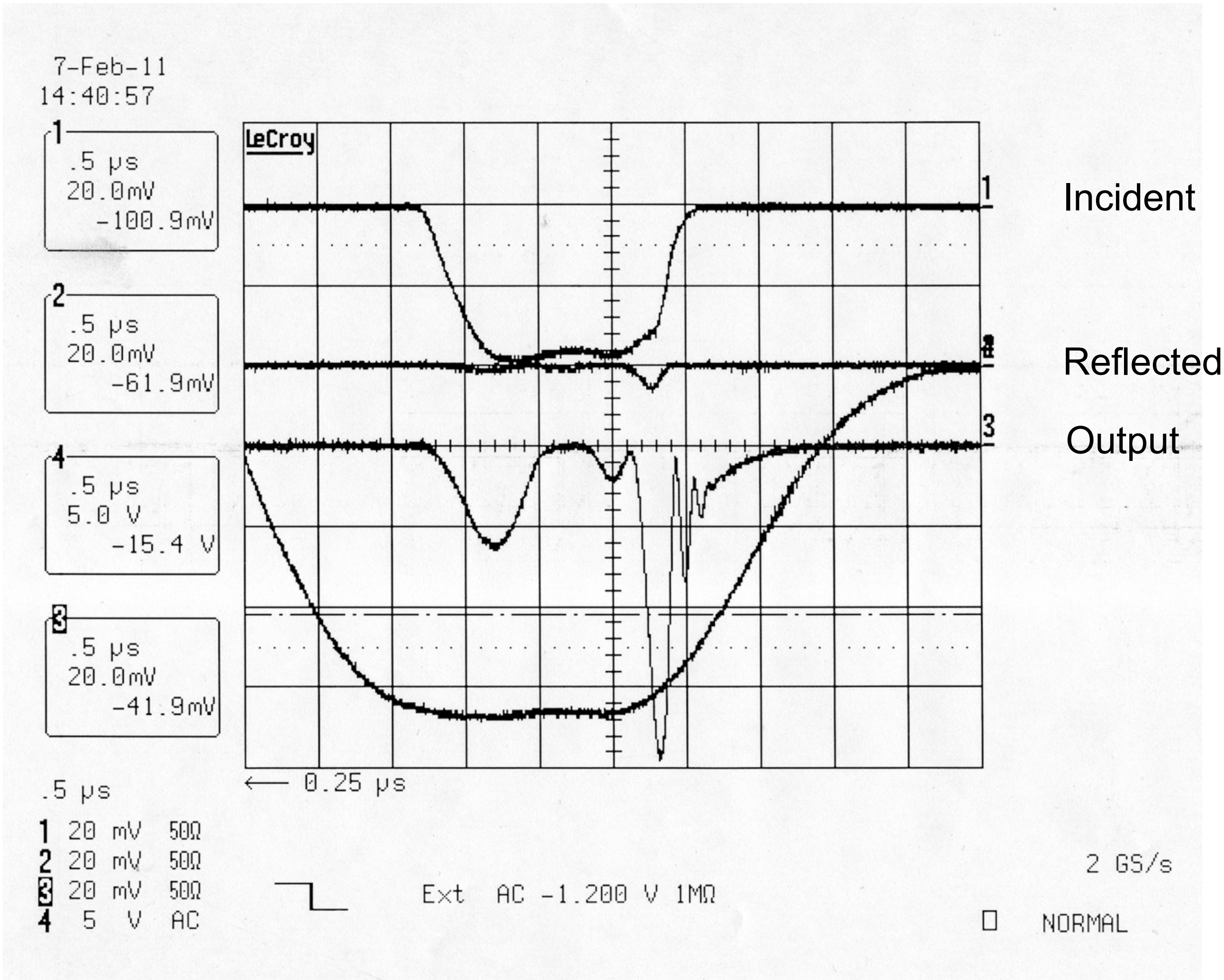


(1) single-channel of the compressor; (2) magnicon; (3) power combiner; (4) output window; (5) single-mode 3-dB hybrid coupler; (6) phase shifter; (7) matched load; (8) 55.5-dB directional coupler; (9) high-voltage pulse generator; (10) ion pump; (12) section of cylindrical waveguide, (13) conical taper, (14) switch, (15), (16), (17) screened enclosure.





Early Traces



Summary

- Low-power testing of a single-channel dual-mode e-beam switched pulse compressor with a TE_{02}-mode energy storage cavity demonstrated 40 ns output pulses at ~20x compression ratio.
- A new high-power two-channel dual-mode pulse compressor with e-beam switching has been set up in the magnicon lab at NRL. The initial experiments are under way and will run through mid-March.
- The estimated power multiplication of the two-channel compressor is 15–20. At 10 MW drive power, output pulses of 150–200 MW are possible.