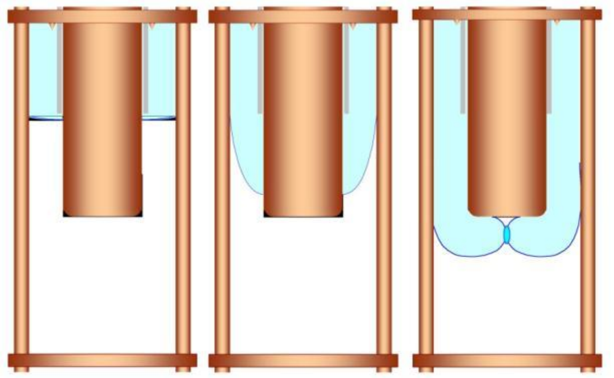
SAND2012-0451 C

SAND2012-0451C

Dense Plasma Focus Neutron Generator for Active Interrogation

Kenneth W. Struve
Sandia National Laboratories
&
Bruce L. Freeman
Raytheon-Ktech Corporation



Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

I will discuss

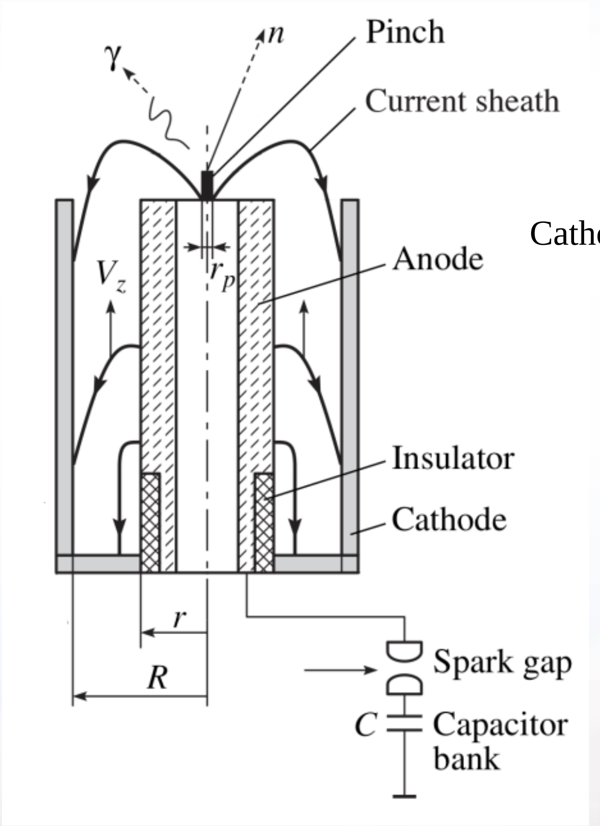
- A neutron source using a dense plasma focus (DPF) can provide up to 2×10^{12} neutrons per shot with no extension of current technology for use in active interrogation

- Demonstrated scaling of neutron yield with current at I^4 or I^5 offers the possibility of a much larger sources

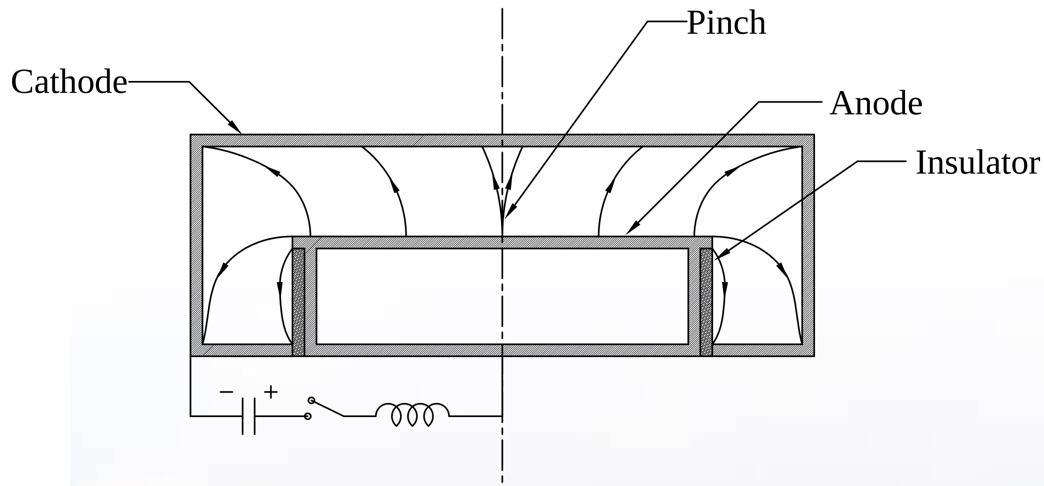
- But no DPF device has demonstrated yields higher than 2×10^{12}

- Joint US-Russian work could progress by using existing designs and adding tritium, and by exploring current scaling limits with higher voltage designs

A plasma focus generates intense beam-induced x-ray and neutron fluxes from plasma instabilities



Mather-style DPF



Filippov-style DPF

Neutrons are not thermonuclear, but are beam induced

- **Origin of the ion and electron beams can be best explained in a magnetohydodynamic analysis by the breaking of symmetry of each side of an m = 0 instability neck by Hall and FLR terms.**
- **Current density in the neck evolves into a disruption with anomalous resistivity when the line density in the neck drops below the critical value.**
- **This leads to energetic on-axis singular ion beams and off-axis reversed ion flow of lower energy deuterons.**
- **Electron beams typically have energies in the range of than 100 keV to 1 MeV.**

Ref. M. G. Haines, "A review of the dense Z-pinch," Plasma Phys. Control. Fusion **53** (2001) 093001**.**

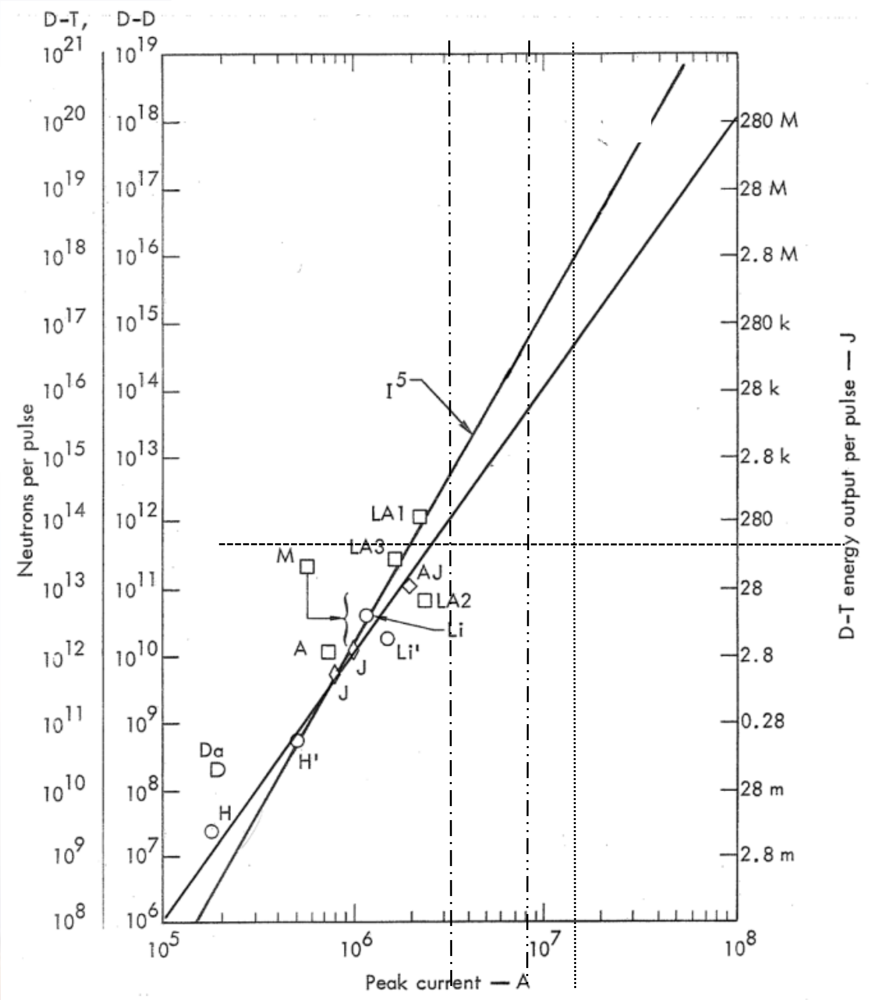
A plasma focus device can be a good neutron source

- **Potential applications are:**
  - activation analysis
  - neutron radiography
  - actinide waste reduction
- **Activation analysis of closed containers may require significant neutron flux**
- **A dense plasma focus (DPF) can be portable and have a small volume**
  - Reactors not feasible
  - Z-pinch compression devices are too large
- **DPF devices have demonstrated over 10^{12} neutrons per shot with deuterium gas fills**
- **Past experiments have shown that neutron yield *Y* scales with current *I* to the fifth power**

$$Y_{neutrons} \mu I^{5}$$

DPF Scaling: Neutron Yield ∝ I^4 to I^5

- DD neutron scaling has been well demonstrated across more than 5 orders of magnitude (I^5 and conservative I^4 scaling are shown).
- The 14-MeV DT neutron yield is experimentally ~ 80 - 100X larger than the DD yield.
- The low-cost, slow-pulsed-power requirement allows one to build a high current DPF for ≤ $10M.
- Modern capacitors and switches AND existing designs reduce the risk.



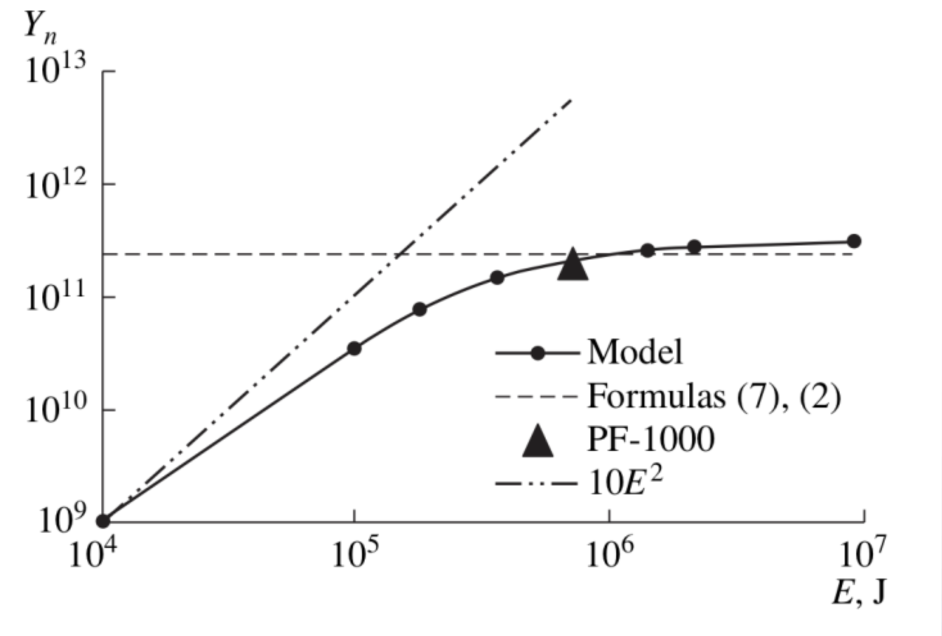
O. Zucker, et. al., “Design of a repetitively pulsed megajoule dense-plasma focus,” Lawrence Livermore Laboratory report UCRL-51872, Aug. 1, 1975.

Demonstrated Performance & Scaled Systems Projections

Status	Peak Current (MA)	Bank Voltage (kV)	DD Neutron Yield (n/shot)	Est. DT Neutron Yield (n/shot)
Demonstrated 72 kJ LANL	1.0	20 of 20	$2\text{-}4 \times 10^{10}$	$\sim 2.4 \times 10^{12}$
Demonstrated 480 kJ TAMU	1.5	30 of 60	2×10^{11}	$\sim 1.6 \times 10^{13}$
Demonstrated LANL DPF 6.5	2.2	50 of 50	$1\text{-}2 \times 10^{12}$	$\sim 1.1 \times 10^{14}$
Scale ($\sim I^5$)	4.0	70-80	$\sim 2 \times 10^{13}$	$\sim 1.6 \times 10^{15}$
Scale ($\sim I^5$)	6.0	120	$\sim 1.5 \times 10^{14}$	$\sim 1.2 \times 10^{16}$

But the neutron yield appears to saturate under some conditions

Neutron yield vs bank energy for a Mather-style PF



V. Ya Nukulin and S. N. Plukhin, "Saturation of the Neutron Yield from Megajoule Plasma Focus Facilities," Plasma Physics Reports, 2007, Vol. 33, No. 4, pp. 271-277.

Neutron yield saturation

"As the discharge energy increases, the neutron yield is saturated. As a result, attempts to reach neutron yields higher than ~10^{12} neutrons per shot have not yet met with success in most PF experiments."

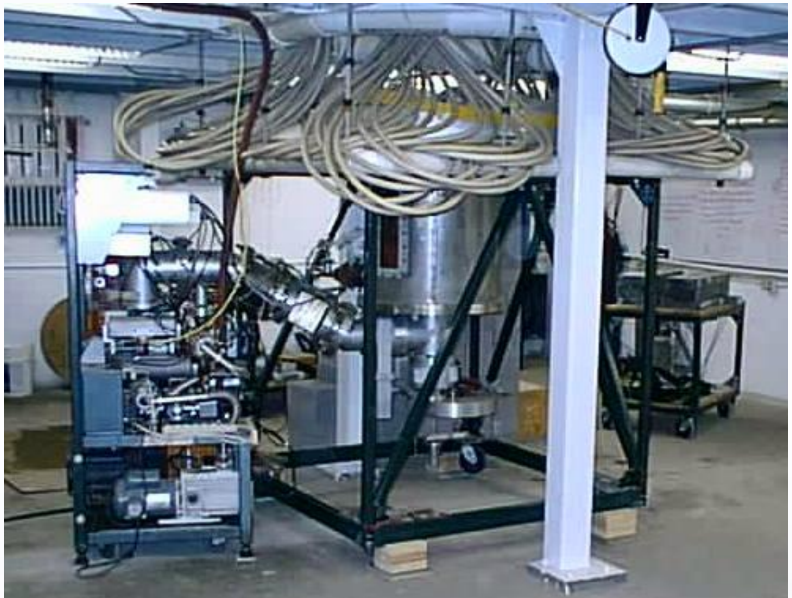
V. I. Krauz, et. al., "Dynamics of the Structure of the Plasma Current Sheath in a Plasma Focus Discharge," Plasma Phys. Reports **37**, No. 9, pp 742-754 (2011).

Two options for the yield saturation problem

1. Limit designs to the 2 x 10^{12} neutrons/shot level
   - Operate at the 2 – 3 MA level
   - Investigate DT fills to increase yield to 10^{14}
   - Potential use with a neutron multiplier
2. Address yield scaling with current and voltage
   - Previous research has focused on increasing capacitance
   - Instead look at increasing bank voltage

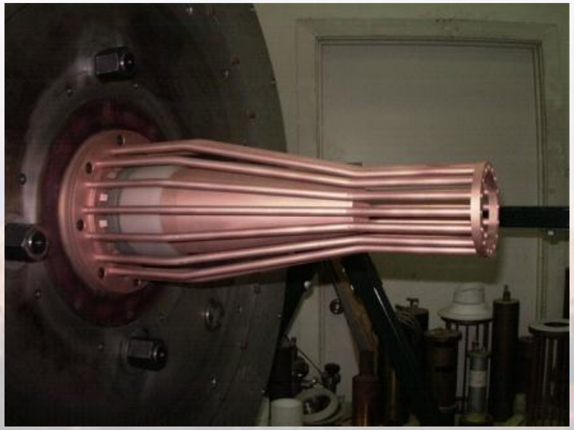
Plasma Focus Characteristics

- Pulsed power used is relatively low voltage, long rise-time design.
- The plasma focus electrode structure is physically very small.
- The capacitor bank can be relatively small and cable connected to the plasma focus load.



480 kJ Bank above experimental area

Anode = 10 cm OD
Cathode = 15 cm ID
Pyrex glass insulator



Reduced neutron pulse width electrode set

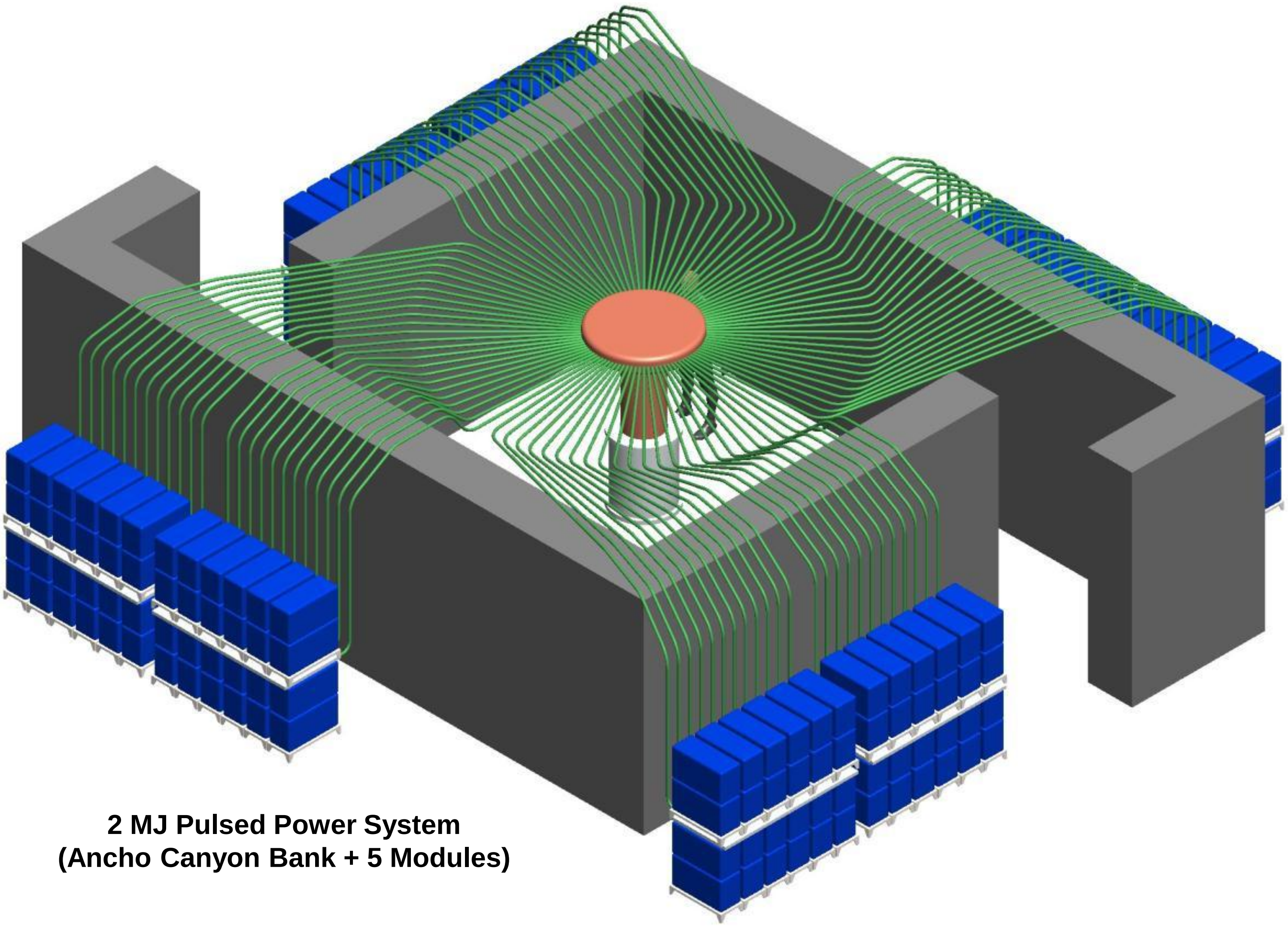
The pulsed power risk for a 1 to 2 MA DPF is small

- **The required current rise time for such a DPF is ~ 4 - 5 μs.**
  - Present capacitor designs are adequate.
  - Existing low inductance switch designs are adequate for a DPF application.
- **The DPF load can be physically separated from the pulsed power elements.**
  - Use cable coupling between the capacitors/switches and the load.
  - Place the DPF load 5- to 8-m from the capacitors.
- **The voltage for a full-scale DPF is relatively low (< 120 kV).**
  - Insulator technology at these voltages is understood.
  - Existing cable technologies are adequate for a scaled facility.
- **Therefore, minimal or no pulsed power risk is present.**
- **This provides a technical approach to quantify science risks at low cost.**

A 2 MA magnetic field driver built for laser-plasma experiments at the Univ. of Texas is an example

- 2 MA, 1.7 μs risetime
- Consists of ten 3.1 μF, 100 kV capacitors
- Each has its own switch
- Current delivered to load through 150-kV cables
- Portable. Can be moved to a laser

A DPF neutron generator

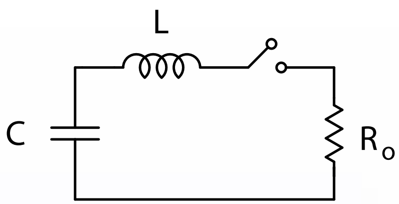


2 MJ Pulsed Power System
(Ancho Canyon Bank + 5 Modules)

The second option is to investigate higher voltage designs

Based on the premise that pinch current is limited by plasma resistance.
S. Lee, "Neutron yield saturation in plasma focus: A fundamental cause," Appl. Phys. Lett. **95**, 151503 (2009).

Driver is modeled as an LRC circuit



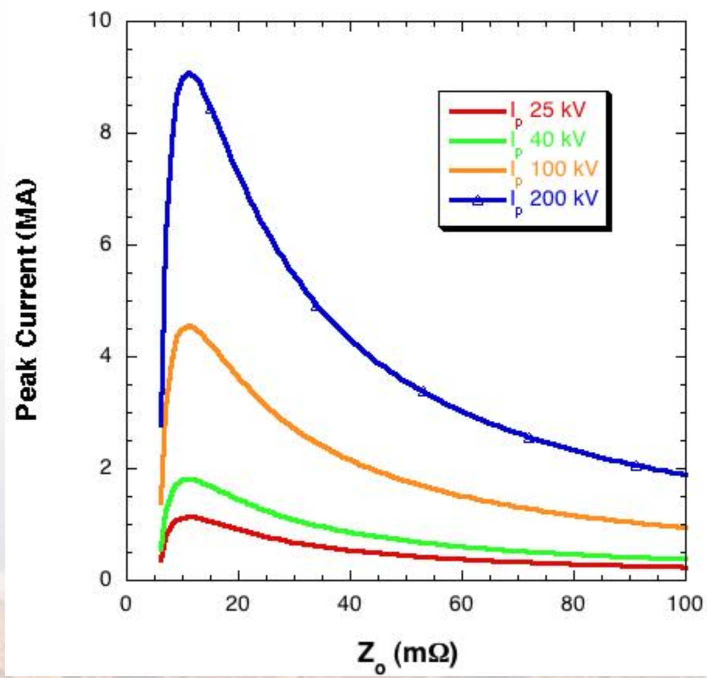
$$I_{peak} \approx \frac{V_o}{Z_o}\left(1 - \frac{\pi}{4}\frac{R_o}{Z_o} + \ldots\right)$$

where $Z_o = \sqrt{\frac{L}{C}}$

So, to increase current either:

1. **Decrease impedance Z_o, or**
2. **Increase charge voltage V_o**

Peak current vs. Z_o for several charge voltages, with R_o = 7 mΩ



Two development paths make sense for joint US-Russian collaborations

- ***Path 1*** **– Design a compact machine matching the best yield previously obtainable, and operate with a deuterium-tritium fill to obtain yields near 10^{14} per shot**
  - Use a compact capacitor system similar to earlier LANL designs to access previous performance at the 2 to 3 MA level
  - Reestablish neutron yield at 10^{12} per shot
  - Introduce deuterium-tritium fills to obtain higher yields, with a goal of 10^{14} per shot
  - Develop into an engineered, user-friendly device for neutron applications
- ***Path 2*** **– Design and build higher voltage devices to minimize plasma resistance effects, with the potential of even higher yields**
  - Explore D-D neutron yield scaling with current at higher voltage
  - Validate scaling with deuterium-tritium fills
  - Optimize design for a user-friendly device that can be used for neutron testing

Summary

- **A neutron source using a dense plasma focus (DPF) can provide up to 10^{12} neutrons per shot with no extension of current technology**
  - The driver can be compact and portable
  - Could be used for fast neutron activation, radiography, other applications
- **Demonstrated scaling of neutron yield with current at I^4 or I^5 offers the possibility of a much larger source**
- **But no DPF device has demonstrated yields higher than 2 x 10^{12}**
  - So-called neutron saturation effect
  - Not well understood. May be related to plasma resistance or driver voltage
- **Joint US-Russian work could progress on two fronts:**
  - Develop a compact device using existing designs, but increase yield using deuterium-tritium fills
  - Explore limits of yield scaling with higher voltage devices with the potential payoff of even higher yields