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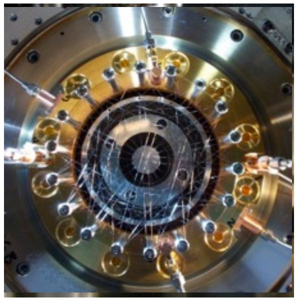
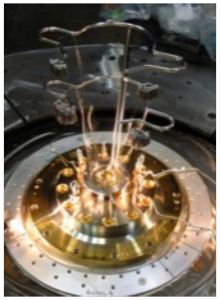
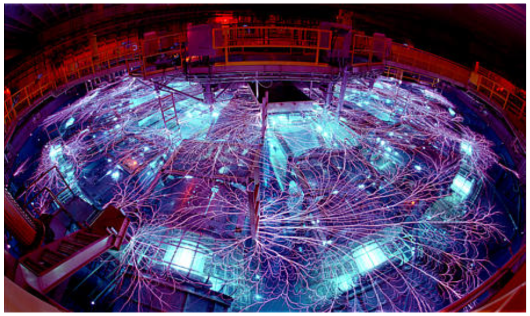






Future DPF Experimental Plans

Mike Cuneo
Senior Manager
Pulsed Power Science and Technology Group
Sandia National Laboratories

DPF Modeling Workshop
Livermore, CA
LLNL
June 30th-July 1st, 2015

Exceptional service in the national interest

We are working with a large team and invite others to join the collaboration

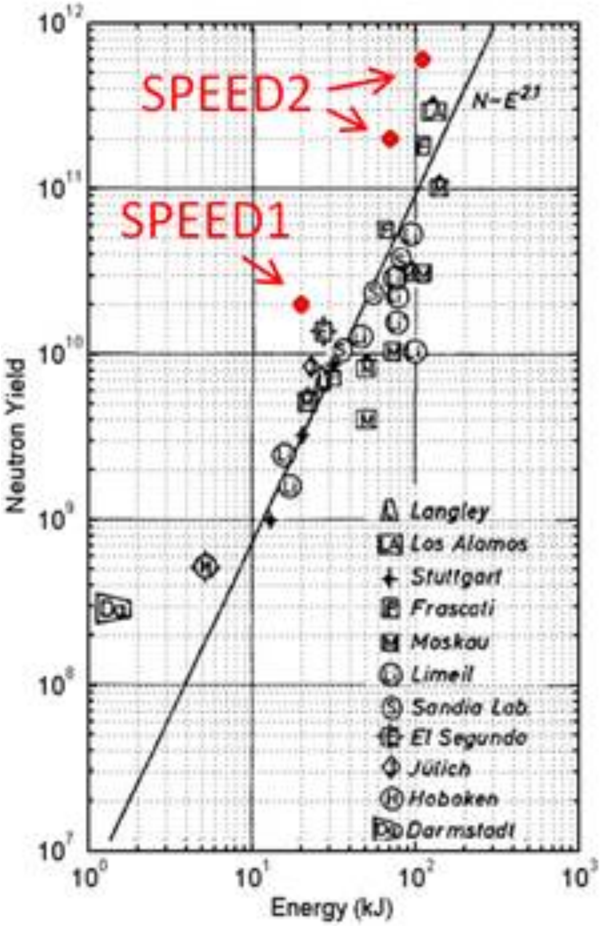
- LLNL: Andrea Schmidt, Jason Sears, Tony Link
- LANL: Russ Olson, Jeff Paisner, Steve Sterbenz, Scott Hsu
- NSTec: Chris Hagen, Aaron Luttman, Darryl Droemer, Nicki Bennett, Steve Goldstein, James Gatling, et al.
- Sandia: Mark Savage, Bill Stygar, Mark Kiefer, Patrick Knapp, Randy Mckee, Peter Jones, Matt Christison, et al.
- Voss: Dale Welch, et al.

Requirements for a new pulsed power driver for the DPF neutron source

- Requirements:
  - Reliably produce 1e12 DT neutrons
  - Increase of 5-10X possible in future
  - Reduce plasma physics risks with a faster pulsed power driver
    - Deliver 3 MA peak current to the plasma load within 1 µs
  - Minimize space and oil volume
  - Utilize existing components where possible
    - Well-developed and tested ZR capacitors
    - Limit output voltage to 200 kV for existing low impedance flexible cable

A higher voltage, higher impedance, faster implosion time system may improve neutron source performance

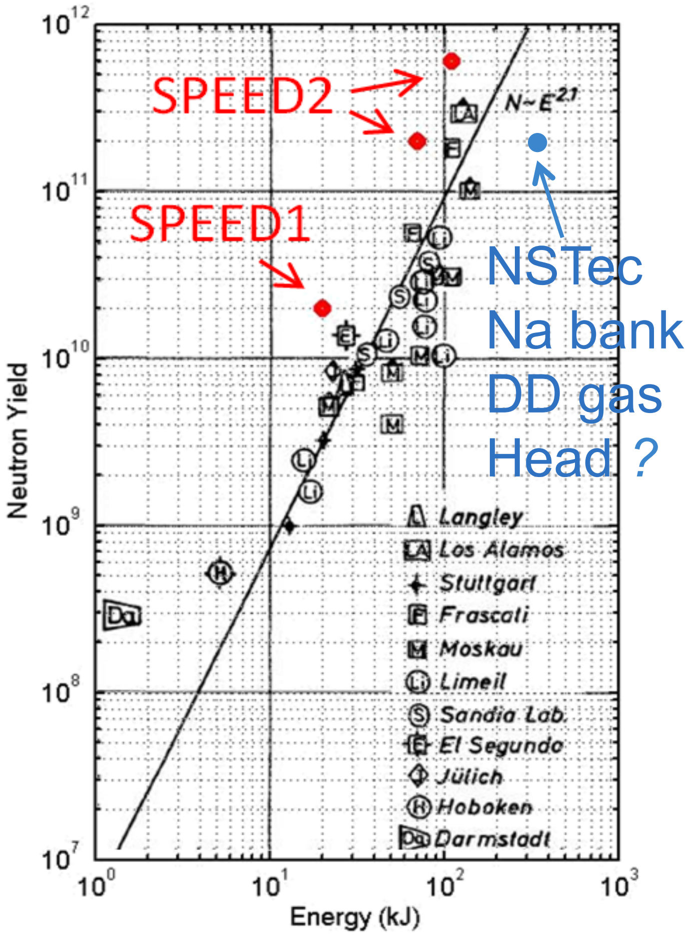
- "Near neighbor" design: cable-coupled head design, but with faster pulsed power.
- We propose to design the highest voltage system that is still compatible with the use of cable coupling (best present understanding: up to 200 kV is possible)
- A higher impedance (higher voltage) Marx-like system maximizes energy transfer efficiency (Zbank ~ Zpinch)
- Published SPEED results are at least ~4 times historic trends of output yield vs bank energy)



Graphic courtesy of Andrea Schmidt (LLNL)

Higher impedance and voltage maximizes neutron yield per unit bank energy

	NSTec (Na bank)	SPEED2
Maximum DD neutron yield	2e11	6e11
Stored energy	345 kJ	110 kJ
Anode length	65 cm?	12 cm
Voltage	40 kV	230 kV
Current rise time	6000 ns	580 ns
Driver impedance	10 mΩ	60 mΩ



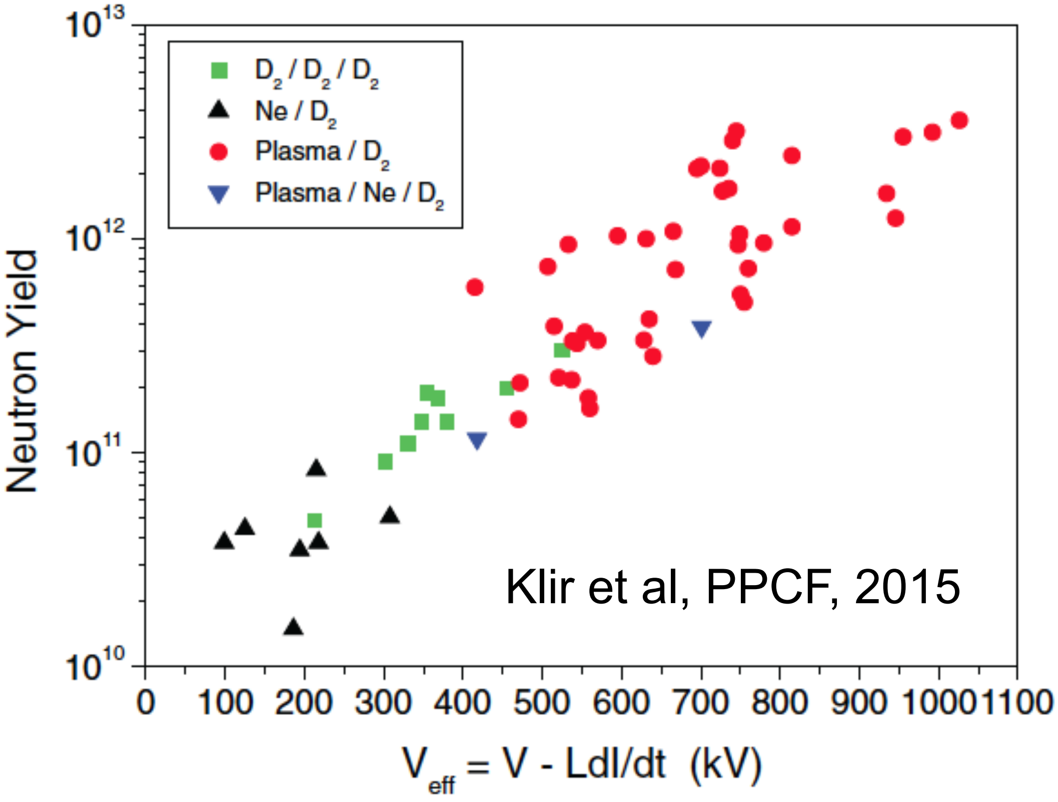
SPEED2

SPEED1

NSTec
Na bank
DD gas
Head ?

Slide courtesy of Andrea Schmidt (LLNL)

Higher effective voltage improves yield in gas puff systems

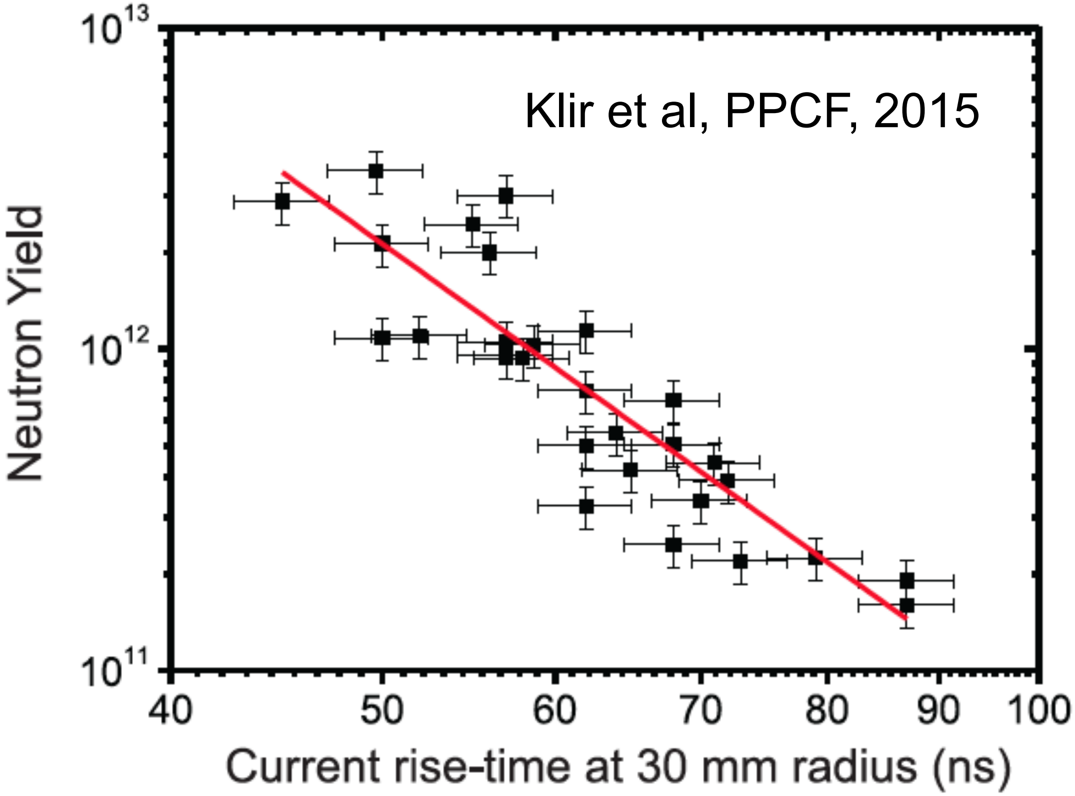


Klir et al, PPCF, 2015

DD yields from gas puffs

Correlations of neutron emission with dynamic variables can be insightful

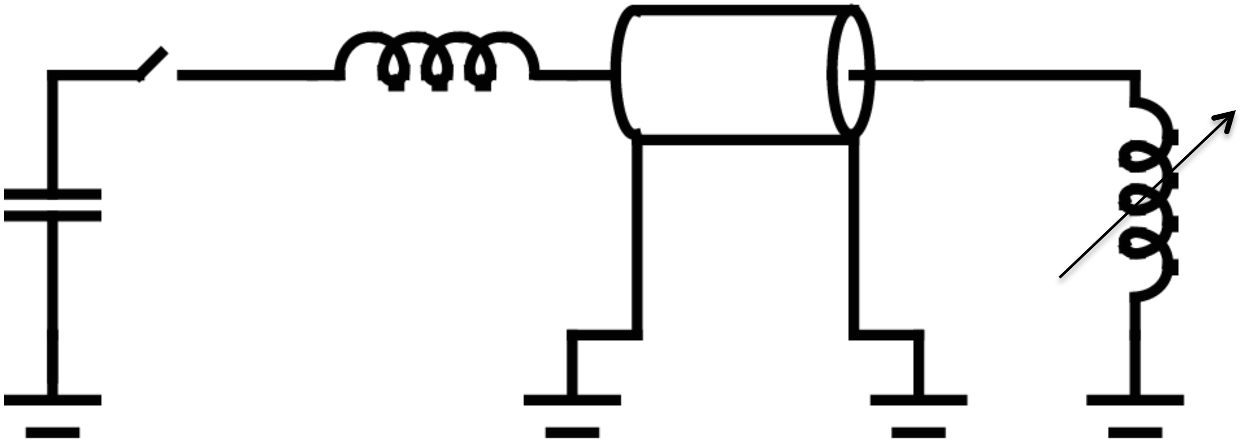
Higher effective delivery of higher dI/dt to small radius is correlated with improved performance for gas puff systems


Klir et al, PPCF, 2015

DD yields from gas puffs

Correlations of neutron emission with dynamic variables can be insightful

At its simplest, a DPF system consists of a DC-charged capacitor bank, switches, transmission lines and the load



Minimizing current rise time requires high voltage and low bank inductance, as well as low impedance transmission lines

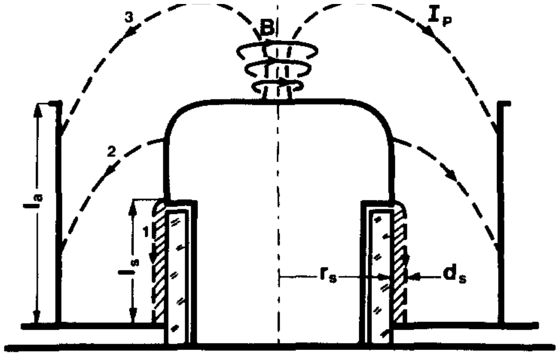
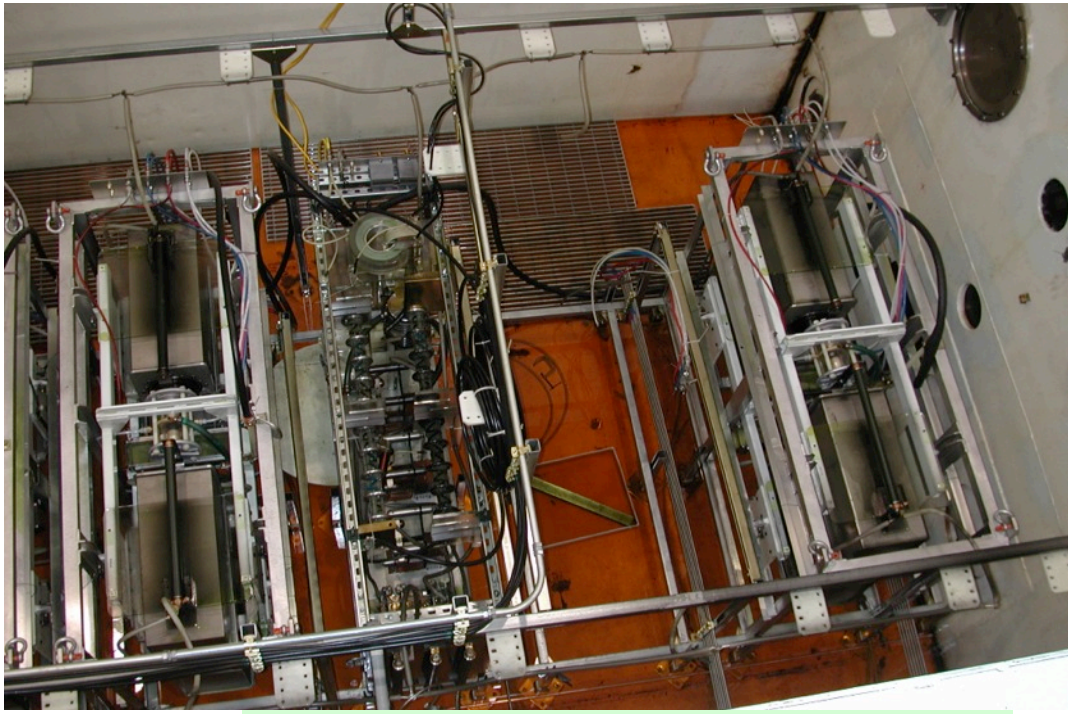


Fig. 8. SPEED 2 plasma focus accelerator. Typical dimensions: $l_a \leq 10$ cm, $l_s = 6$ cm, $r_s = 6$ cm, $d_s < 5$ mm.

Each element of the system contributes to the overall performance

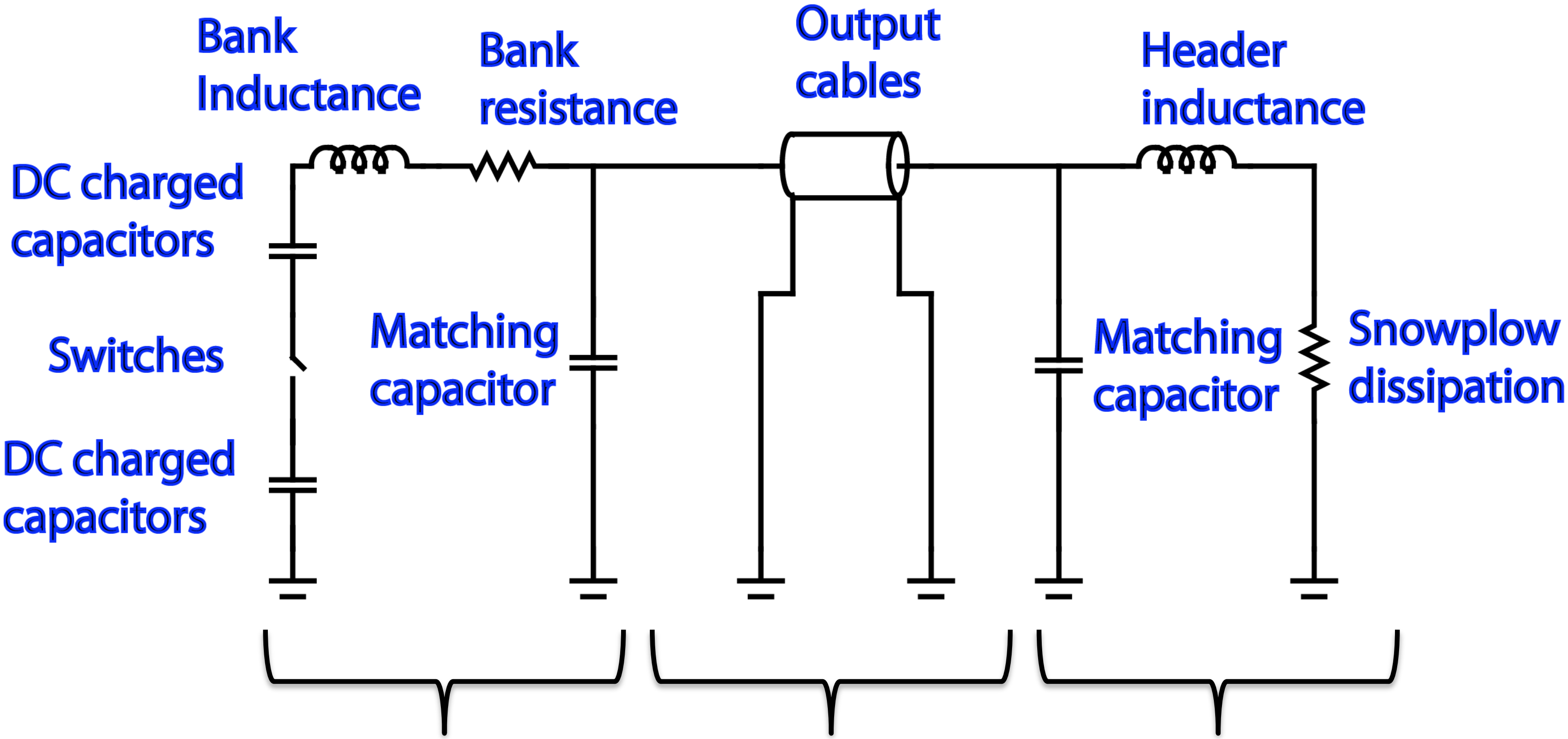
- *Capacitor requirements*
  - Low inductance, high current capability, high reliability
- *Switch requirements*
  - Predictable lifetime, low jitter, low pre-fire rate, low inductance
- *Transmission line requirements*
  - Reliable insulation, flexible, low impedance



ZR capacitor tester ca. 2005

Other work will be leveraged: we have prior and ongoing development programs for all these components

The complete bank design is based on Z Marx measurements for inductance and resistance



Bank Inductance

Bank resistance

Output cables

Header inductance

DC charged capacitors

Switches

DC charged capacitors

Matching capacitor

Matching capacitor

Snowplow dissipation

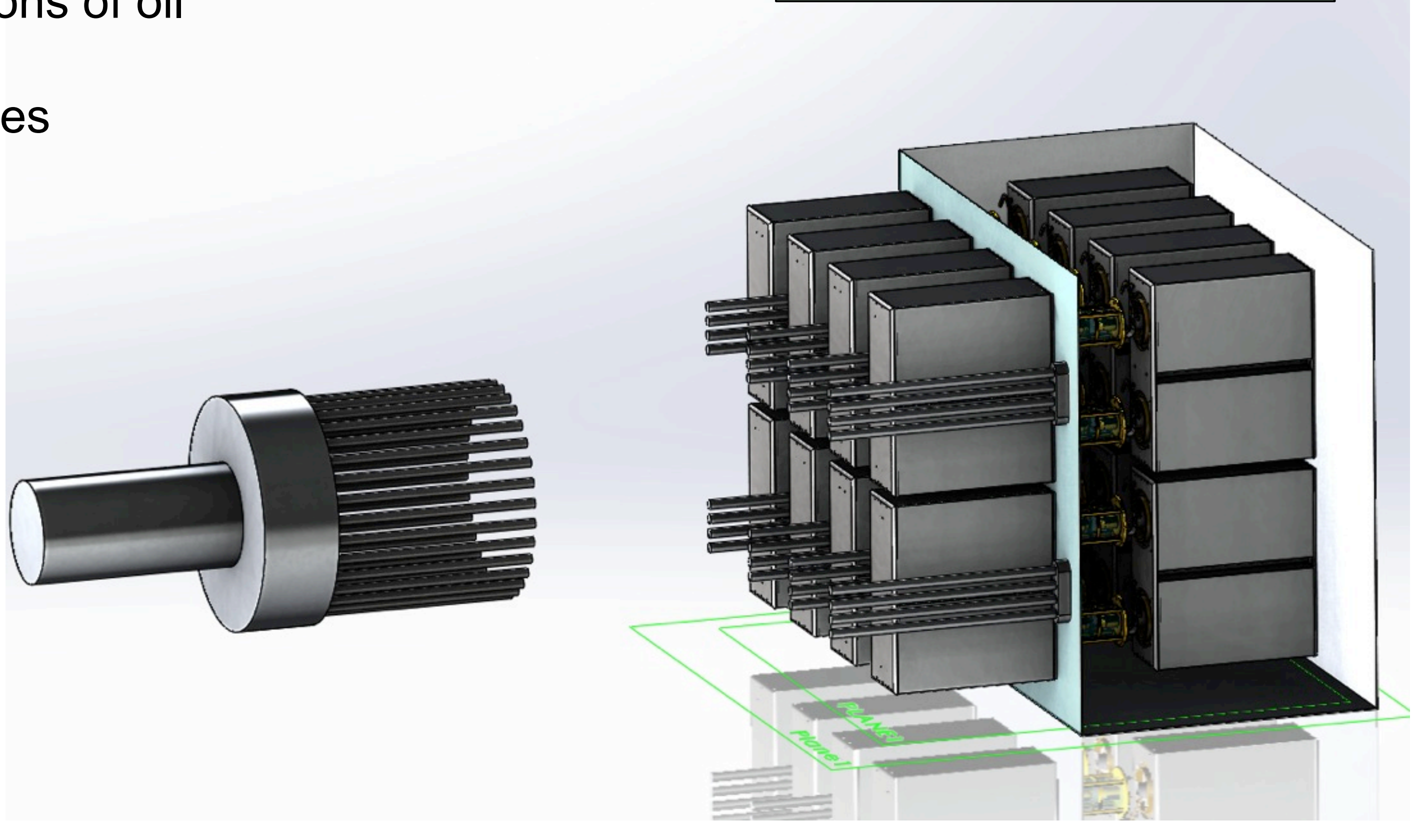
415 kJ bank

Flexible cables

DPF load

The proposed design is comparable in size to the Sodium bank

32 ZR Marx capacitors
Less than 1000 gallons of oil
32 cables
16 spark gap switches

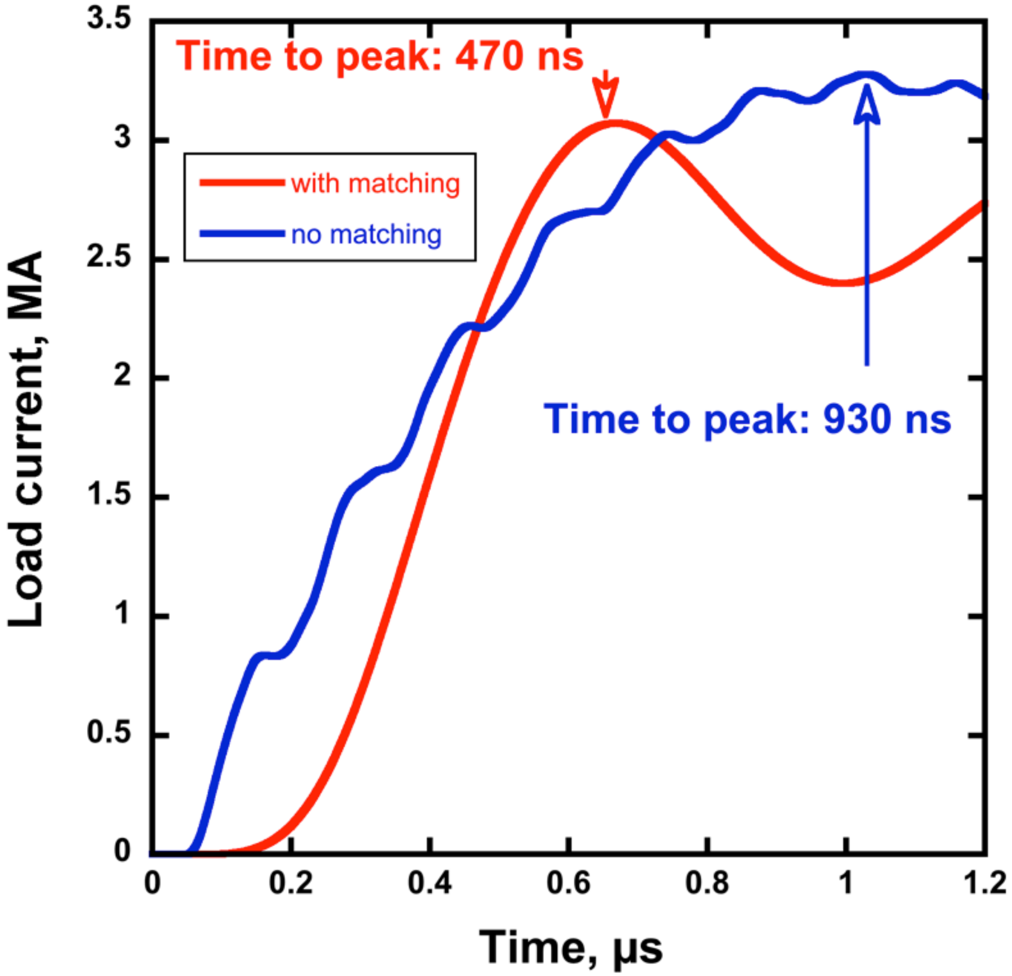


Parallel bank
16 parallel 2-stage Marx

The goal of 3 MA in 1 μs is possible with 415 kJ stored

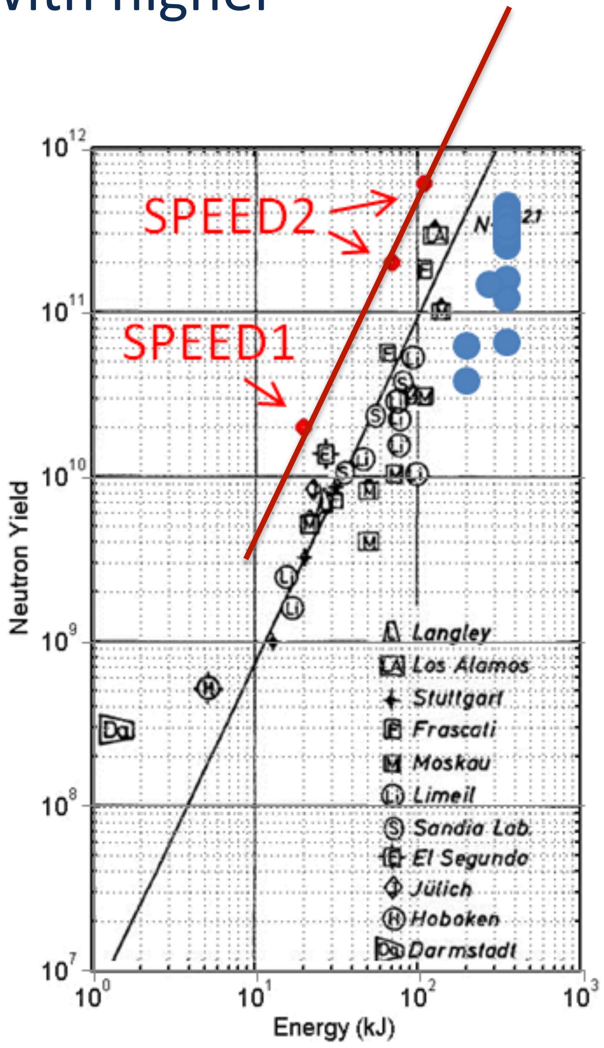
- 32 each 2.6μF 100kV capacitors
  - 416 kJ
- 32 each 10Ω cables
- 16 each 200 kV switches
- Matching uses ~1μF capacitors anc no additional switches
- Voltage limited to 200 kV for cable

Circuit simulations done with constant $\Delta L/t_{peak}$



The proposed system is as fast as Speed2 but with higher energy and current

Parameter	Matched	No matching	Goal
Time to peak	430 ns	930 ns	1000 ns
Peak current	3.1 MA	3.3 MA	3 MA
DT Neutron yield	~10^{14} ?	10^{13}	10^{13}



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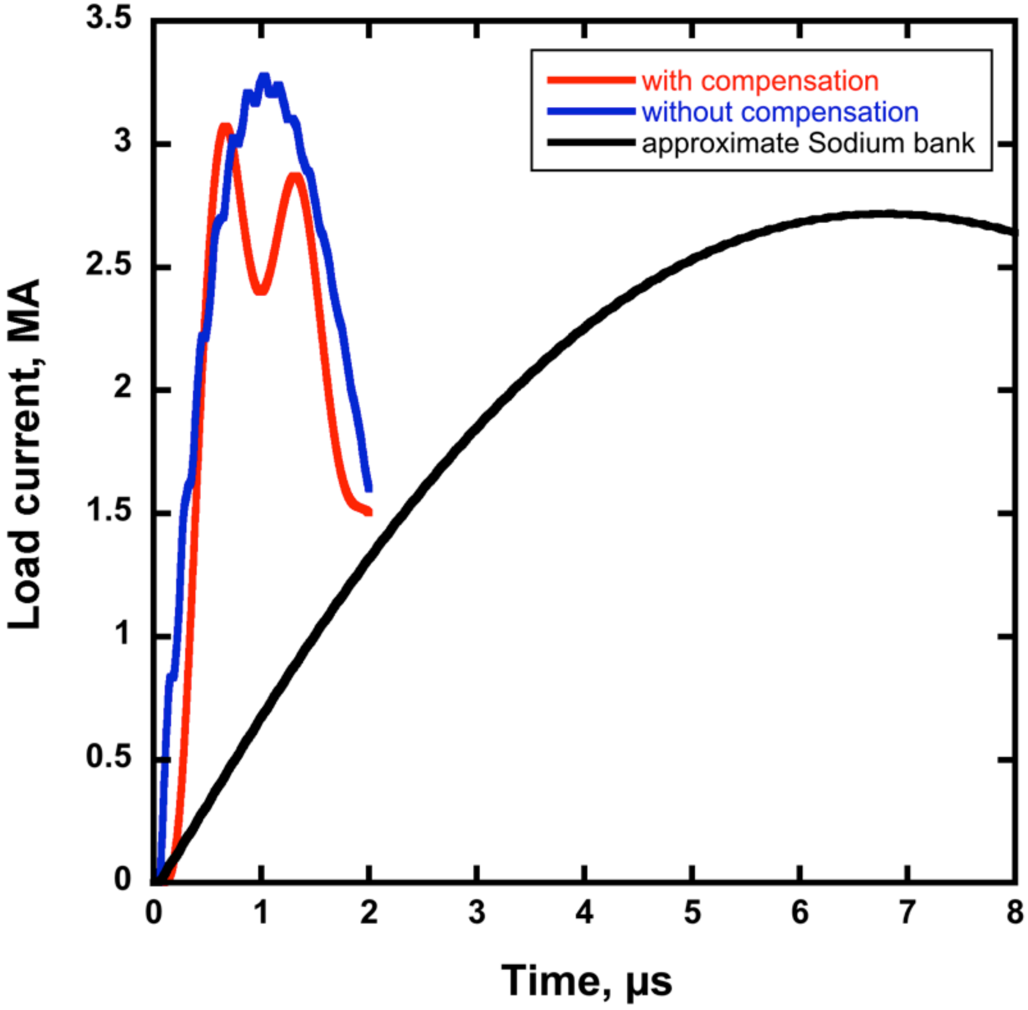
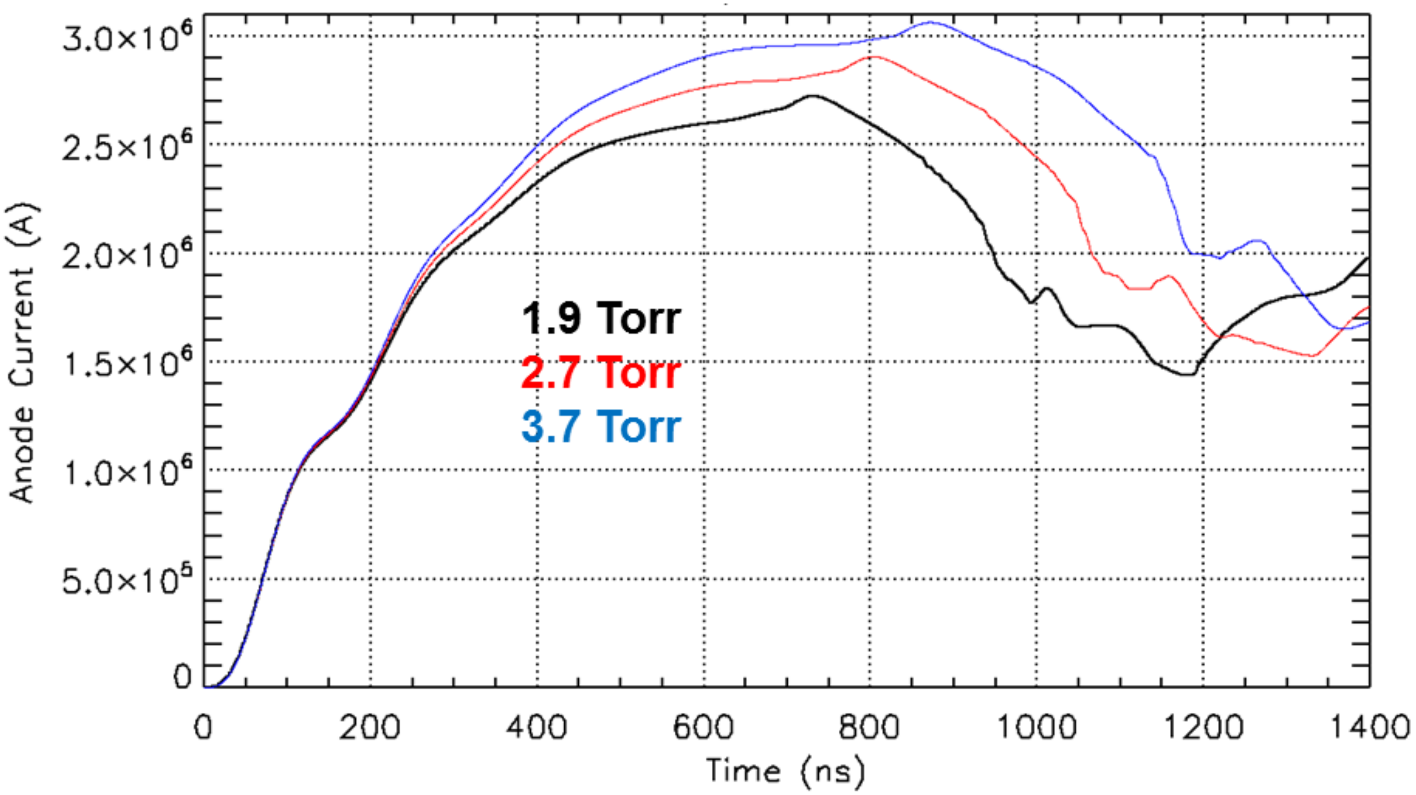
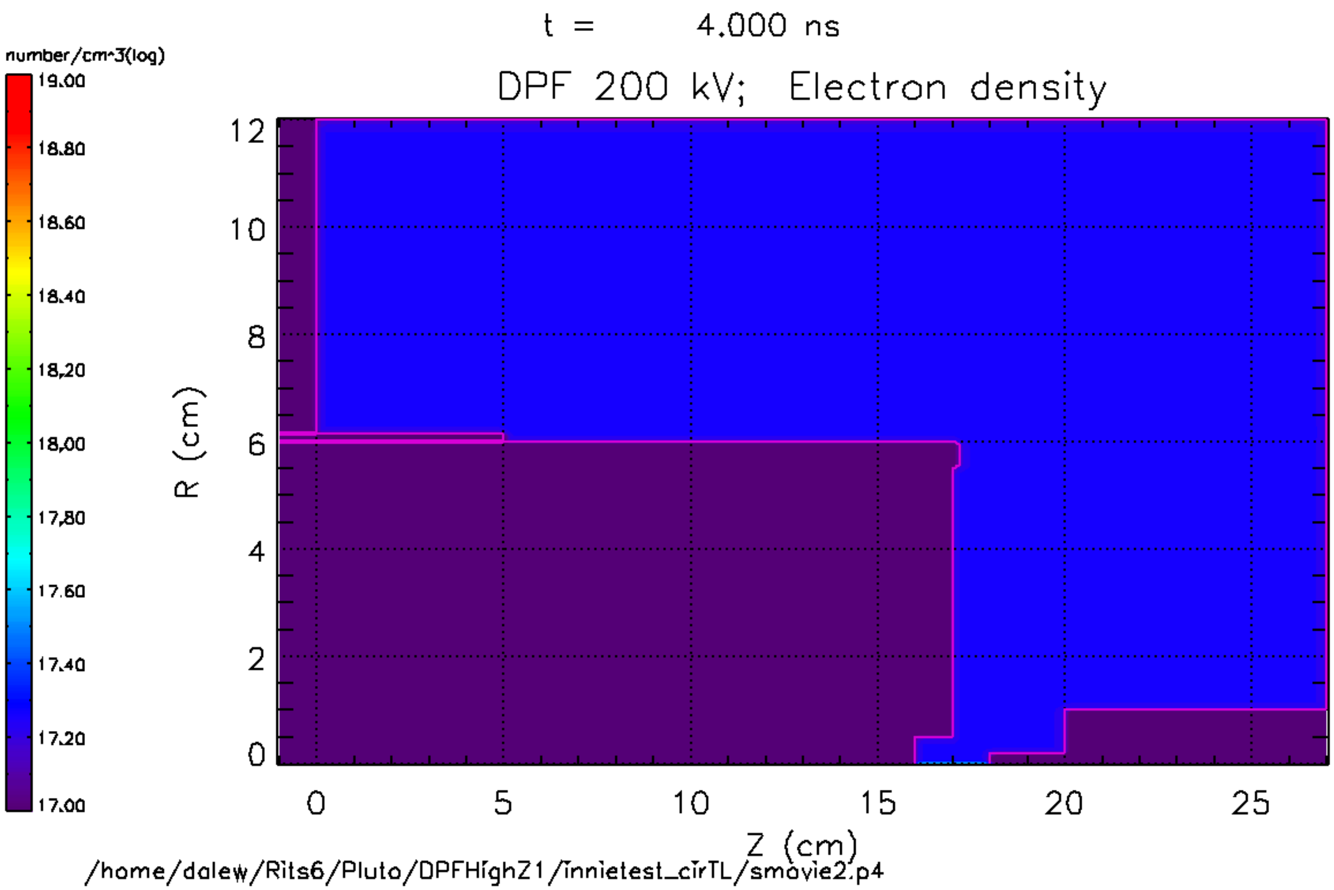


Initial LsP simulations are being done with the 900 ns pulse



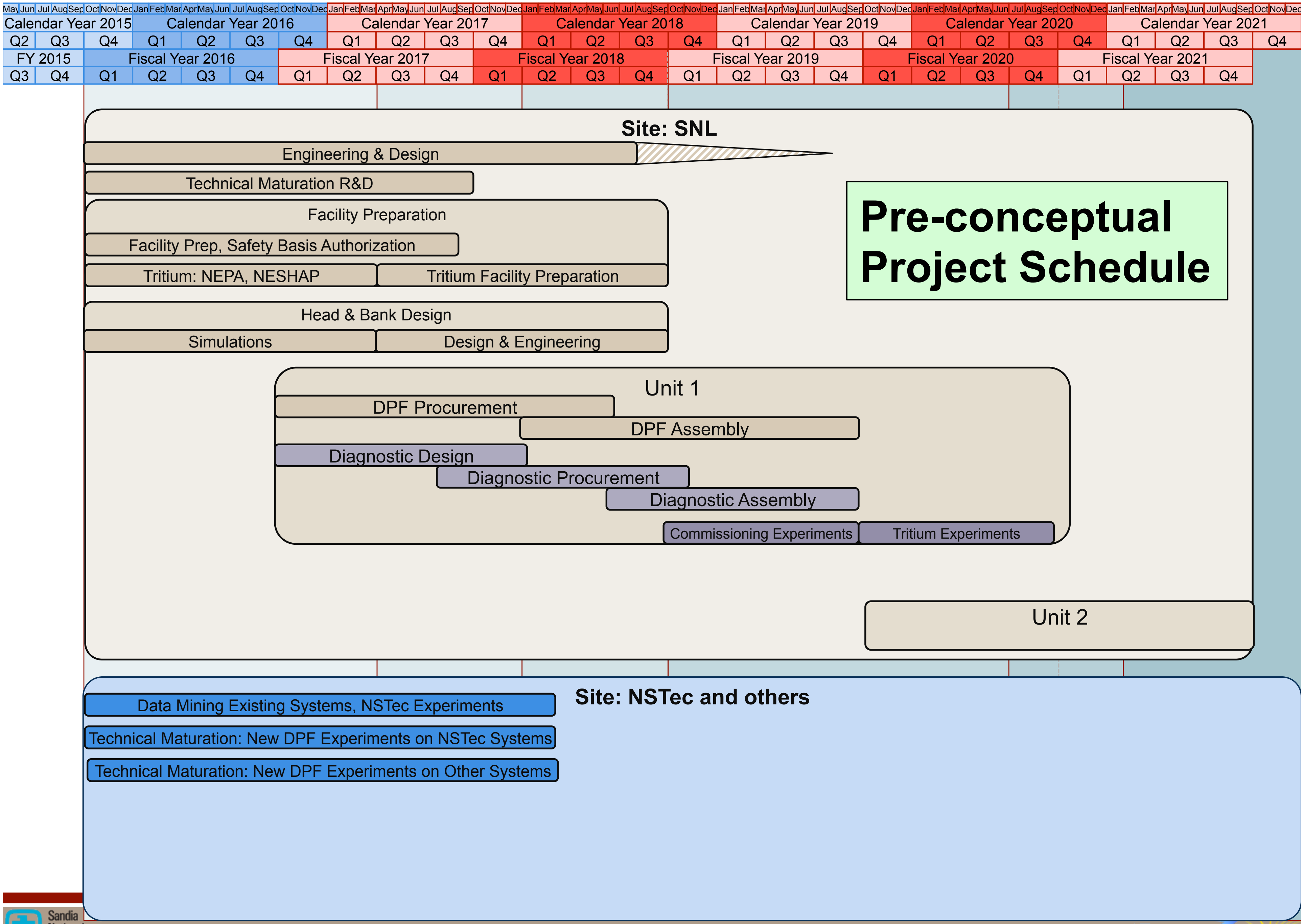
Welch, Savage, Stygar et al

Initial system designs are based on a SPEED-like geometry simulated in LsP



Welch, Stygar, Savage et al

Pre-conceptual Project Schedule



Site: SNL

- Engineering & Design
- Technical Maturation R&D
- Facility Preparation
  - Facility Prep, Safety Basis Authorization
  - Tritium: NEPA, NESHAP
  - Tritium Facility Preparation
- Head & Bank Design
  - Simulations
  - Design & Engineering
- Unit 1
  - DPF Procurement
  - DPF Assembly
  - Diagnostic Design
  - Diagnostic Procurement
  - Diagnostic Assembly
  - Commissioning Experiments
  - Tritium Experiments
- Unit 2

Site: NSTec and others

- Data Mining Existing Systems, NSTec Experiments
- Technical Maturation: New DPF Experiments on NSTec Systems
- Technical Maturation: New DPF Experiments on Other Systems

We identified some project risks

- Can we simultaneously meet the yield, pulse shape and jitter requirements with the required reproducibility?
  - Does any bank/head system presently meet these requirements?
  - Can we design, construct, test, and validate a new bank/head system to meet these requirements?

- Capacitor supply chain (presently qualifying new vendors)

- Can we develop the safety basis and authorization for the use of tritium on a DPF at Sandia? Do we need to?
  - What is the difficulty and cost of performing these experiments at Sandia?

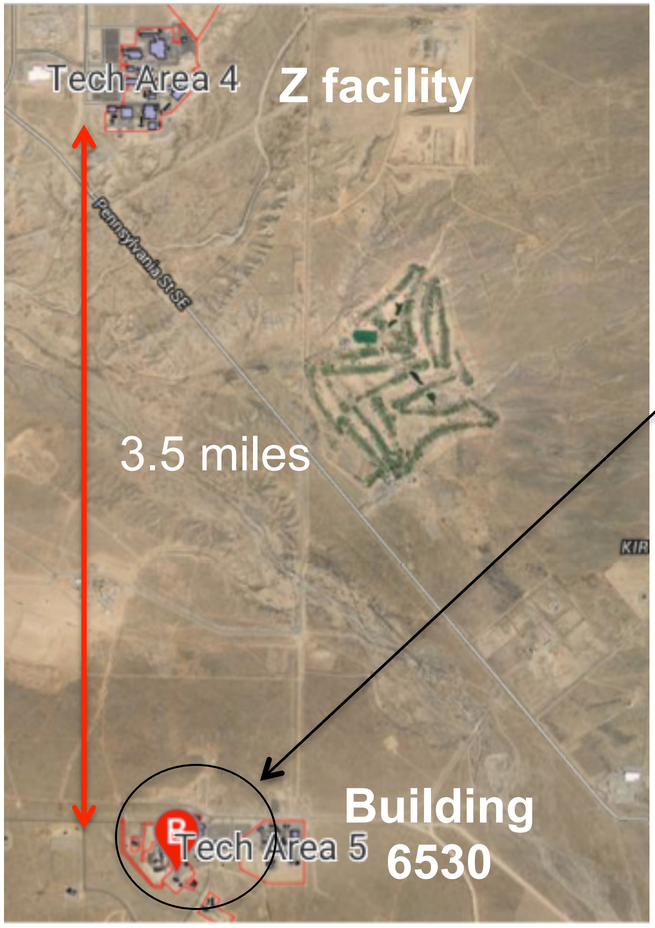
- What is the basis for the scaling factor for DD to DT?

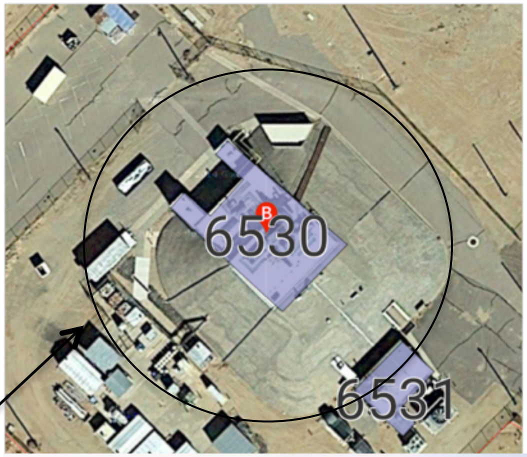
- There is a risk to changing the design away from the present system, but also a risk to not changing the design

- Increase of bank voltage and bank impedance and decrease of current risetime to narrow the neutron pulse width, increase the yield, and possibly decrease the jitter, might increase the risk of double-pulsing (re-strike?)

Risks continued…

We are planning to locate this DPF facility in Area V at Sandia for compatibility with high neutron yields, tritium, and foreign national access





- Building has a berm for shielding
- Remote location will simplify authorization for high neutron yields
- Will remote location simplify authorization for tritium operation?

Building 6530 layout

Experiments and simulations should be designed to answer these questions, and others

- METHODOLOGY and BOUNDARY CONDITIONS
  - How will we approach the numerical design and experimental validation of the head design?
    - Can we validate existing models against existing data well enough to provide confidence in design?

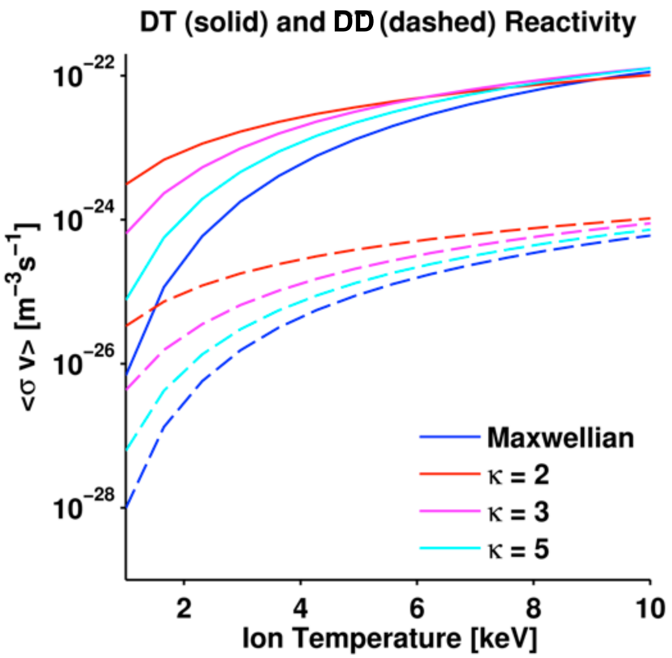
  - Is there a sweet spot in the performance of the present long pulse length, lower impedance bank/DPF configuration that meets both the yield and pulse shaping requirements simultaneously?

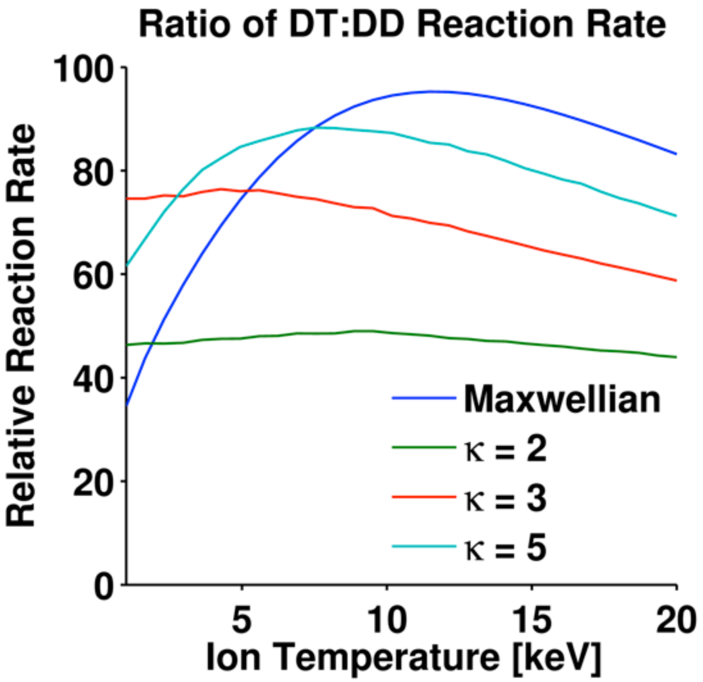
  - Do we have diagnostics that can assess root causes in variation of yield performance, and pulse shape variation?
    - Variations in drive?
    - Variations in the initial conditions (pressure, contaminants)
    - Variations in plasma implosion and assembly
    - Variations in effective voltage at the load
    - Variations in pinching, number of m=0 instability necks

Experiments and simulations should be designed to answer these questions, and others

- What is the scaling of the yield and pulse shape performance between DD and DT? The “cannonical” factor of 80X strictly applies only to >5 keV thermal sources

Patrick Knapp





Kappa distribution
Typical supra-thermal ion tails have κ~1-3

$$f_\kappa(v) = \frac{(\kappa w_t^2)^{-\frac{3}{2}}\Gamma(\kappa+1)}{2\pi\Gamma(\kappa-1/2)\Gamma(3/2)}\left(1+\frac{v^2}{\kappa w_t^2}\right)^{-(\kappa+1)}$$

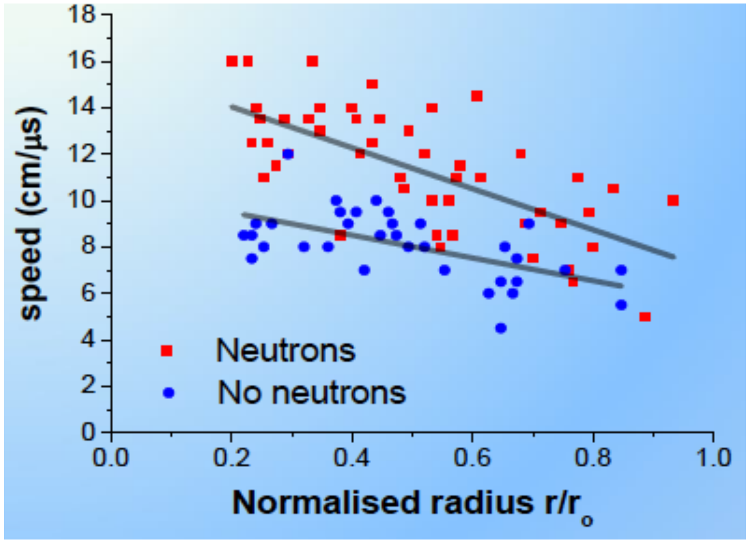
Experiments and simulations should be designed to answer these questions, and others

- Are there methods to improve the reproducibility of output that should be considered?
  - Pre-ionization (β-decay ionization from Ni source in Zakaullah et al reviewed by Soto, 2005)
  - Could Tritium β-decay ionization have the same impact?
  - Will higher dI/dt and higher voltage improve uniformity of breakdown and implosion?
  - Small axial magnetic field of 100 Gauss over entire focus region (Bland et al, DZP, 2014)

Experiments and simulations should be designed to answer these questions, and others

- Are there methods to improve the reproducibility of output that should be considered?
  - Good neutron emission requires a fast radial implosion (Bland et al and others)
  - Higher dI/dt
    - Correlated with faster radial implosion
    - Higher voltage
    - Reduced arcs in plasma during implosion may eliminate alternate current paths
  - Improve the reproducibility of breakdown at insulator – azimuthally non-uniform breakdown at insulator may not impact performance (Bland et al)

Bland et al, DZP 2014



Neutron producing shots have faster radial implosion
Have a higher dI/dt
Have a higher voltage

Experiments and simulations should be designed to answer these questions, and others

- ENGINEERING and OPERATIONS QUESTIONS
  - Can we develop a protocol to condition or “season” the tube in a reproducible manner?
    - Alumina covered quartz as on SPEED
  - Is firing the tube the best way to season the tube or would there be other ways (discharge cleaning)
  - What is the impact of the build up of impurities in the head, and could recycling of the gas improve reproducibility?
  - Can the tube design be modified to lower the cost, improve the number of experiments than can be performed without replacing the head?
  - What is the cost of performing experiments with Tritium and are there methods to decrease the tritium inventory without giving up yield?

Experiments and simulations should be designed to answer these questions, and others

- ADVANCED PINCH DESIGNS
  - Can we use numerical design to improve the reproducibility of plasma assembly?

  - Can we use numerical designs to increase the yield
    - Increase the density of material beams interact with
    - Doped foils
    - Gas puff/DPF hybrid

  - Are there methods to improve the reproducibility and narrowness of the output pulse width?

  - Are there other configurations we should consider?

The system should be designed to allow compatibility with a path forward for more advanced pinch designs, for example gas puffs – this also suggests shorter implosion times and higher voltages

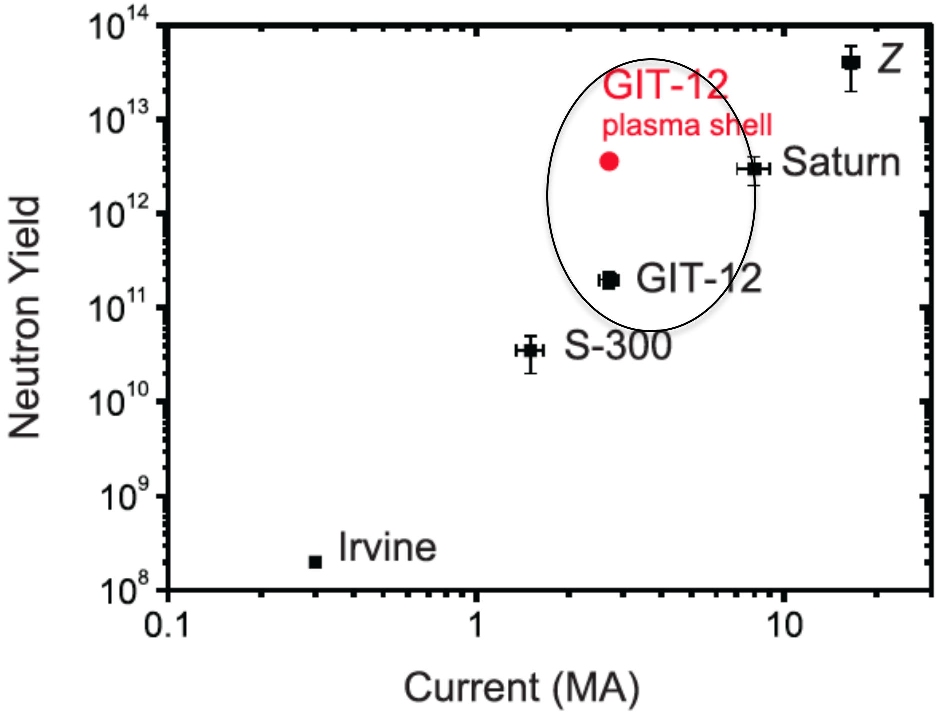
- There is significant upside to optimize magnetically driven implosion performance

2.7 MA in 700 ns
50 kV initial voltage
Plasma shell on puff
    improves ionization
    improves uniformity of breakdown
    decreases mass left behind
    voltage during disruption increases
from Veffective = 400 kV to 800 kV
20 shots with constant conditions
    The average yield was 1.7e12.
    The standard deviation was 1e12.
    The peak yield was 3.7e12.
    The lowest yield was 0.4e12.

Deuterated polyethylene foil doubles yield from
    2.9 ± 0.3e12 to 3.7 ± 0.4e12

DD yields from gas puffs at 2.7 MA ~4e12

Daniel Klir et al, PRL, 2014, PPCF, 2015



Pulse widths need to be evaluated

Diagnostic layouts

Summary

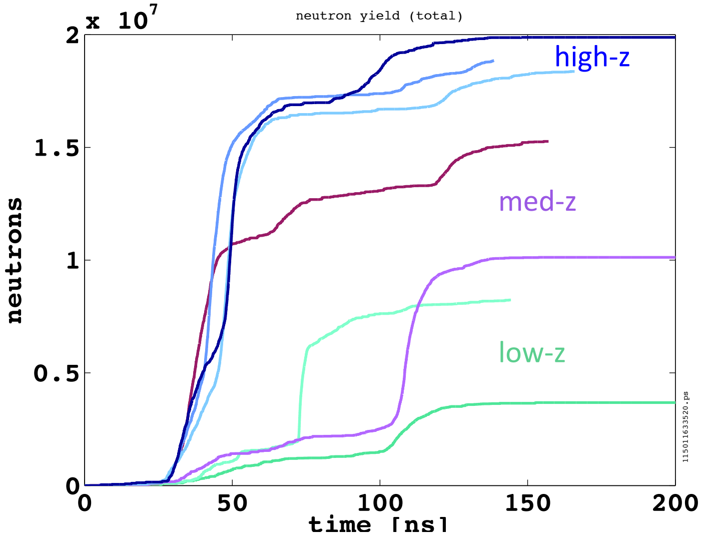
Backup

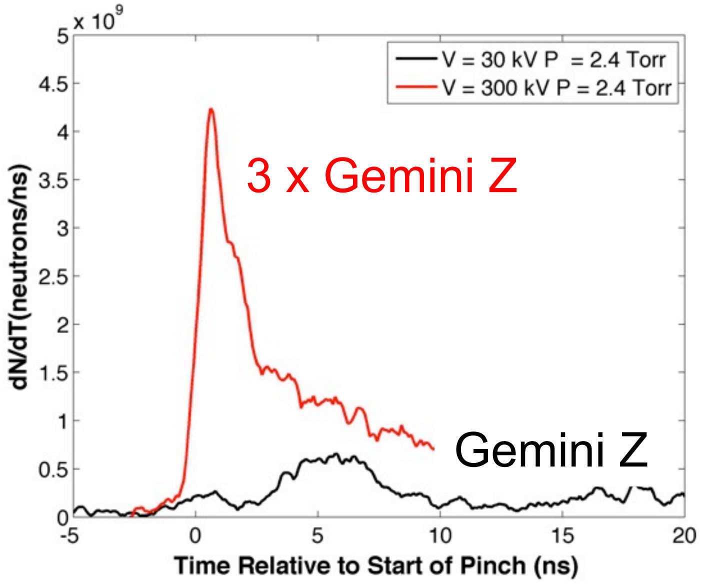
Higher impedance drive may have other benefits, based on LsP simulations

- A higher impedance driver may reduce the shot-to-shot variation of the yield (simulations by Schmidt et al)

- A higher impedance driver may maximize neutron emission rate and may therefore maximize our ability to produce a narrow pulse (simulations by Schmidt et al)

These simulations were conducted by Andrea Schmidt, Jason Sears, Tony Link (LLNL), and colleagues.





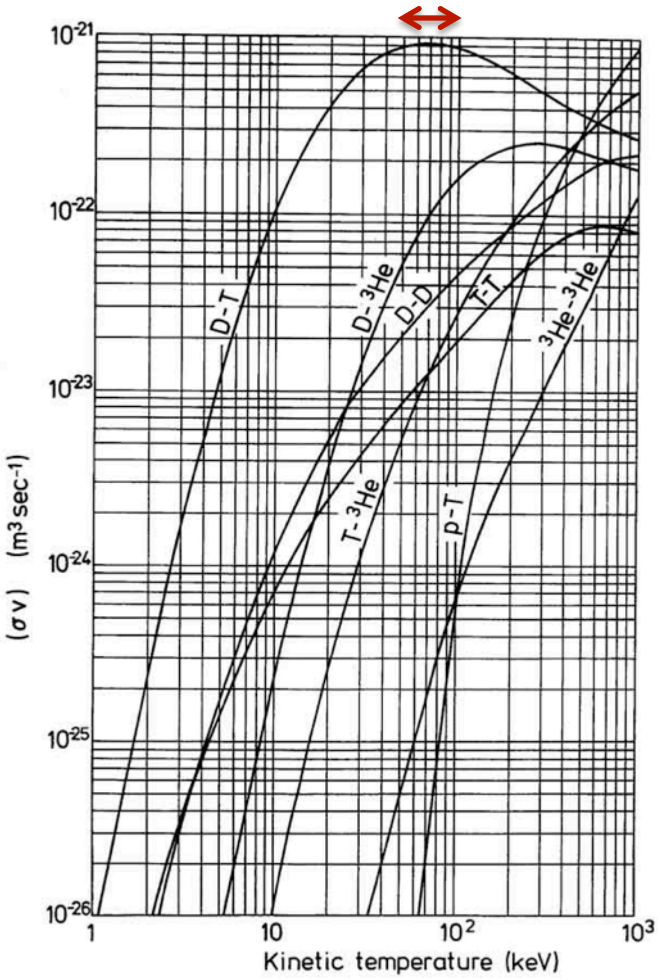
Higher voltage may have other benefits for maximizing output for both beam-driven (and TN) neutrons

- A higher effective pinch voltage (to generate ion beams with a power law energy distribution overlapping the peak of the DT reaction cross section) at 50 to 100 kV may be more optimal than 25-35 kV systems.
  - Effective voltage = V-L(dI/dt)

- A higher effective pinch voltage to generate ion beam energy distribution above the peak of the cross section may also be more optimal

- Generating beams near the peak of the cross section (where the cross section varies more slowly with energy) may reduce sensitivity of output to pinch variations that change the inductive voltages generated along the pinch column

- Caveat: Ions beams in these systems are generated at energies much larger than the estimated effective inductive voltage at the pinch (Klir et al)



Shorter implosion time implosion systems may perform better based on other experience

- Long implosion times for DPFs are historically chosen not based on optimum design, but simply from the lower cost of multi-microsecond pulsed power and availability of low cost components

- Long history with classical z-pinches suggest that higher dI/dt's and shorter implosion times allow higher performance
  - Higher implosion velocities are better
  - Historic data from DPFs also suggest the same scaling (Soto et al, Klir et al)

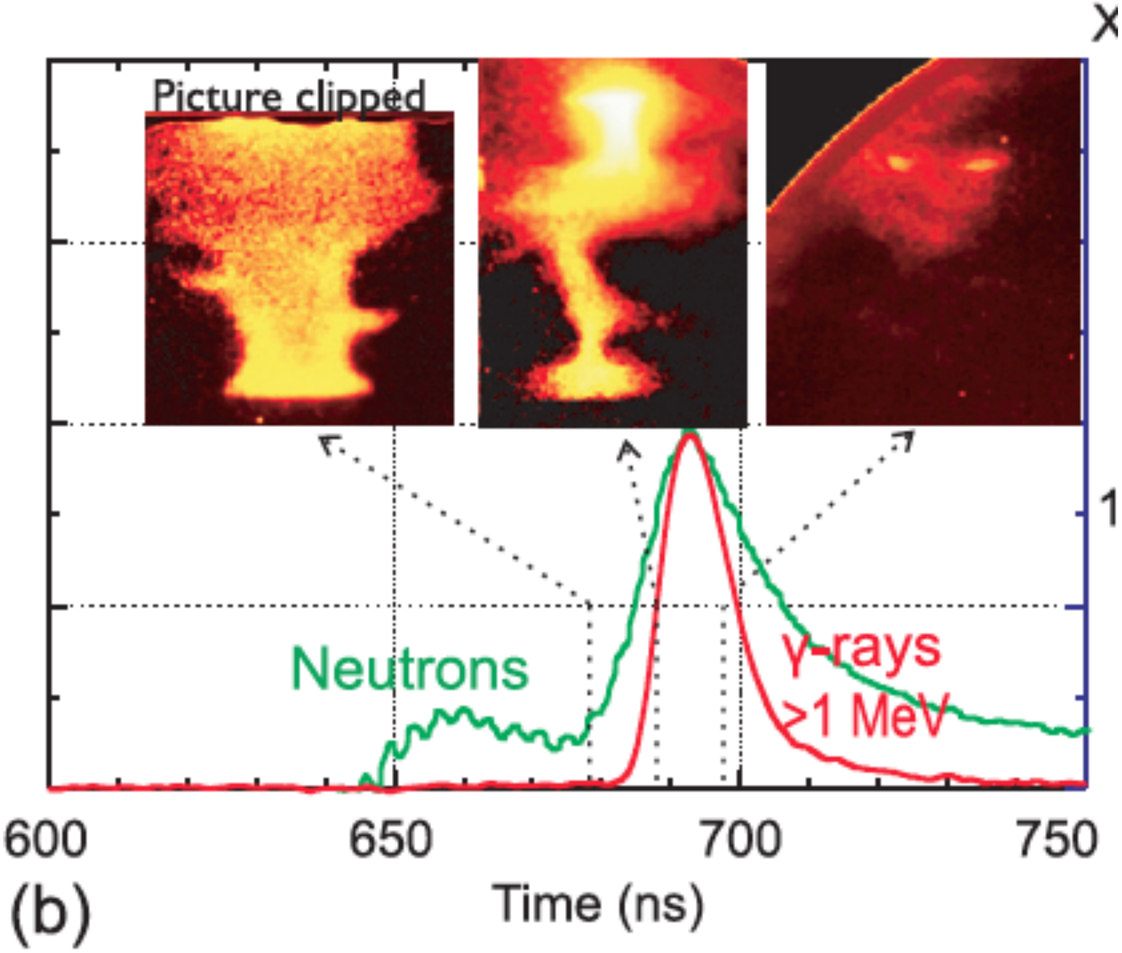
- A shorter implosion time system may reduce the shot-to-shot variation of the output pulse jitter (suggested by conventional pinch experiments, TBD for DPFs)

- Will higher voltage systems increase or decrease the probability of current restrike or reconnection (in the axial run down region? In the pinch?)

We identified some project assumptions

- There will be a strong collaboration between NSTec, LANL, LLNL, and SNL to execute this project
- There will be strong MOU's and accountability between all parties
- As a project we will get access to the existing NSTEc DPF data
- As a project we will get access to facility time on the NSTEc DPF systems
- We will get enough funds and authorization for early procurement of components, such as capacitors
- In general, funding is available as needed

Hard x-ray output is not a perfect surrogate for neutron emission



Budget breakdown by task