Overview of Fusion Research at Los Alamos

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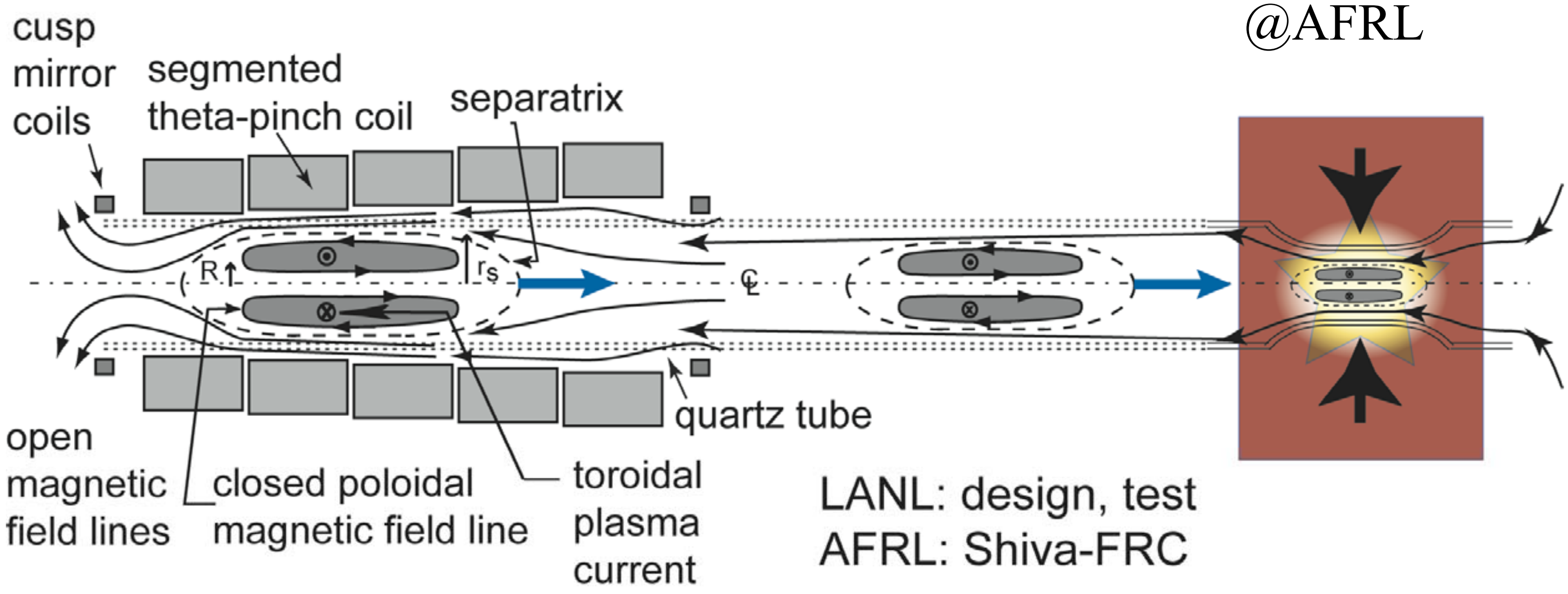
Fusion Power Associates Annual Meeting and Symposium
Fusion Energy: Countdown to Ignition and Gain
Dec. 3-4, 2008

MFE and HEDLP research at LANL

- Magnetized Target Fusion: First shot in Jan. 2009!
- Ion-based fast ignition science: Trident Laser user facility
- Theory & simulation: using Roadrunner!
- ITER construction: secondees and Tritium Exhaust Plant
- Concept development: IEC, FRC
- Plasma diagnostics, national collaborations: UW, MIT
- Fusion materials testing planning: MTS & MARIE @LANL

Magnetized Target Fusion, liner compression of FRC, physics test

Formation: LANL Translation Compression @AFRL



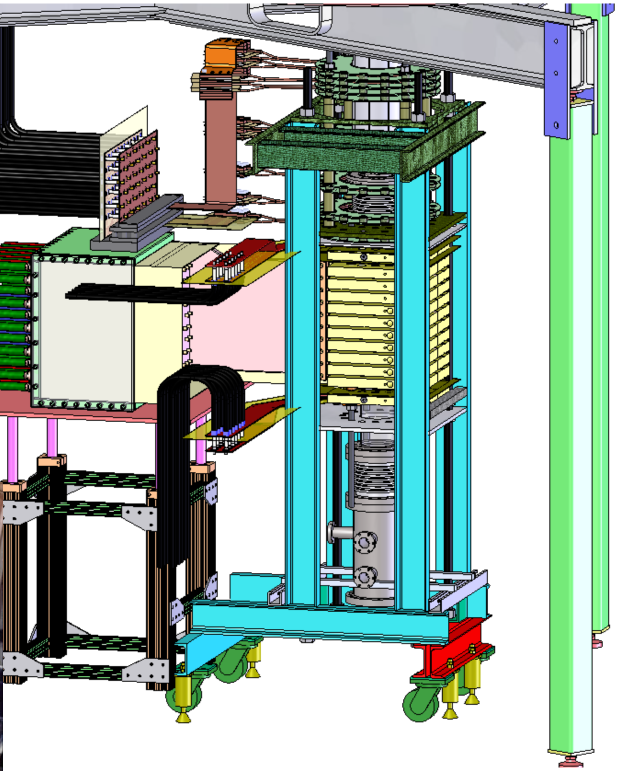
LANL: design, test
AFRL: Shiva-FRC

- Pulsed, high pressure (HEDLP) approach to fusion
- Inertial + magnetic confinement
- **Goal: Achieving a multi-keV fusion grade plasma**

Plasma/Liner implosion experiments are beginning at AFRL Shiva Star facility, with a load assembly named FRCHX

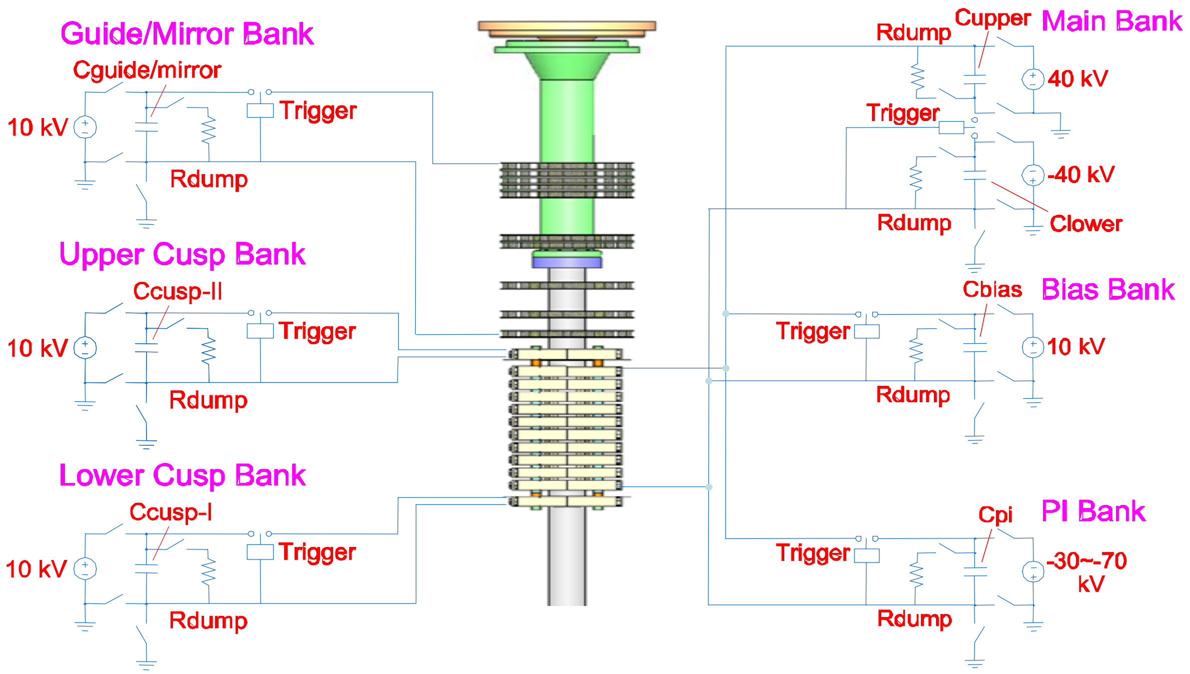
Some of the MTF Team

Shiva Star 9 MJ, 12 MA cap bank



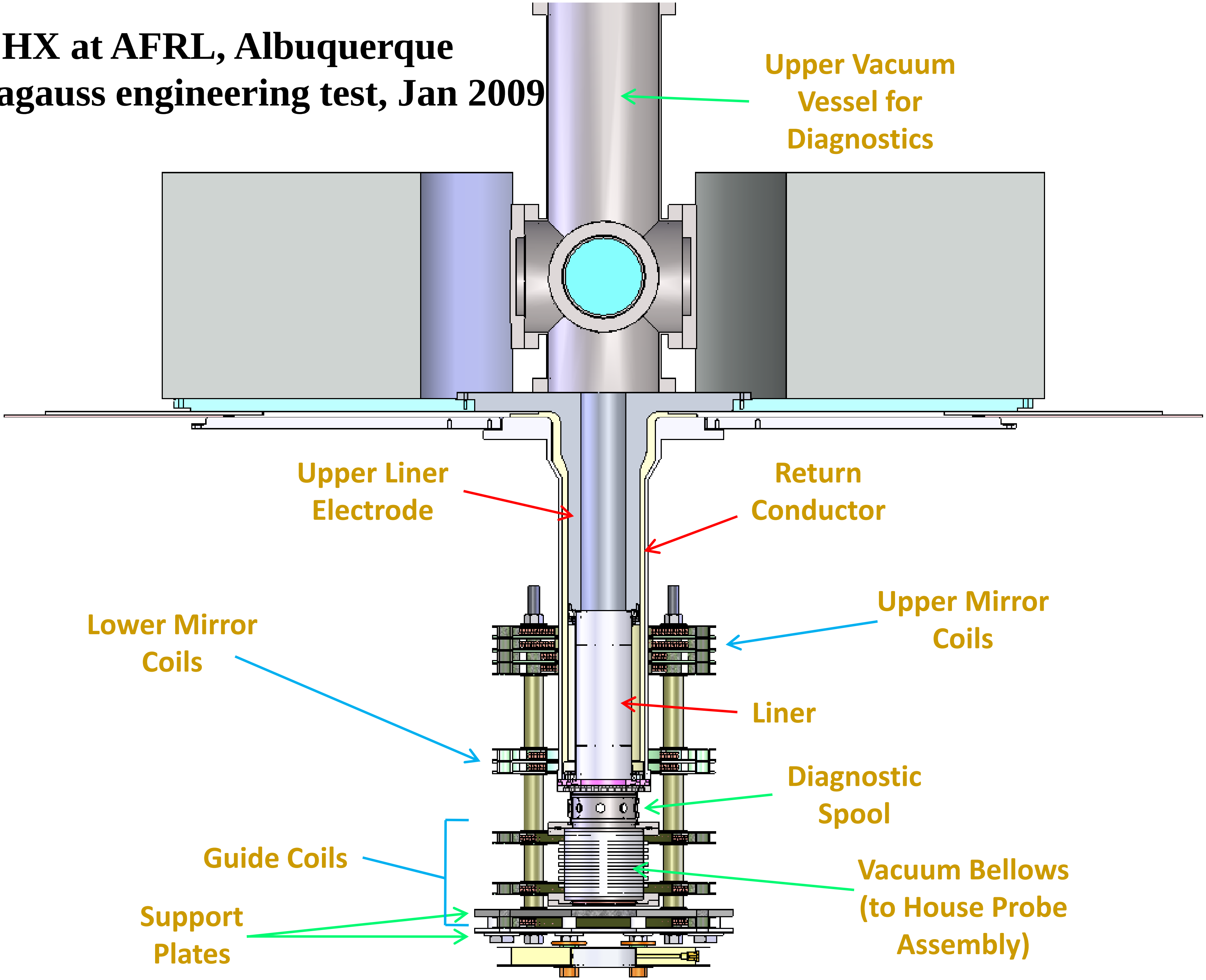
FRCHX load stack, 2-m tall, underneath center of Shiva Star

FRCHX PULSED POWER SYSTEMS



- Bias bank – *Consists of two cap bank modules, ~2.5 mF per module*
- PI bank – *Single 2.1 μF capacitor, oscillation frequency of ~230 kHz*
- Main bank – *Single Shiva Star bank module, caps turned sideways to reduce bank height (Cupper = Clower = 72 μF)*
- Upper and Lower Cusp banks – *three 500 μF capacitors each, switched with ignitrons*
- Guide/Mirror Bank – *total capacitance of 12 mF, switched with 6 ignitrons*

FRCHX at AFRL, Albuquerque
Megagauss engineering test, Jan 2009



Upper Vacuum Vessel for Diagnostics

Upper Liner Electrode

Return Conductor

Lower Mirror Coils

Upper Mirror Coils

Liner

Diagnostic Spool

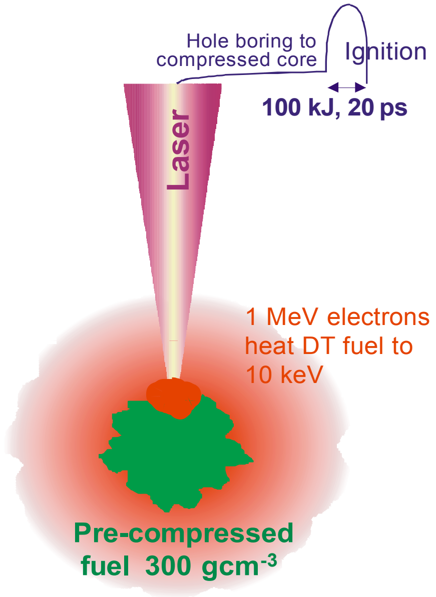
Guide Coils

Vacuum Bellows (to House Probe Assembly)

Support Plates

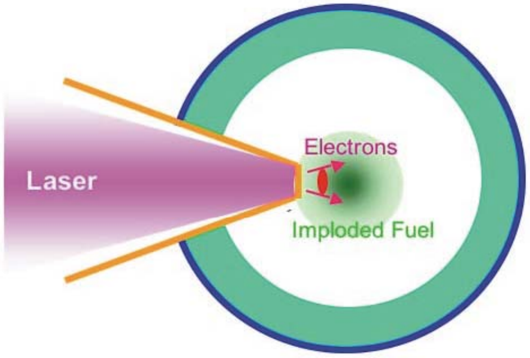
HEDLP Science for Fast ignition (FI)

- FI is isochoric ignition (conventional is isobaric)
- Long-pulse (> 10 ns) driver to compress DT to 300 – 500 g/cm^3 , ρr ~ 3 g/cm^2
- Particle beam must deposit ~ 10 kJ in ~ 25 ps (~ 4 PW) within hot-spot (HS) volume (~ 25 -- 50 μm)^3 , i.e., ~10^{22} W/cm^3 → laser driver

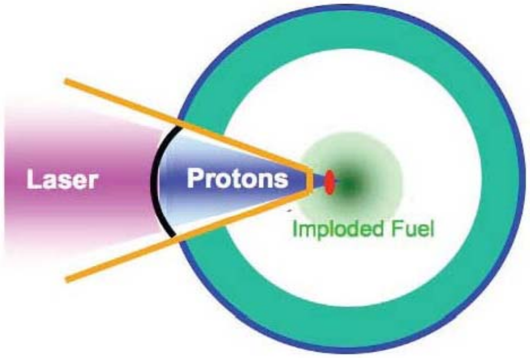


M. Tabak *et al.*, PoP
1 1626 (1994)

Alternative schemes:



R. Kodama *et al.*,
Nature 412 798
(2001)

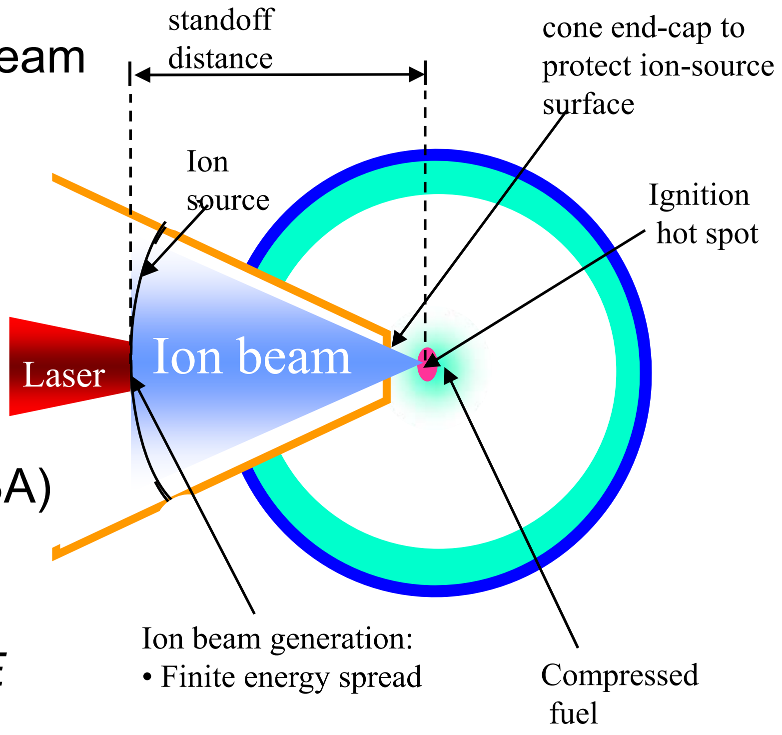


M. Roth *et al.*, PRL
86 436 (2000)

We consider a laser-driven Z > 1 ion ignitor beam (e.g., C).

Issues relating to ion-driven fast ignition:

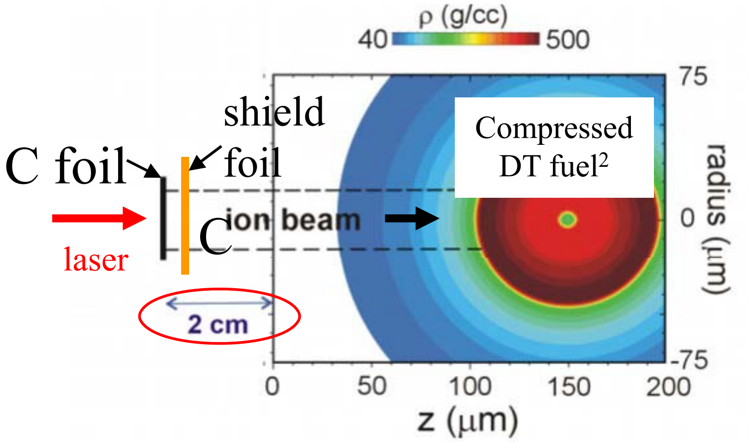
- Fuel assembly
  - shield ion-source from implosion → **want large standoff**
  - cone → difficult implosion
- Laser conversion efficiency to particle beam
  - Laser → hot e^-
  - Hot e^- → ion ignitor beam
- Fuel ρr ~ particle range → laser I
  - e^- → ~ 1 MeV → $I \sim 5\times10^{19}$ W/cm^2
  - Protons → ~ 13 MeV → $I \sim 10^{20}$ W/cm^2
  - **C → ~ 440 MeV → $I \sim 10^{21}$ W/cm^2**
- Req. power density & I → beam area (BA)
  - BA >> hot spot area → focus beam
  - Problem for e^--based FI
- Finite particle beam energy spread $\delta E/E$
  - High $\delta E/E$ → wasted ignitor energy
- Particle-beam transport
  - Arrival time spread → **$\delta E/E$ trade versus standoff**



Issues

Quasi-monoenergetic low-Z ions (e.g., C) have potential advantages as a fusion ignitor beam.

- Potential advantages over electron* or proton-based[1] FI:
  - Quasi-monoenergetic-ion source may be placed far from the fuel
  - Sharper deposition (higher efficiency)
  - Most robust particle-beam transport
  - Many fewer ions than protons required
  - Required thin targets and very high contrast now demonstrated!



- Potential issues:
  - Laser – ion conversion efficiency: ~ 10% desired
  - Focusing C ion beam: only proton focusing demonstrated

Beam Ion	Energy (MeV)	Number of Ions	Laser Irrad. (W/cm^2)	Minimum areal densities, layer thickness @ 0.1 mm^2
Protons	7 – 19	10^{16}	~ 10^{20}	10^{18} cm^{-2}, ~ 2 μm (CH)
C^{6+}	**400-480**	10^{14}	~ 10^{21}	10^{16} cm^{-2} , **~ 10 nm**

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* Tabak *et al.*, PoP 1, 1626 (1994); [1] Roth *et al.*, PRL 86, 436 (2001);
[2] D. Clark & M. Tabak, Nucl. Fus. 24, 1147 (2007)

Technology

Two key technological requirements to study ion acceleration at the ~ GeV level are now in place:

- **Ultra-thin targets (10-100 nm)**
  - Have settled on diamond-like C (DLC) as a technologically convenient species
  - As part of our collaboration with LMU (Munich), they have provided DLC targets in thicknesses of 3, 5, 10, 30, 50 & 60 nm.

- **Laser pulses with ultrahigh contrast (~ 10^{10}) and no prepulse**
  - Have discovered that post-pulses can turn into prepulses.
  - Invented new scheme for pulse cleaning ("SPOPA").*
  - Improved laser contrast ratio on Trident (10^7):
    prepulses $< 5 \times 10^{-10}$ & ns pedestal $< 2 \times 10^{-12}$.
  - These targets (down to 3 nm) have been
    fielded successfully on Trident with new high-contrast front end.

* R. Shah, et al., Optics Letters (2008) submitted

Summary of laser-driven ion acceleration:

Laser couples to target electrons → Relativistic e$^-$ population out of equilibrium → Relativistic e$^-$ population couples to ions → Directed ion beam

Laser couples to target electrons

- Ponderomotive force – $q^2 \nabla E^2 / 4m\omega^2$
- Heating (with linear polarization)
- Pressure (circular polarization)

Relativistic e$^-$ population out of equilibrium

- $I\lambda^2 > 1.33 \times 10^{18}$ Wcm^{-2} μm^2, KE > rest mass
- High energy Effic. ~ 30 – 50%
- Directed motion
- Expansion

Relativistic e$^-$ population couples to ions

- Charge separation
- Kinetic instability

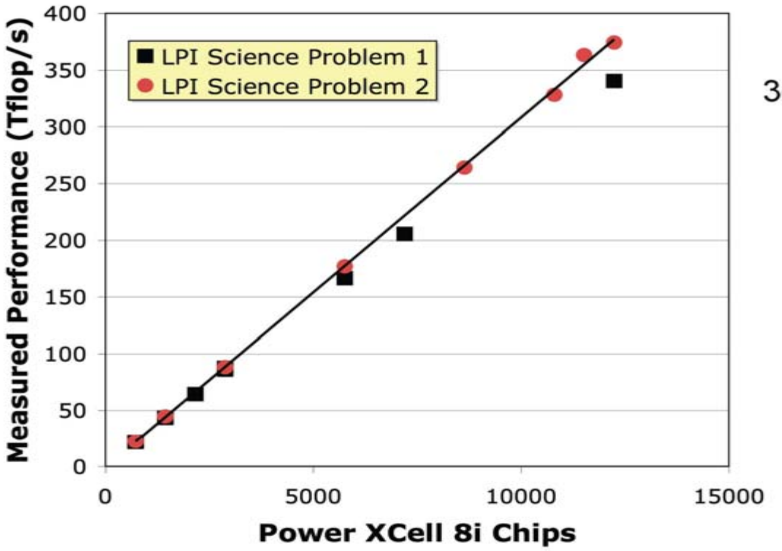
Directed ion beam

- MeV – GeV
- Born in ps
- Neutralized → high current

- Very large multi-scale computational problem in relativistic laser-plasma interactions

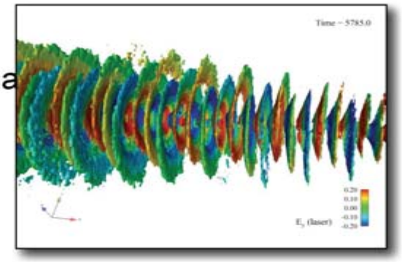
We are applying unique LANL resources to discover & model ion-beam generation physics.

- World’s most powerful PIC code (VPIC) on the world’s most powerful supercomputer (Roadrunner): first sustained ~ Petaflop performance, 10^{12} particles
- VPIC has been extensively validated in relativistic laser matter interactions, LPI, magnetic reconnection, etc.



Bowers et al., ACM/IEEE
Gordon Bell Prize finalist, 2008.

3d laser plasma interaction



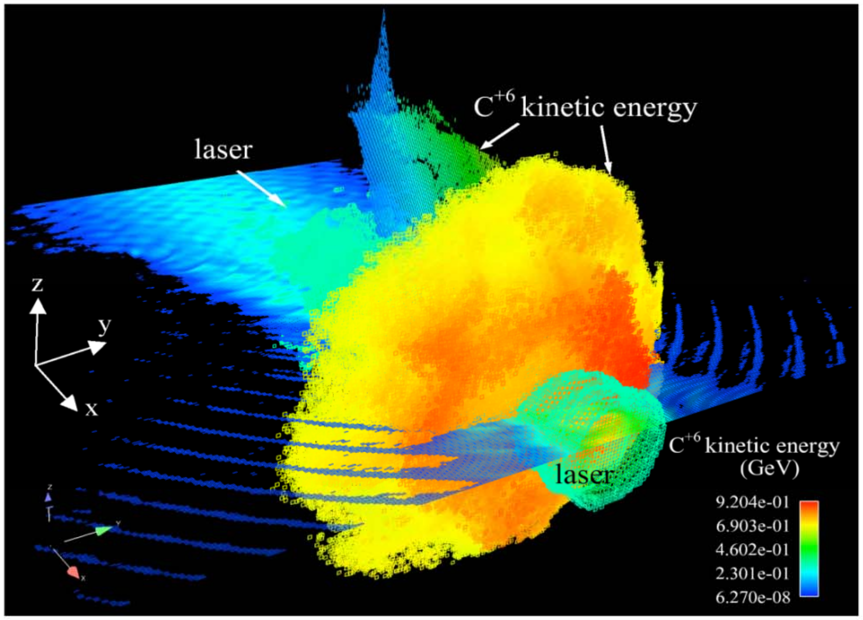
Results

3D simulations of ultra-thin foil Carbon acceleration

Circular polarization, 30nm C and $I_0=10^{21}$ W/cm^2 & 312 fs pulse

Our largest simulation to date on ion acceleration (run on Roadrunner base system):

- Physical domain 25x25x20 μm w. solid target density 14×10^9 cells, 21×10^9 particles, 4096 processors
- Contrasting with sim. size at the time of the proposal: 0.5×10^9 cells, 2.2×10^9 particles, 510 processors
- 3D visualization using EnSight server-of-servers mode enables viewing, analysis of very large (multiple-TB) data sets.

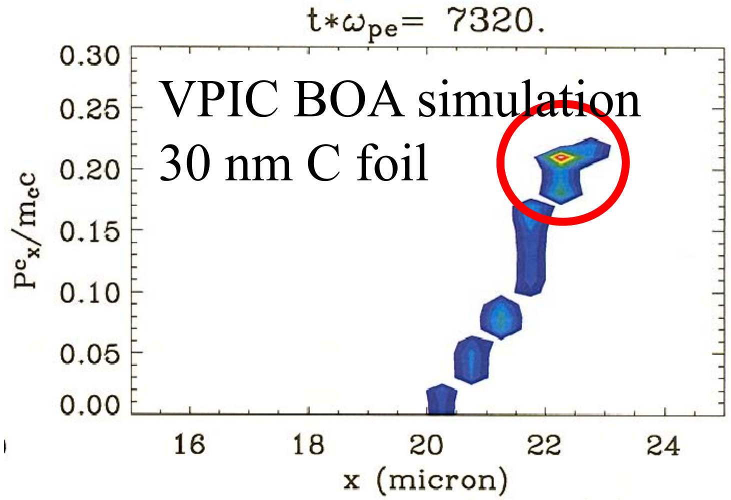


- VPIC has been modified to run efficiently on Roadrunner (Opteron hosted hybrid supercomputer with 12960 IBM Power Xcell 8i chips)
- We anticipate an additional factor of ~10 in speed over Opteron, enabling routine trillion-particle PIC simulations
- We have obtained a significant allotment of time (13 million hours, >1/3 of time when whole system is available) on the full 3 Pflop/s (single precision) Roadrunner system

BOA

Discovery of the laser-breakout afterburner* (BOA): a path to high efficiency & high energy ion beams

- Requirements:
  - $I \sim 10^{20}$ -- 10^{21} W/cm^2
  - Ultra-thin targets (*e.g.*, ~ 30 nm C)
  - Ultra-high laser contrast (~ 10^{10})
- 1D, 2D, 3D Simulations using VPIC code
  - Start with solid density C, including with H contaminants
- Ion acceleration mechanism:
  - Enhanced TNSA
  - Laser penetration across target
  - Electron heating & drift relative to ions
  - Electron energy → ion energy via kinetic Buneman instability.


VPIC BOA simulation
30 nm C foil

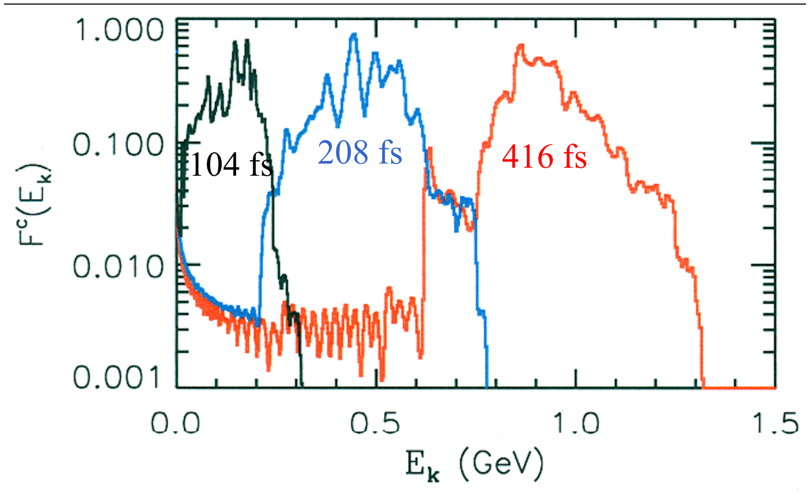
- Initial simulations ($I \sim 10^{21}$ W/cm^2 , 30 nm targets, C):
  - 35% (in 1D), 15% (in 2D) of all ions accelerated to 0.3 GeV ± 7%, 4% efficiency.
  - C-ion acceleration is “immune” to surface or volumetric proton contamination!

The key to realize this concept is a high (~ 10^{10}) laser-pulse contrast to prevent the pre-pulse shock from destroying the ultra thin target.

* L. Yin *et al.*, Phys. Plasmas 14, 056706 (2007); Laser and Part. Beams 24, 291 (2006);

VPIC has been used to study Radiation Pressure Acceleration (RPA) of C, showing acceleration to ~ GeV.

- Requirements:
  - $I \sim 10^{21}$ W/cm^2 with ultra-high laser contrast
  - Ultra-thin targets (*e.g.,* ~ 30 nm C)
  - Circular polarization
- 1D simulations using solid density C 208 fs pulse (blue curve)
  - 60% of ions accelerated to 450 MeV ± 10%, 13% conversion eff.
  - 1D scaling with pulse length
  - C-beam energy increases with length
- Concern: effects of higher-dimensions
- 3D VPIC simulations show:
  - high sensitivity to curvature, which may negate benefits of circular polarization
  - ~ GeV energies
- Further optimization is needed.

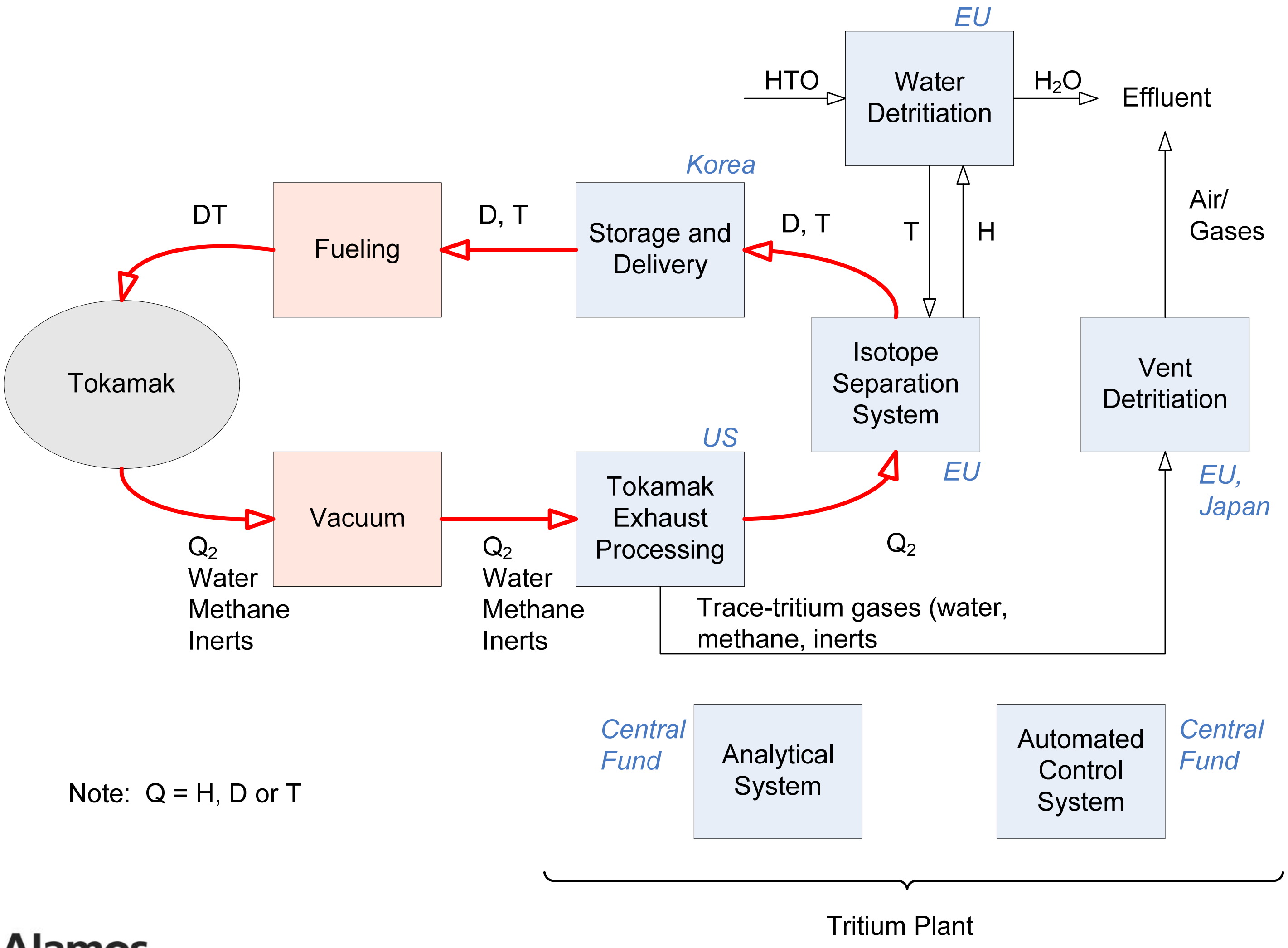


RPA deserves further consideration for ~ GeV ion acceleration.

LANL (T-15 now T-5) theory efforts

- Toroidal confinement theory/modeling.
  - First-principles models for long mean free path toroidal plasmas.
  - Effect of transport on macrodynamics.
  - Alternate concepts (including mirror) assessment and innovation.
  - Stellerator theory and computation.
- Computational fusion plasma physics.
  - Innovations in 3D grid adaptation, high order conservative discretization, nonlinearly implicit time stepping, and scalable solvers.
  - Integrating grid, discretization, and solvers for FSP applications.
  - Software engineering and management issues for FSP.
- Fusion Materials
  - Predictive modeling of plasma/materials interaction.
    - From the sheath plasma turbulence (PIC) to the erosion of displacement damaged materials (MD & accelerated MD).
- High energy density laboratory plasmas
  - MIF: standoff driver development and transport in dense magnetized plasmas (underlying target selection and optimization).
  - Fast Ignition and ICF: electron-ion coupling and ion stopping in dense (unmagnetized) plasmas.

The ITER Tritium Plant is a chemical plant consisting of seven systems built by multiple nations



EU
Water Detritiation
HTO
H_2O
Effluent
Air/ Gases
Korea
Storage and Delivery
D, T
Fueling
D, T
DT
T
H
Isotope Separation System
EU
Vent Detritiation
EU, Japan
Tokamak
Vacuum
Q_2
Water
Methane
Inerts
US
Tokamak Exhaust Processing
Q_2
Water
Methane
Inerts
Q_2
Trace-tritium gases (water, methane, inerts
Central Fund
Analytical System
Automated Control System
Central Fund
Tritium Plant

Note: Q = H, D or T

USA has the Tritium Exhaust Processing responsibility

TEP must separate three types of gases into one stream of hydrogen isotopes and a separate stream of tritium-free gases

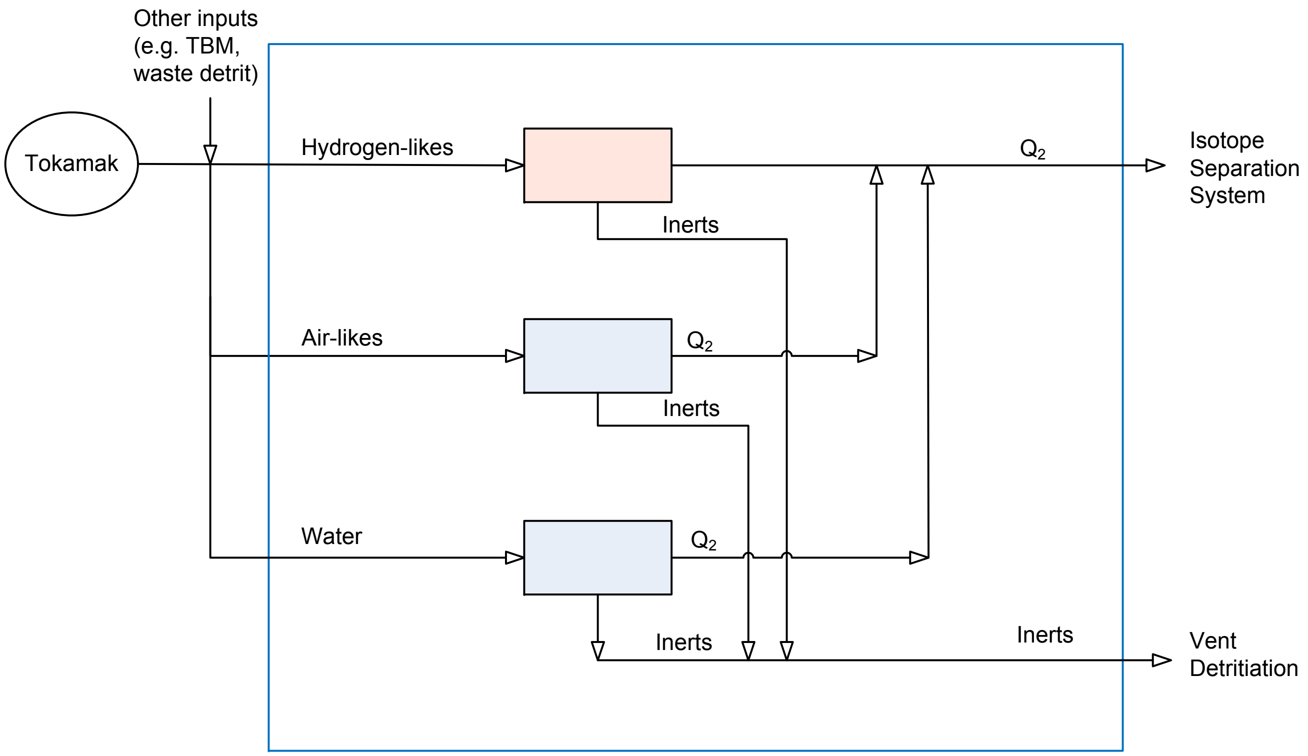
$Q2 = H_2, HD, HT, D_2, DT$ or T_2

Hydrogen-likes
He, Ne, Q_2

Air-likes
N_2, O_2, Ar, CO, CO_2, CQ_4

Water
Q_2O

"Inerts"
Tritium-free mixtures of species above



Tokamak Exhaust Processing System

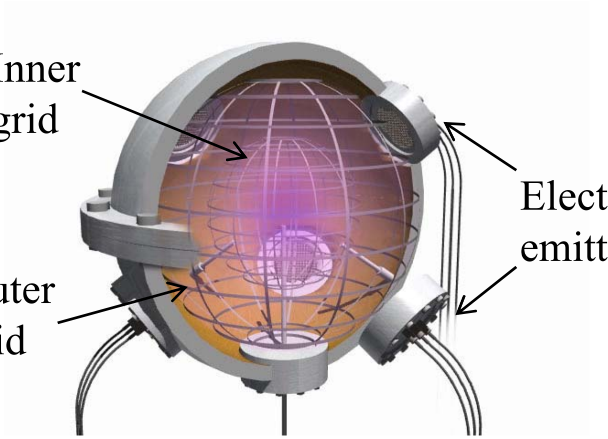
UNCLASSIFIED

Savannah River and LANL: Hydrogen Processing Laboratory prototyping

Oscillating Inertial Electrostatic Confinement Fusion

Y. Kim, H. Herrmann, A. McEvoy

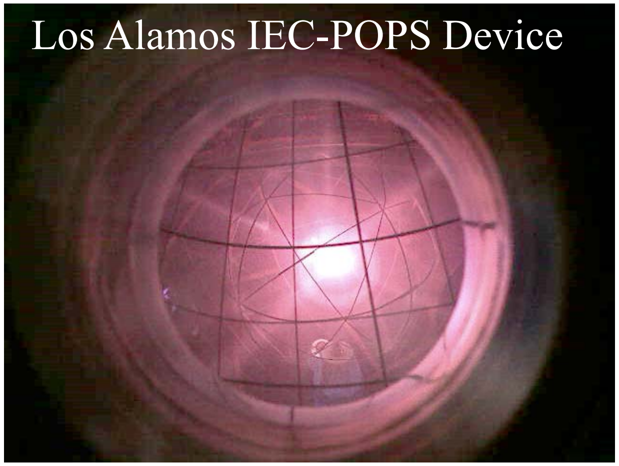
- Conventional IECs cannot obtain $Q > 1$
  - useful as neutron source- simple, portable, long lifetime, 2×10^{10} n/s (DT) by Hirsch (1968)
  - $\langle\sigma v\rangle_{i-i} \gg \langle\sigma v\rangle_{fusion}$: no net fusion power
- LANL POPS concept (Periodically Oscillating Plasma Sphere) has the potential to achieve $Q > 1$
  - Constant density electron background produces spherical harmonic potential well
  - Resonantly-driven ions simultaneously converge to the center with maximum kinetic energy
  - High plasma compression shown in 1D simulation (~ 10,000× in density)


Inner grid

Electron emitters

Outer grid

Emissive probe

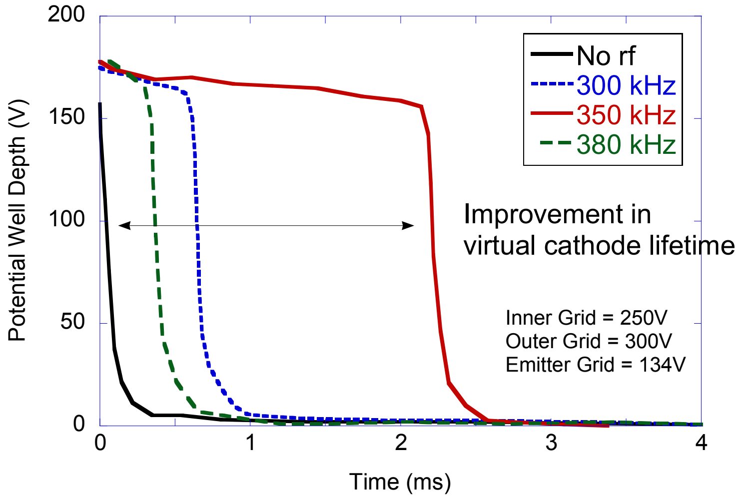

Los Alamos IEC-POPS Device

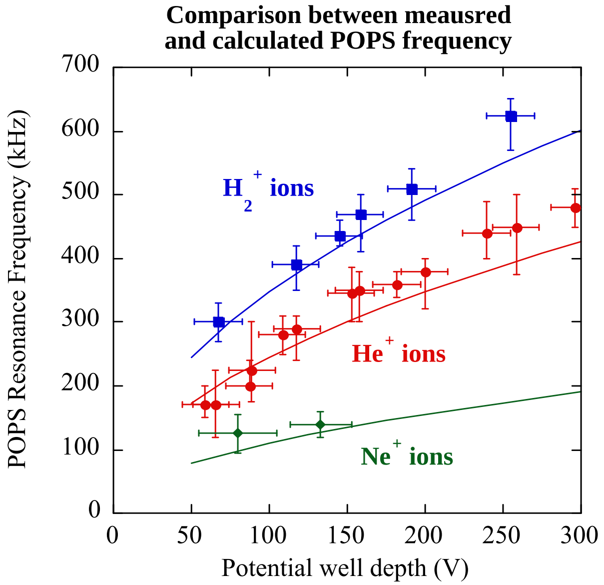
IEC-POPS Operation has been observed

- Experimentally observed POPS
  - Formation of potential well demonstrated
  - POPS oscillations shown to extend virtual cathode lifetime
  - POPS frequency shown to agree with theory:

$$f_{POPS} = \frac{\sqrt{2eV_{well} / M_{ion}}}{2\pi r_{VC}}$$

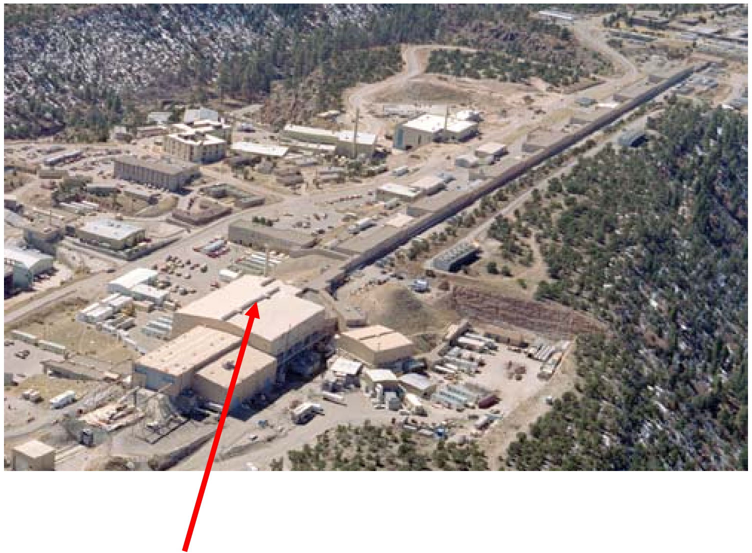
- On-going Work
  - Extend virtual cathode lifetime with:
    - dynamic electron injection
    - POPS frequency feedback control
    - controlled fuel injection
  - Upgrade for deeper wells
  - Improved diagnostic capabilities



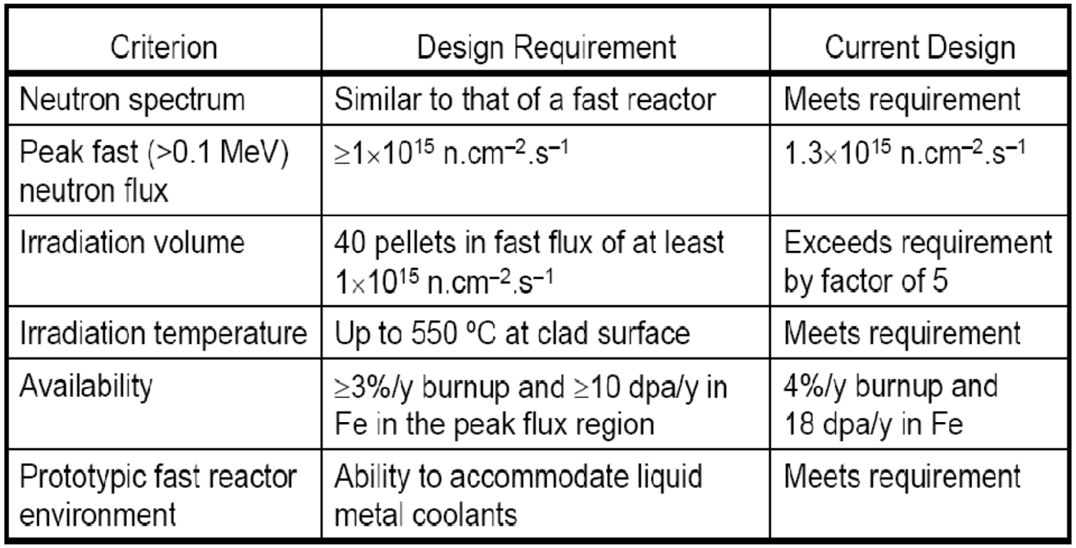


LANL Materials Test Stand (MTS) will provide irradiation capability for candidate fast fission fuels, targets & materials

- Fuels containing the transuranics (Np, Pu, Am, Cm) are being developed for transmutation in fast reactors
- Irradiation testing in a fast neutron spectrum and prototypic temperature environment is essential for understanding performance
- A substantial modeling and simulation effort is needed to qualify and license fuels, targets and materials. Validation data from MTS is a key component.



MTS is being built in an existing 3,000-m^2 experimental hall located at the end of the Los Alamos LANSCE linac ,which has successfully delivered 800-kW, 800-MeV beam to this area for a quarter century.



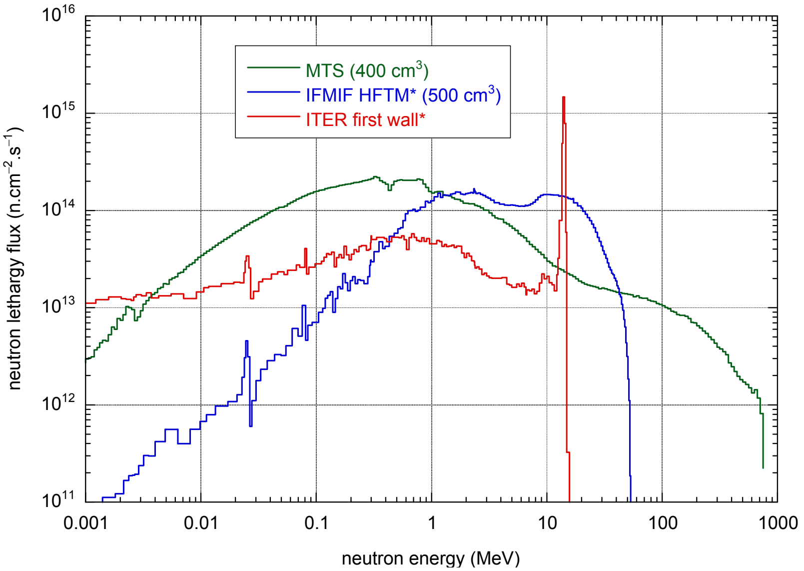
Criterion	Design Requirement	Current Design
Neutron spectrum	Similar to that of a fast reactor	Meets requirement
Peak fast (>0.1 MeV) neutron flux	$\geq 1\times10^{15}$ n.cm^{-2}.s^{-1}	1.3×10^{15} n.cm^{-2}.s^{-1}
Irradiation volume	40 pellets in fast flux of at least 1×10^{15} n.cm^{-2}.s^{-1}	Exceeds requirement by factor of 5
Irradiation temperature	Up to 550 °C at clad surface	Meets requirement
Availability	≥3%/y burnup and ≥10 dpa/y in Fe in the peak flux region	4%/y burnup and 18 dpa/y in Fe
Prototypic fast reactor environment	Ability to accommodate liquid metal coolants	Meets requirement

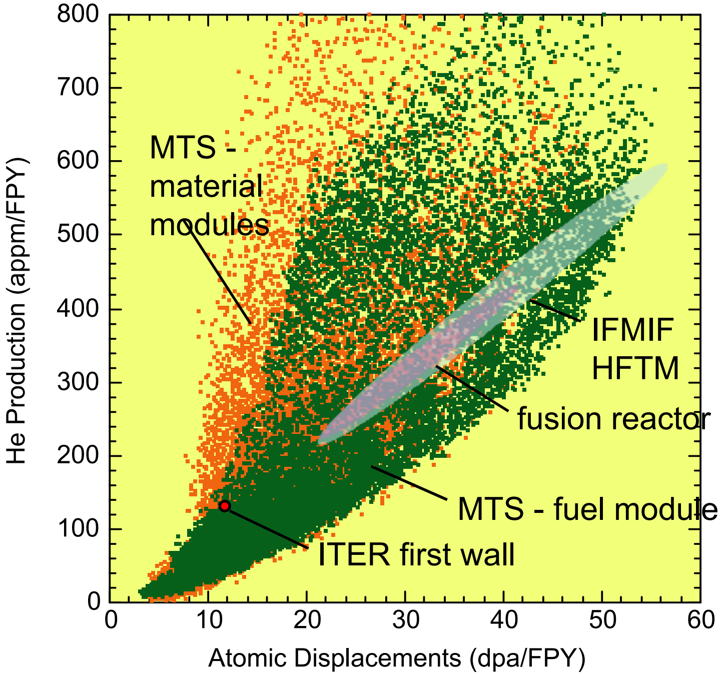
Ref: E.J. Pitcher, in *Utilization & Reliability of High Power Proton Accelerators* (OECD Publishing, 2008) pp. 427-433.

MTS neutron spectrum has potential application for fusion materials research

- The He/dpa ratio of materials samples irradiated in the MTS spans the range of fusion reactor systems
- At 1.8 MW beam power, the peak damage rate in the materials sample modules is 44 dpa/FPY
- In the materials sample modules, the irradiation volume exceeding 20 dpa/FPY is 250 cc, or half that of IFMIF
- For most candidate materials, the burn-in of contaminants from spallation reactions does not significantly alter material composition
- The pulsed nature of the radiation should not negatively impact test results

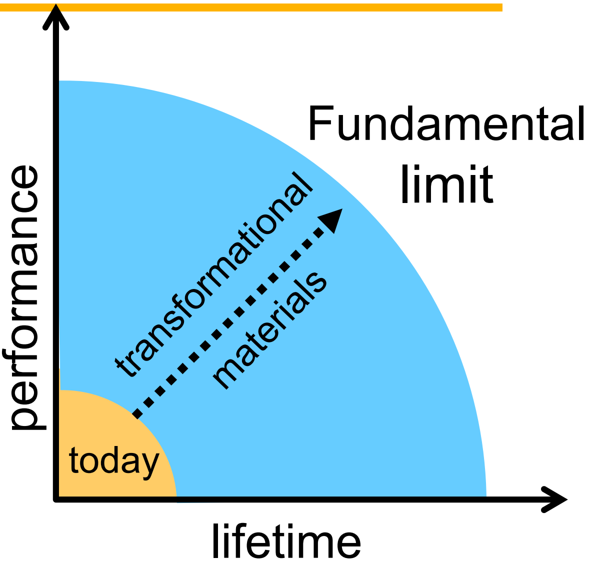
Ref: E.J. Pitcher *et al.*, *Proc. 8th International Topical Mtg on Nuclear Applications and Utilization of Accelerators* (Pocatello, 2007)





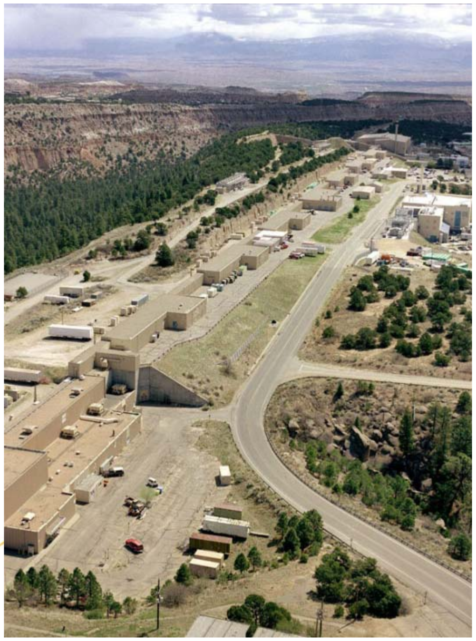
MaRIE will address high priority materials challenges identified by fission and fusion energy communities

MaRIE (Matter-Radiation Interactions in Extremes) is an experimental facility concept providing transformational materials solutions for today's & tomorrow's National security needs.



FESAC Priorities, Gaps and Opportunities for Magnetic Fusion Energy

- ***"…understand the materials and processes that can be used for replaceable components that can survive the enormous heat, plasma and neutron fluxes without degrading the performance of the plasma."***
- ***"… The potential for alternative irradiation facilities to reduce or possibly eliminate the need for the US to participate as a full partner in IFMIF needs to be assessed."***



MaRIE will create extreme radiation fluxes for materials qualification and advance the frontiers of radiation damage science through unprecedented in situ measurements in these extremes

MaRIE builds upon planned investments at LANSCE & strong LANL programs in stockpile stewardship, energy research, & threat reduction.

Summary

- Multiple small-scale fusion projects at LANL

- Looking for growth in HEDLP activities: MTF, ion-based fast ignition

http://trident.lanl.gov

- Working on the NIF ignition campaign

- Working on ITER construction (also 3 staff at ITER)

- Fusion materials studies using the NE funded Materials Test Stand neutron irradiation facility at LANSCE, and future upgraded capabilities with the LANL's Matter-Radiation Interactions in Extremes (MARIE)