# GEM*STAR: ACCELERATOR-DRIVEN SUBCRITICAL REACTOR FOR IMPROVED SAFETY, WASTE MANAGEMENT, AND PLUTONIUM DISPOSITION

Rolland P. Johnson
Muons, Inc. (http://www.muonsinc.com/)

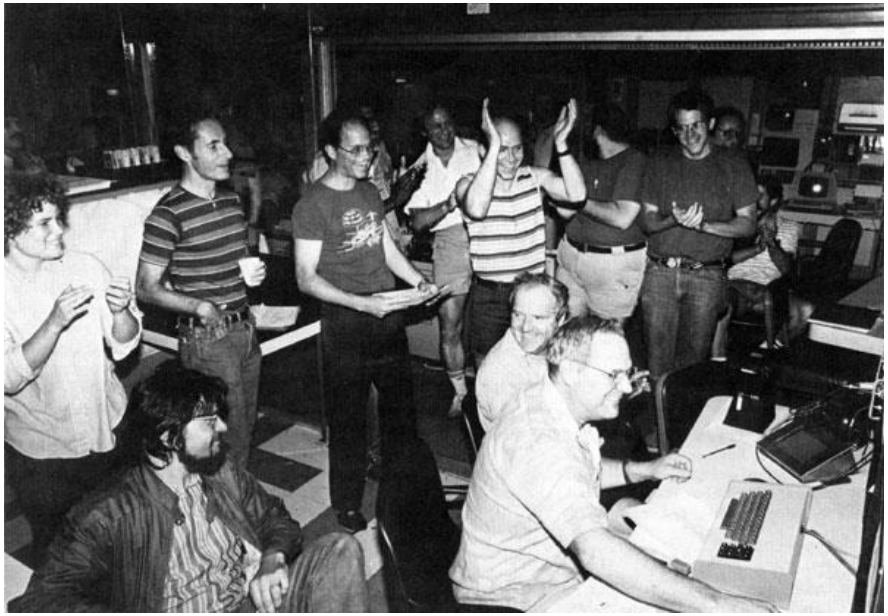
- Designing a new kind of Accelerator-Driven Subcritical Nuclear Reactor (ADSR)
  - intrinsically safe, with large profits
  - producing synthetic diesel from natural gas and carbon for the US Navy
- Destroy and utilize weapons-grade plutonium
  - under 2000 U.S.-Russian Pu Management and Disposition Agreement
- Proposed to design GEM*STAR Pilot Plant to DOE NE for $50M
  - With very strong team - 4 industries, 2 National Labs, 2 Universities
- Mu*STAR a new company has been formed to fund a $800M pilot plant

Muons, Inc.

# GEM*STAR

## Goal: Develop Intrinsically Safe Power
## First Customers: NNSA, DOD

**Rolland P. Johnson, Ph. D.**
**President , Muons Inc.**



512 GeV at Fermilab

**Charles D. Bowman, Ph. D.**
**President ADNA Corporation**
***Accelerator-Driven Neutron Applications***

Charlie at LANL

# GEM*STAR

*Reinventing Nuclear Power by Combining Accelerator Technology with Molten Salt Reactor Technology*

*GEM*STAR*

*Green Energy Multiplier-Subcritical Technology for Advanced Reactors was first described in the 2010 Handbook of Nuclear Engineering:*

Charles D. Bowman, R. Bruce Vogelaar, Edward G. Bilpuch, Calvin R. Howell, Anton P. Tonchev, Werner Tornow, R.L. Walter, "GEM*STAR: The Alternative Reactor Technology Comprising Graphite, Molten Salt, and Accelerators," Handbook of Nuclear Engineering, Springer Science+Business Media LLC (2010).

GEM*STAR is enabled and extended by recently developed and demonstrated superconducting radio-frequency particle accelerator technology:

Powerful – Affordable – Efficient – Reliable – Still Improving

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# New Nuclear Technology to Produce Inexpensive Diesel Fuel from Natural Gas and Renewable Carbon

**Charles Bowman** — ***ADNA & CLF Corps***

**Rolland P. Johnson** — ***Muons, Inc.,***

The long-range goal is to sell intrinsically safe and versatile nuclear reactors to address world energy needs.

The first application is an Accelerator-Driven Subcritical Reactor that burns non-enriched Uranium, Thorium, spent fuel from conventional nuclear reactors (SNF), or excess weapons-grade plutonium in a molten salt fuel to produce high-temperature heat to convert Natural Gas and renewable Carbon into liquid fuel for vehicles.

Requires development and interfacing between known technologies that

-use an SRF accelerator to produce an intense source of neutrons to

-generate process heat in GEM*STAR, a molten-salt-fueled subcritical reactor, to

-prepare methane and carbon for the Fischer-Tropsch generation of diesel fuel.

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# However!

- The price of diesel fuel has fallen dramatically in 4years - >$4/g to as low as $1.65/g
- Using nuclear power to produce fuel reduces its carbon footprint, especially if it can be made from natural gas and renewable carbon (e.g. forest fire remnants or urban trash). But without a carbon tax, this is not an incentive yet.
- So we have changed our proposal to emphasize profitably burning up weapons-grade plutonium.

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# GEM*STAR

**Green Energy Multiplier*Subcritical Technology Alternative Reactor**

GEM*STAR burns the w-Pu and renders it permanently unusable for nuclear weapons

one 10 MW, 1 GeV proton accelerator feeding four GEM*STAR units burns 34T w-Pu to provide the US DOD with 42Bg green diesel fuel, half of that needed for next 30 years

Profits from producing (renewable) diesel fuel at <$2.00/gallon will inspire funding for a Conceptual Design Report prior to a 3-year demo construction project

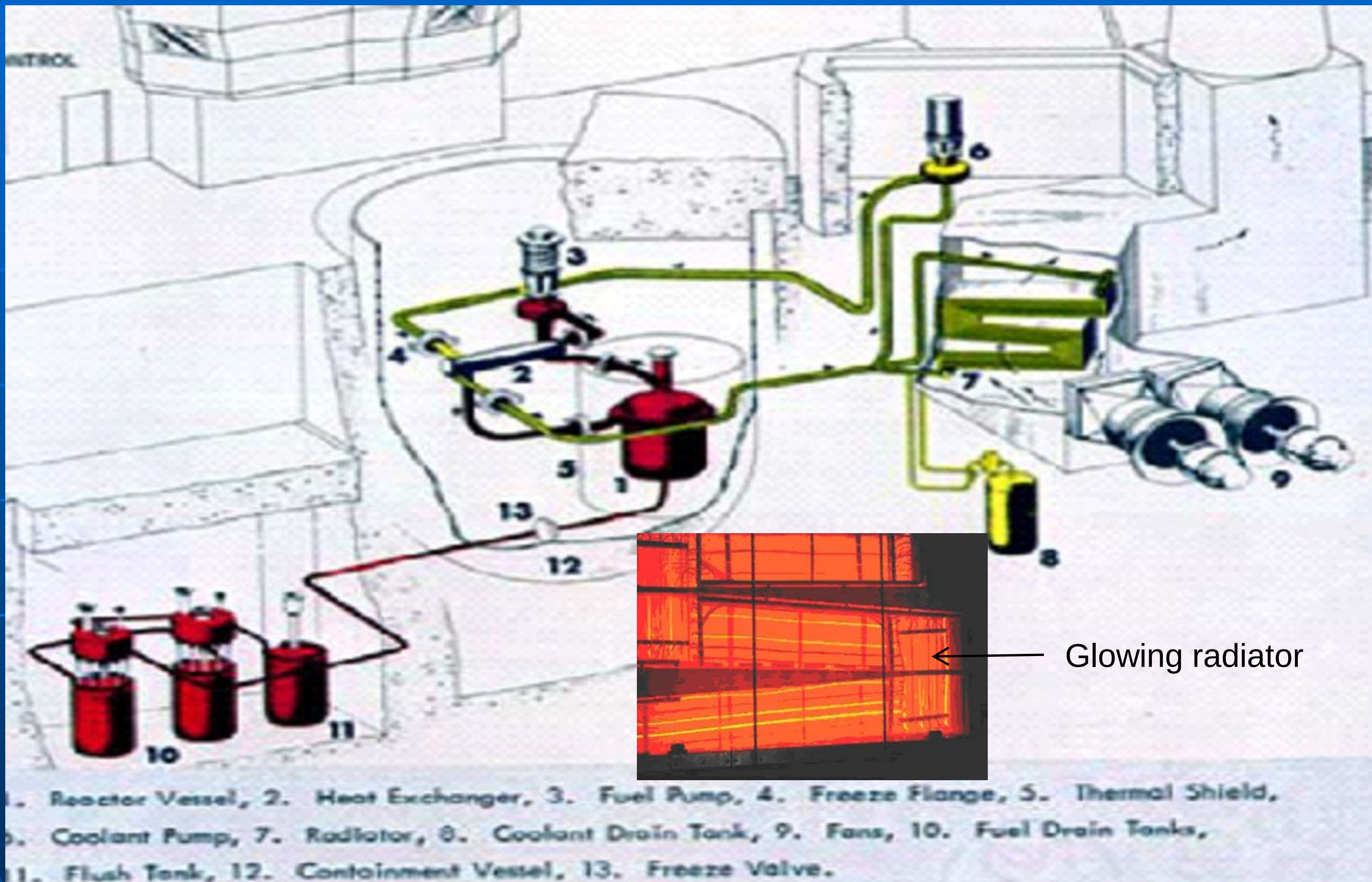
DOD (US Navy) interest in 40 billion gallons of green diesel from burning 34 tons of w-Pu on a DOE site could expedite the project

# What is new:

- SRF Proton Linacs can now provide extraordinary neutron flux and
  - ADSR - safer than BRs,
    - That operate at criticality, with many critical masses of fissile material, and fewer delayed neutrons
  - ADSR - more weapons proliferation resistant than BRs
    - which require enrichment and reprocessing
  - ADSR - probably less expensive than BRs
- Molten salt fuel is an advantage over solid fuel pins
  - allows continuous purging of volatile radioactive elements
  - without zircaloy, that can lead to hydrogen explosions
- Molten salt fuel eases accelerator requirements – no solid fuel fatigue
- Subcritical ADSR operation has always been appreciated
  - fission stops when the accelerator is switched off

- An intrinsic safety problem for conventional reactors is enclosed solid fuel.
- a natural solution is to use molten-salt fuel
- that is also well suited to accelerator-driven subcritical reactors.
  - A major difficulty is fatigue of $UO_2$ fuel in rods caused by accelerator trips – no such problem for molten salt fuel
- The technology of molten-salt fuel was developed in the 1960s in the Molten-Salt Reactor Experiment (MSRE) at ORNL.
  - Use of molten salt fuel was later abandoned
    - not enough Pu-239 for bombs?
    - President Nixon?
      (See MSRE on wikipedia for nice summary)

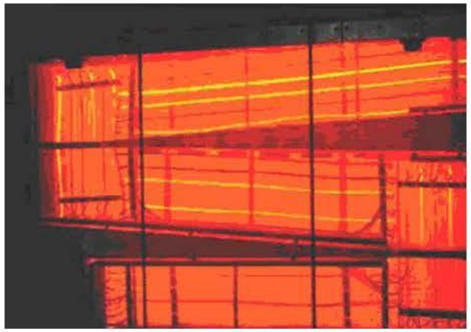
# Molten-Salt Reactor Experiment



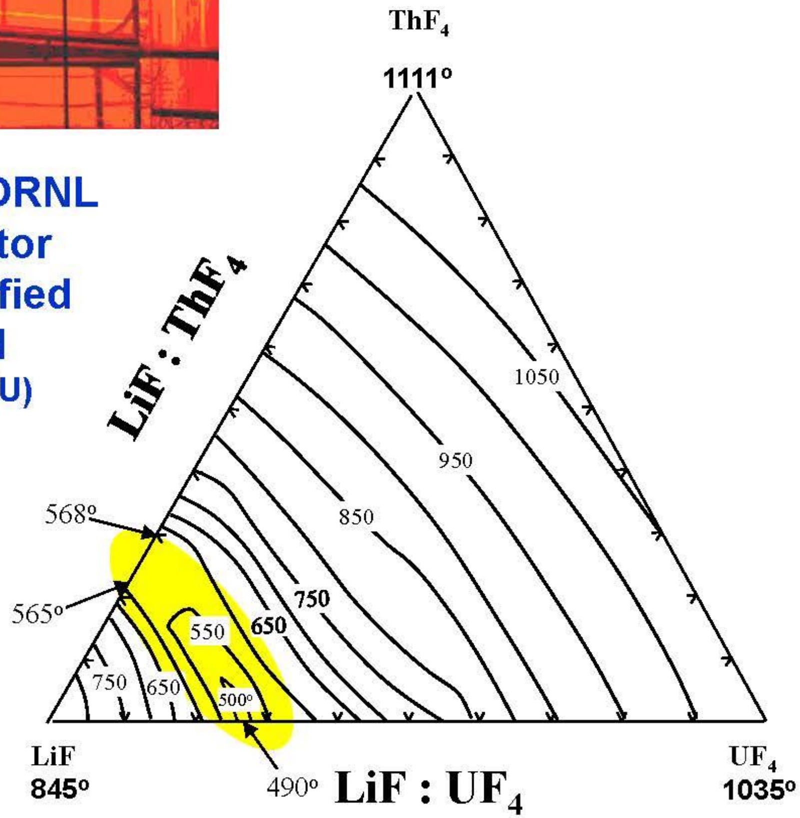
# Molten-salt Reactor Experiment

ADNA & GEM*STAR Consortium

# Molten Salt Eutectic Fuel



**Proven in ORNL MSRE reactor using Modified Hastelloy-N**
**($^{235}U$, $^{239}Pu$, $^{233}U$)**




**Uranium or Thorium fluorides form eutectic mixture with $^7LiF$ salt.**

**High boiling point → low vapor pressure**



GEM*STAR

# *From 1969 MSRE Report Abstract*

*"The MSRE is an 8-MW(th) reactor in which molten fluoride salt at 1200°F (650 C) circulates through a core of graphite bars. Its purpose was to demonstrate the practicality of the key features of molten-salt power reactors.*

*Operation with 235U (33% enrichment) in the fuel salt began in June 1965, and by March 1968 nuclear operation amounted to 9,000 equivalent full-power hours. The goal of demonstrating reliability had been attained - over the last 15 months of 235U operation the reactor had been critical 80% of the time. At the end of a 6-month run which climaxed this demonstration, the reactor was shutdown and the 0.9 mole% uranium in the fuel was stripped very efficiently in an on-site fluorination facility. Uranium-233 was then added to the carrier salt, making the MSRE the world's first reactor to be fueled with this fissile material. Nuclear operation was resumed in October 1968, and over 2,500 equivalent full-power hours have now been produced with 233U.*

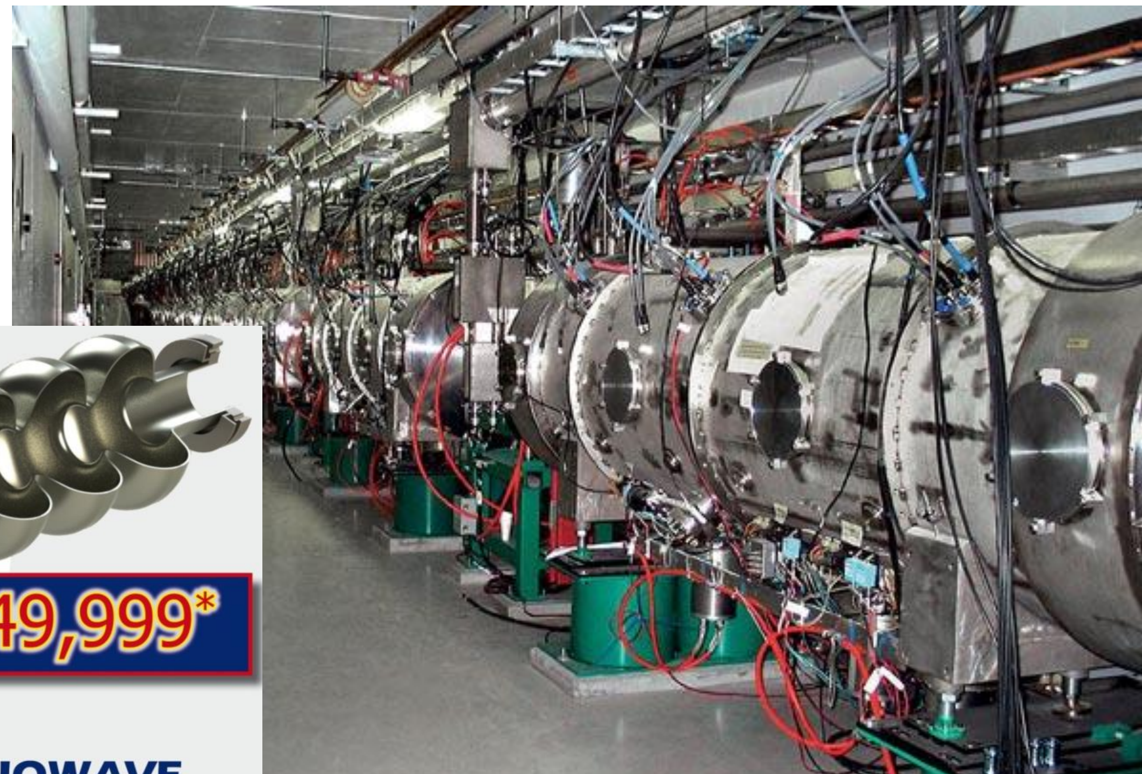
*The MSRE has shown that salt handling in an operating reactor is quite practical, the salt chemistry is well behaved, there is practically no corrosion, the nuclear characteristics are very close to predictions, and the system is dynamically stable. Containment of fission products has been excellent and maintenance of radioactive components has been accomplished without unreasonable delay and with very little radiation exposure.*

*The successful operation of the MSRE is an achievement that should strengthen confidence in the practicality of the molten-salt reactor concept."*

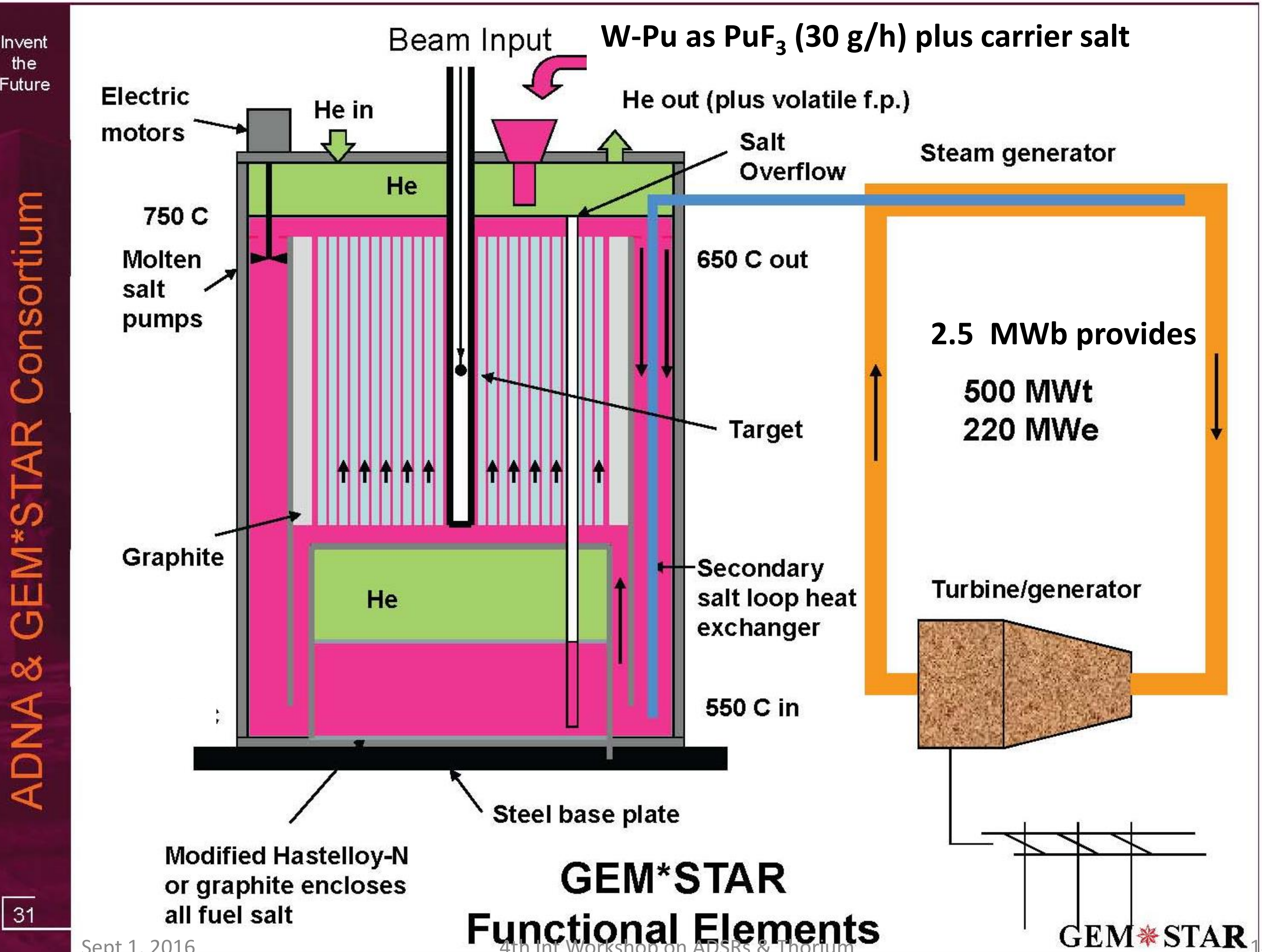
NOW FAST FORWARD 50 YEARS and add an accelerator

# New Accelerator Technology Enables GEM*STAR

OAK RIDGE, Tenn., Sep. 28, 2009 — The Department of Energy's 1 GeV Spallation Neutron Source (SNS), breaks the one-megawatt barrier! Operating at <10% duty factor, this corresponds to >10 MW at CW. Based on Superconducting RF Cavities, available from U.S. Industry:



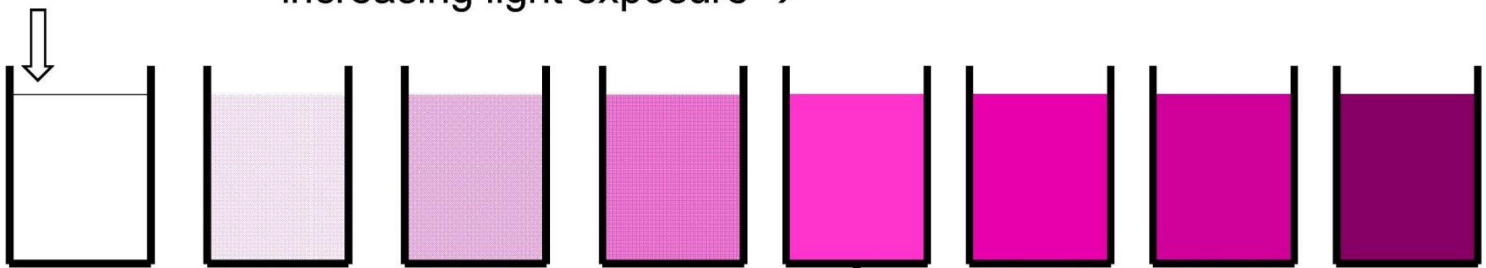
# W-Pu as $PuF_3$ (30 g/h) plus carrier salt

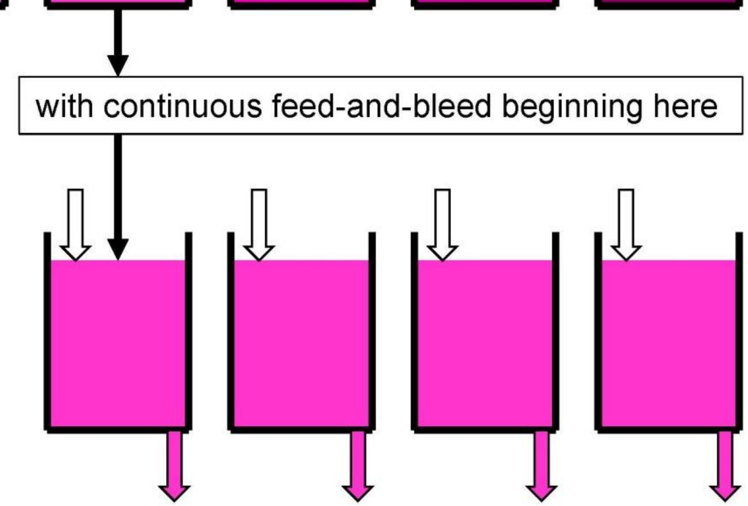


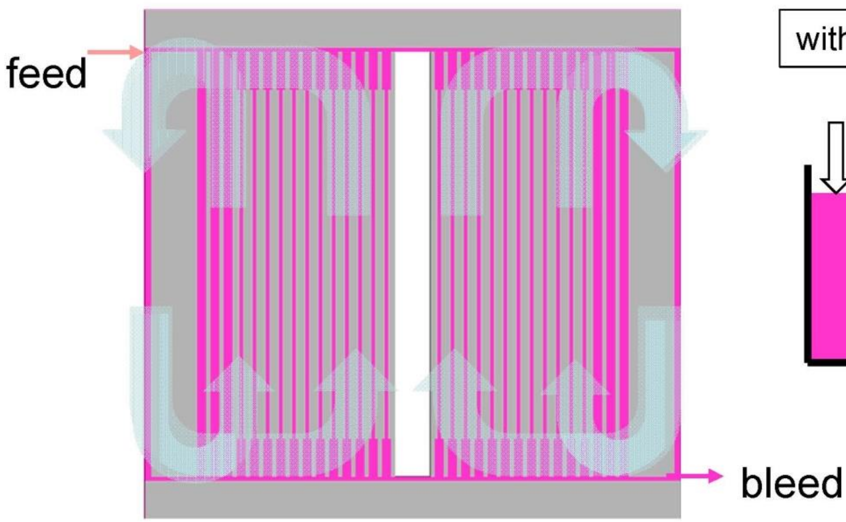
# consider a clear liquid which releases heat when exposed to light, eventually turning a dark purple

Initial fill

increasing light exposure →






fast internal mixing

**color and heat output remains constant indefinitely**

→ **equilibrated isotope fractions throughout core and throughout time**

$10^{-6}$ less volatile fission-product build-up in core

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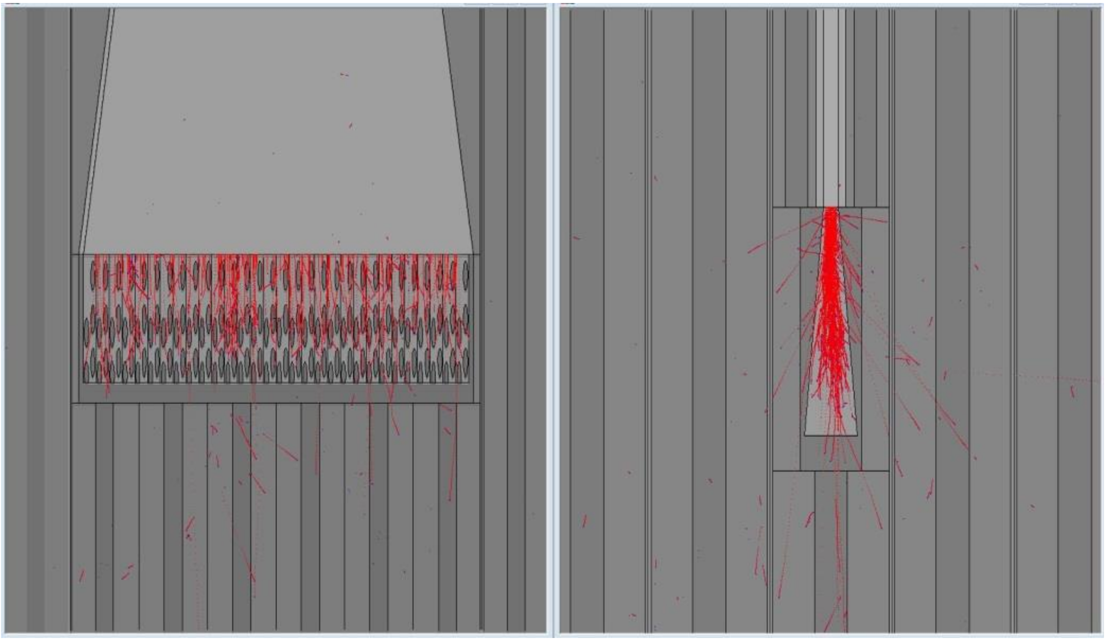
GEM*STAR Consortium

# Target Considerations



GEM*STAR Internal Target

**Work of Bruce Vogelaar of Virginia Tech (co-author of GEM*STAR article in HB of NE)**

- diffuse (or multiple) beam spots
- molten salt used for heat removal
- high neutron yield from uranium

  (but minimize target fission)
- spent target fluorinated and used as fuel
- minimize impact on local reactivity



GEM*STAR

# First MuSim Application -GEM*STAR

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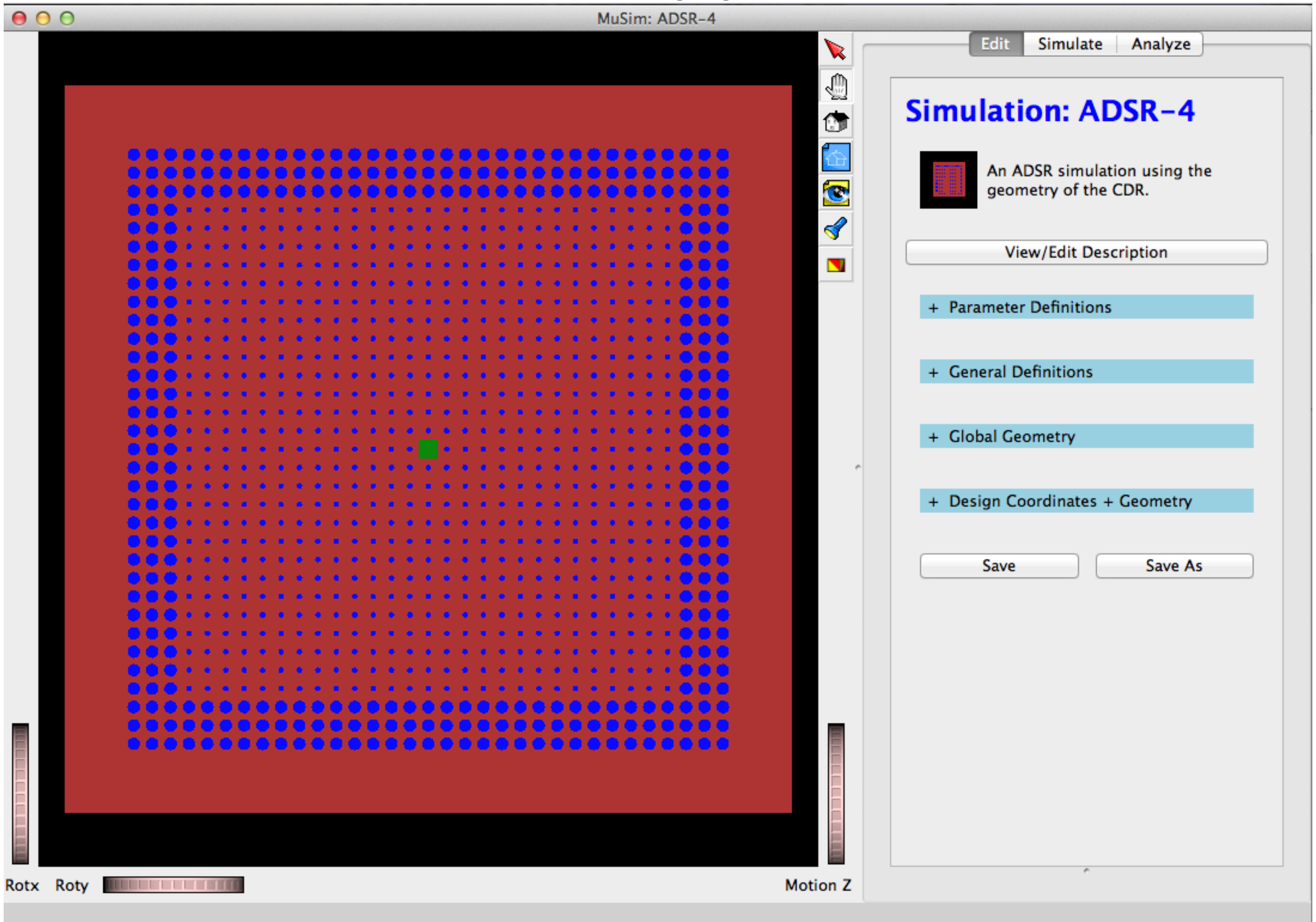
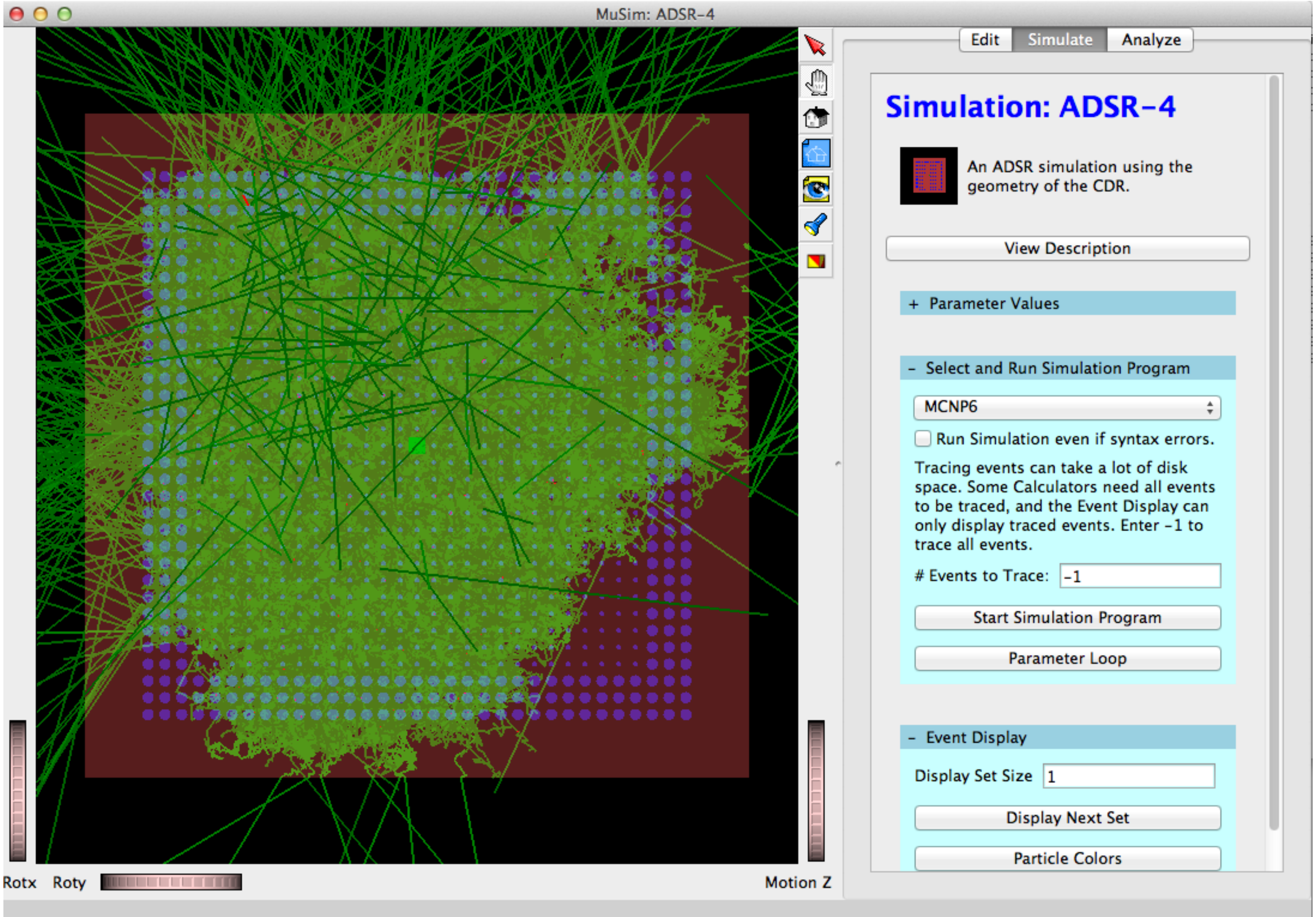



Screen shot of MuSim: carbon is brown, salt is blue, the spallation target (natural uranium) is green; the right side is an editing pane: ADSR-4 is the name of this simulation, and the blue headers are categories to specify the simulation that can be edited; Parameters are for parametrizing the simulation; Definitions define general things like materials; GlobalGeometry includes all objects, solids, sources, and detectors (except objects placed via design coordinates); DesignCoordinates are for a beamline and define its centerline for placing objects.

# MuSim MCNP6 single event display

Muons, Inc.




Here is a single event, green=neutron, darkgreen=gamma. This single proton generated 402,138 tracks (not counting e- < 0.5MeV). I used a "transparency slider" to make the solids mostly transparent, so tracks inside them can be seen. This makes the solids darker, because the black background show through; tracks inside them affect their color.

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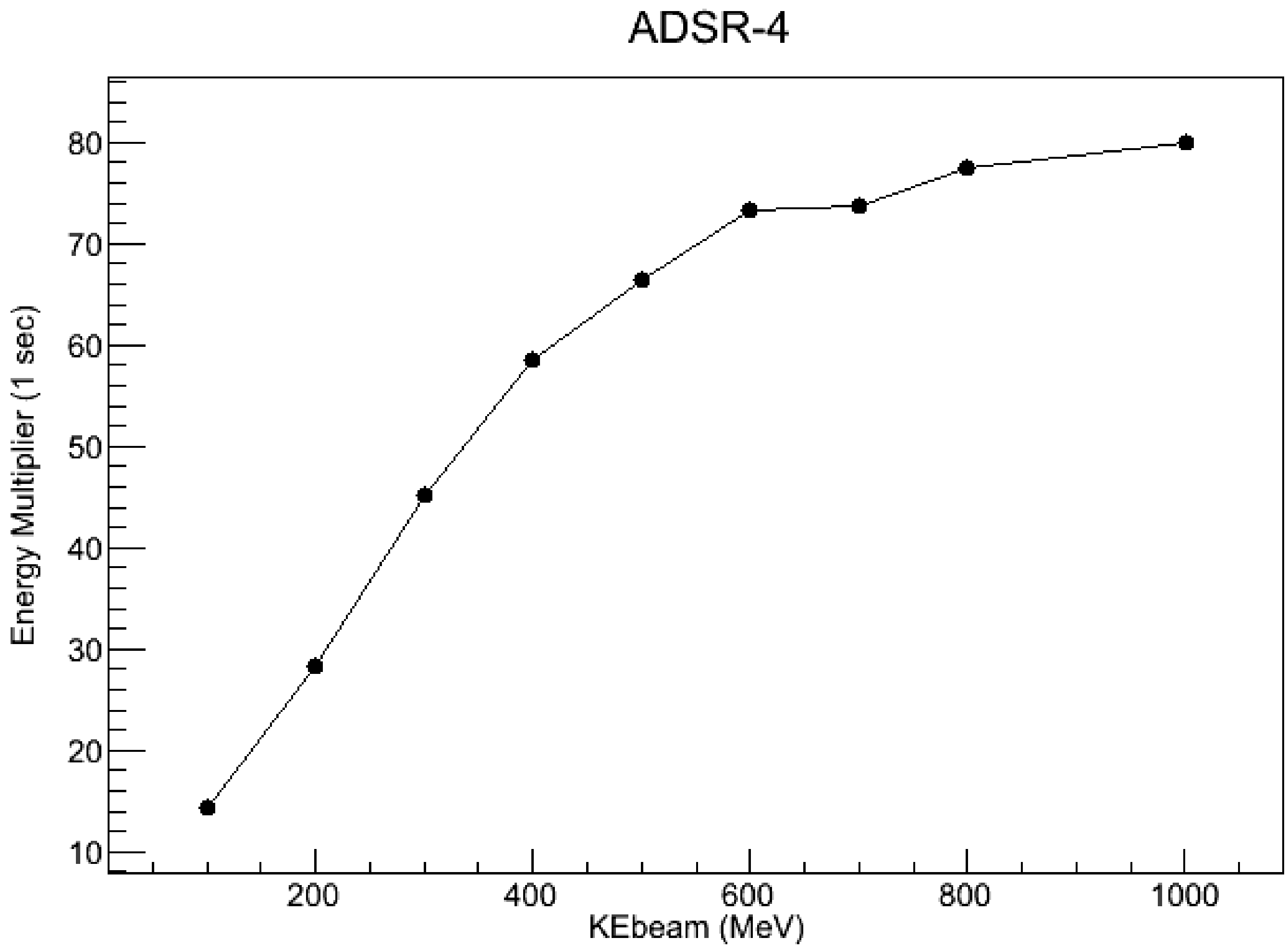
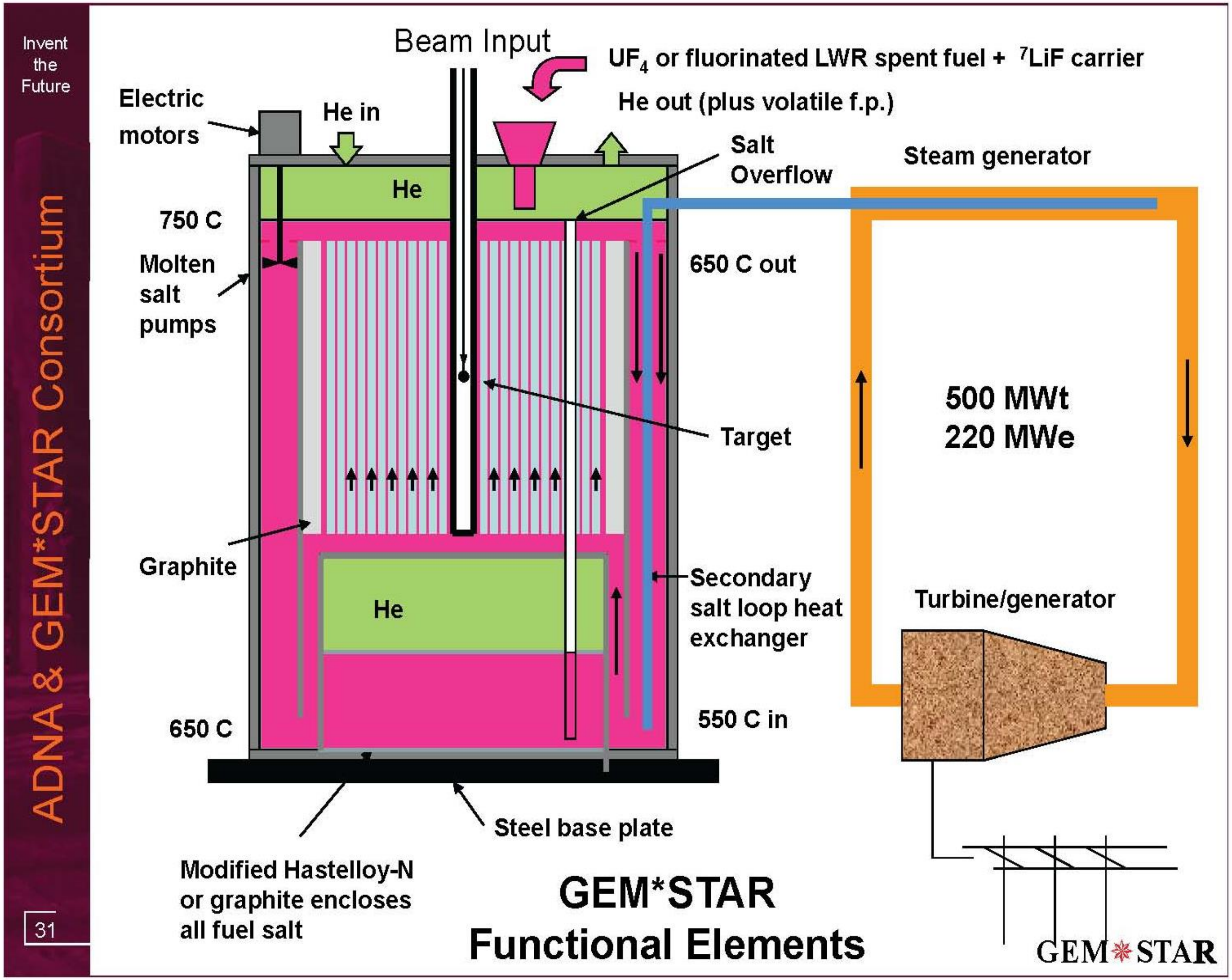
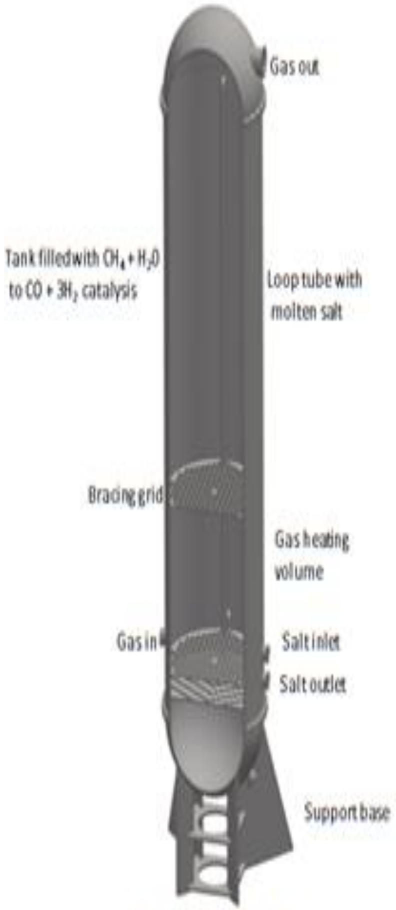
# Optimum Beam Energy






$CH_4 + H_2O$ to $CO + 3H_2$

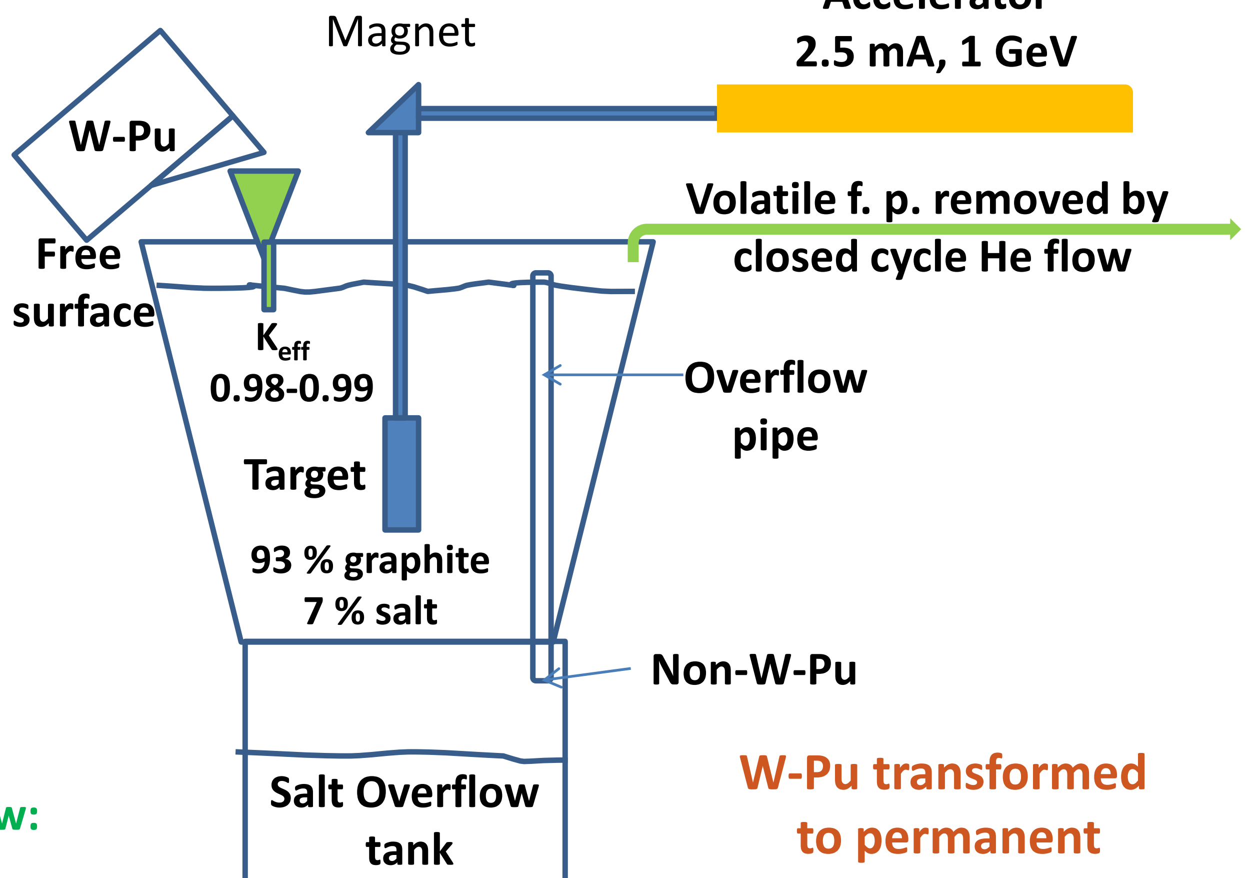
# Is W-Pu a Killer Application?

- 34 metric tons of excess weapons-grade plutonium slated to be destroyed by the troubled 2000 U.S.-Russian Plutonium Management and Disposition Agreement (PMDA)[2]
- GEM*STAR allows a better solution than either MOX (US) or BR (Russia)
- <7% Pu240 vs >19%

# GEM*STAR Burns W-Pu Without U or Th
# 34 Tons in 30 Years

**Hourly fill:**
30 g W-Pu
as $PuF_3$ +
carrier salt

**Inflow W-Pu:**
93 % $^{239}Pu$
7 % $^{240}Pu$




Fission power 500 MWt

**Hourly overflow:**
7.5 g as $PuF_3$ +
carrier salt +
22.5 g of fission product

**Non-weapons Pu Outflow:**
52.4 % $^{239}Pu$
25.4 % $^{240}Pu$
10.6 % $^{241}Pu$
11.7 % $^{242}Pu$

**W-Pu transformed to permanent non-weapons Pu immediately upon adding and mixing**

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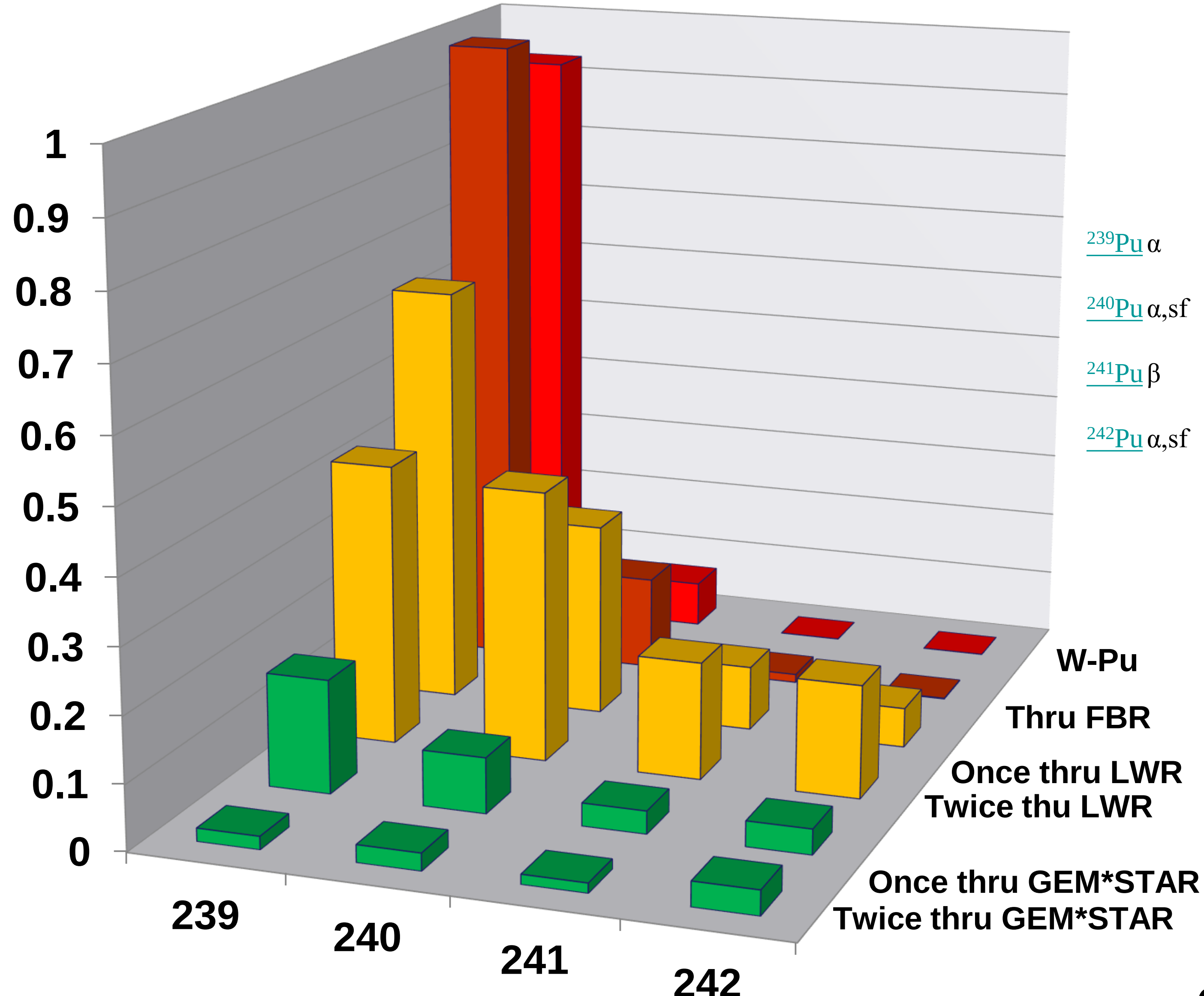
# FB BN800 MOX-LWR GEM*STAR




| | | |
|---|---|---|
| $^{239}$Pu | α | 24,110 years |
| $^{240}$Pu | α,sf | 6,561 years |
| $^{241}$Pu | β | 14.325 years |
| $^{242}$Pu | α,sf | 373,300 years |



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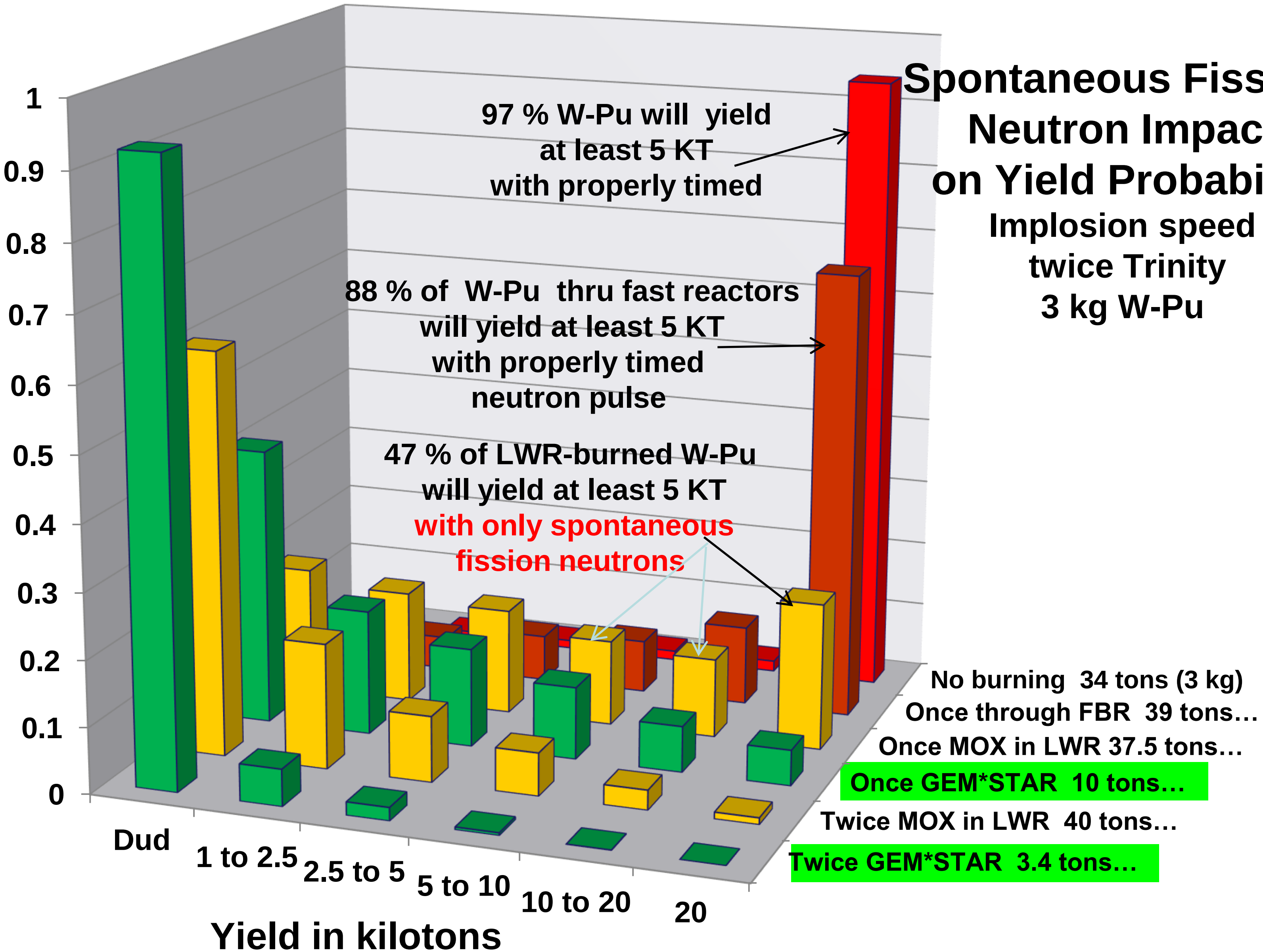
# Spontaneous Fission Neutron Impact on Yield Probability

Implosion speed twice Trinity 3 kg W-Pu



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# Benefits of GEM*STAR for W-Pu

**Burned W-Pu never useful for weapons**
**Burned W-Pu never decays to back to weapons useful material**
**Conversion to non-W-Pu in minutes**
**Pu isotopic mixture can be reduced from 34 tons to 0.2 tons if desired**
**Also converts C-Pu to-non-weapons-useful material**
**Never requires a critical mass so no control rods**
**No reprocessing or enrichment required**
**No conversion to MOX; simple conversion of Pu metal and $PuO_2$ to $PuF_3$**
**Fission energy converted to diesel and sold as green fuel to DOD**
**No stored large volatile fission product inventory as in LWRs (Fukushima)**
**Liquid fuel moved by He pressure; no radiation exposure to humans**
**No pressure vessel**
**Passive recovery from loss of coolant (LOCA)**

***Eliminating problems***
***avoids the need for***
***Defense in Depth***

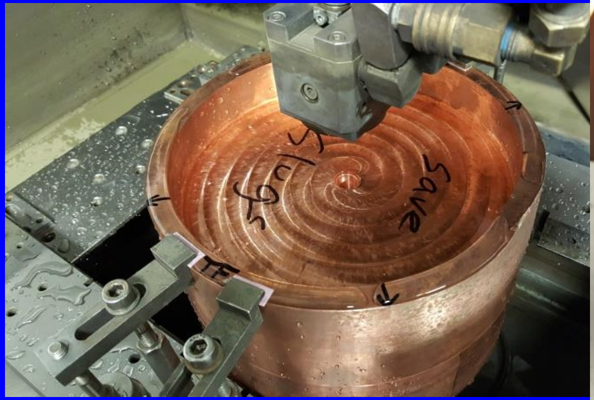
# Magnetron Power Sources

- Magnetron is a good RF source for SRF
  - Inexpensive (<$2/W vs $5 to $10/W for klystron or IOT)
  - Efficient (~85% vs 50-60% for klystron or IOT)
  - Frequency and phase stabilization are an issue for accelerators
  - Muons, Inc. has several magnetron projects underway that are relevant to ADS
    - 350 MHz CW 120 kW for radioisotope production
    - 650 MHz for medical application
    - 1500 MHz for CEBAF klystron replacement

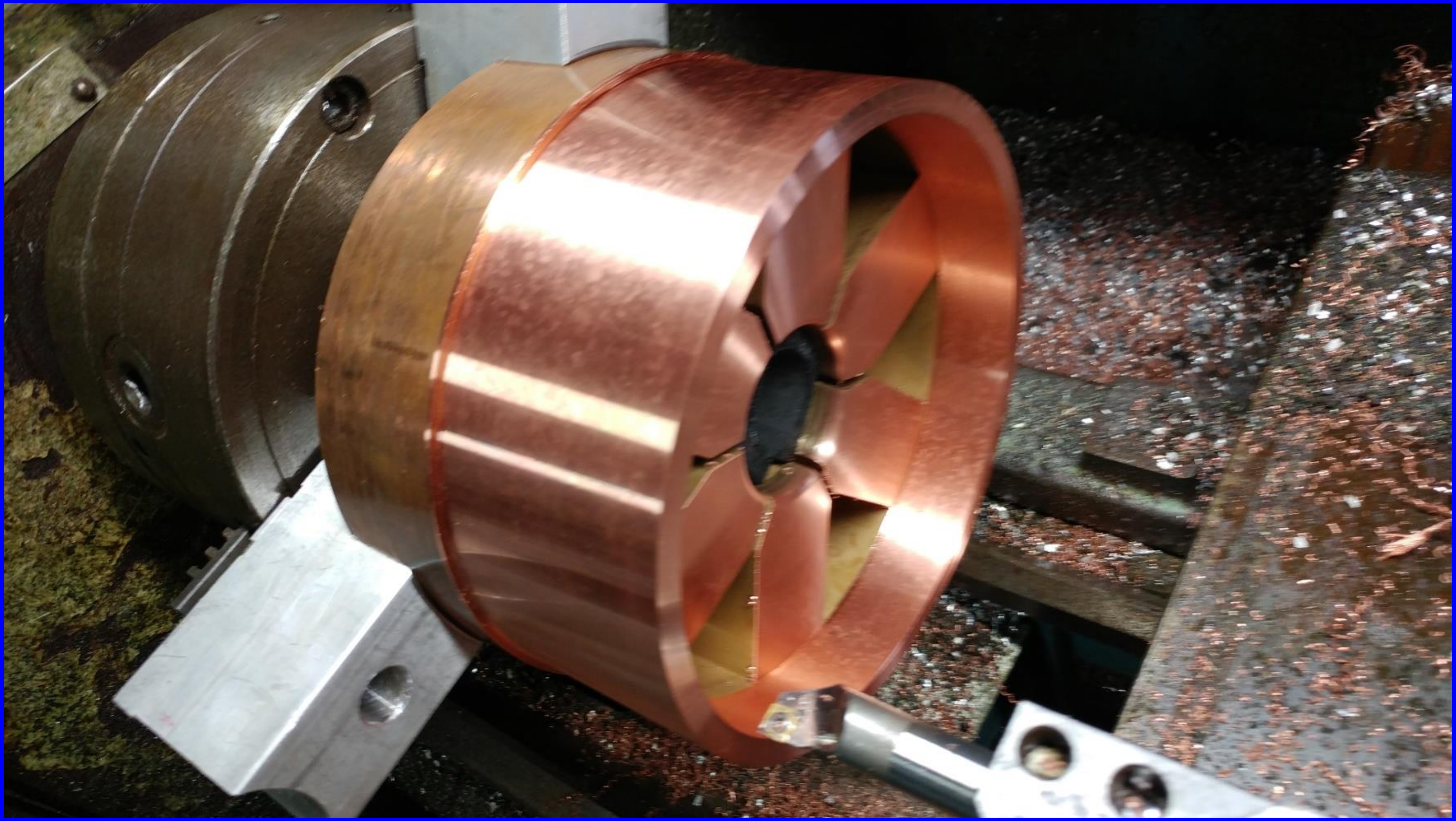
μ

*Muons, Inc.*

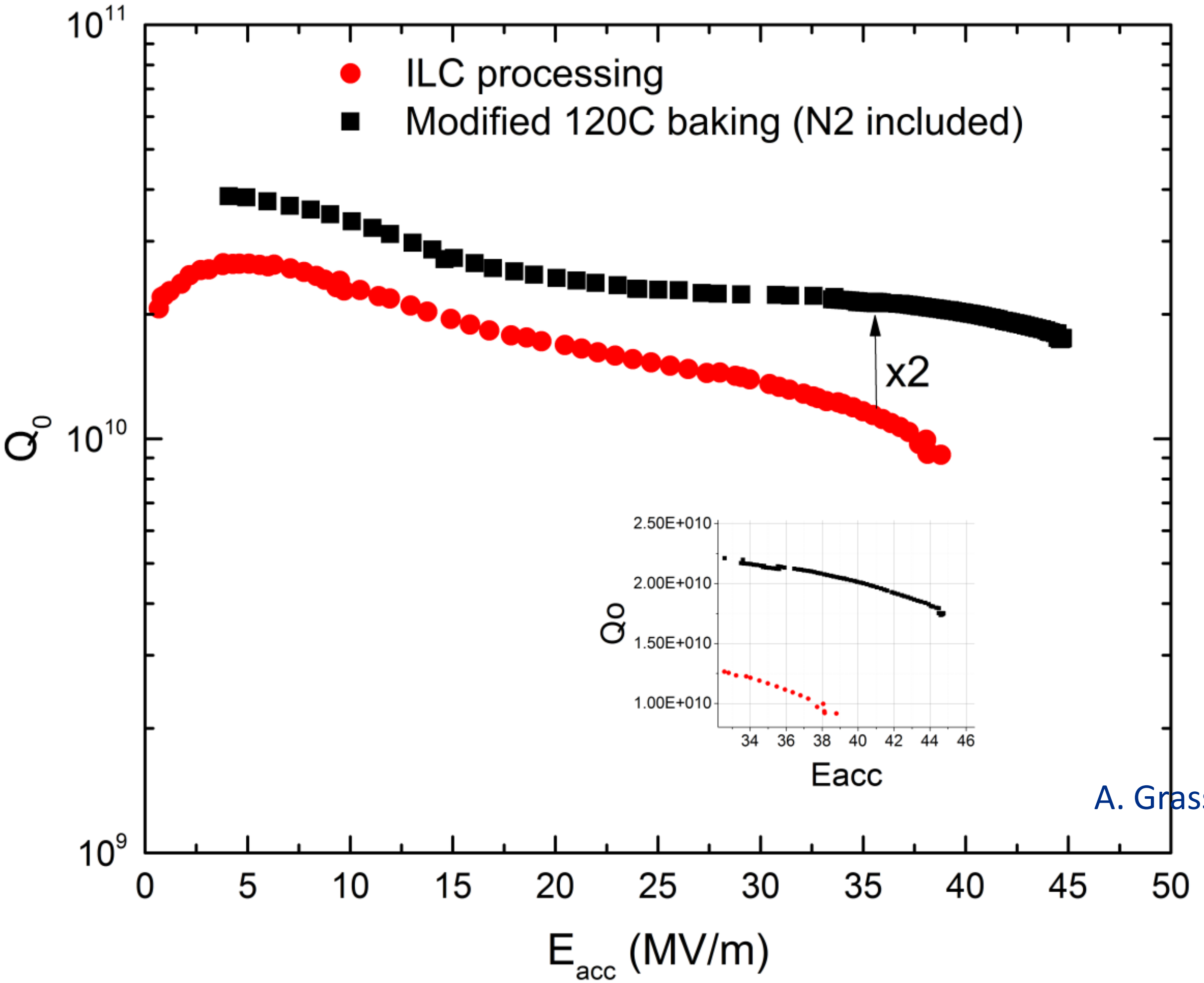
# EDM of 350 MHz Magnetron Anode




# Machining of 350 MHz Anode



# Results comparison :
# "standard" 120C bake vs "N infused" 120C bake




A. Grassellino et al, in submission to SUST rapid

- Achieved:
45.6 MV/m → 194 mT
With Q ~ 2e10!

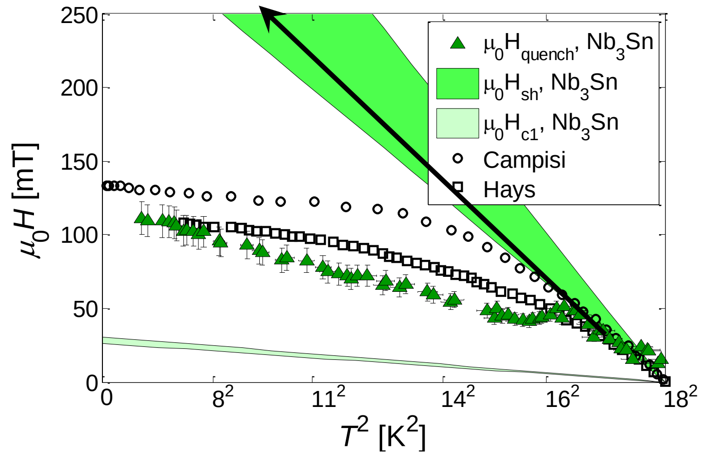
- Q at ~ 35 MV/m ~ 2.3e10!

Increase in Q factor of two, increase in gradient ~15%

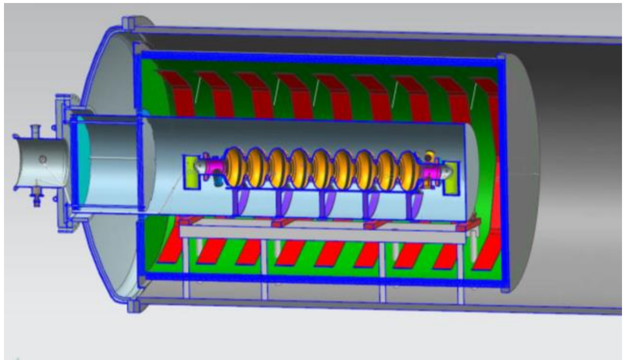
# $Nb_3Sn$ SRF Cavities

- Predicted superheating field 2x as high as niobium: potential to increase reach of SRF accelerators
- High $Q_0$ at high temperature: simpler cryoplant with 3-4x higher efficiency at 4.2 K vs 2 K
- New Fermilab program aims to understand and overcome limitation mechanisms in this material and coat multicell cavities

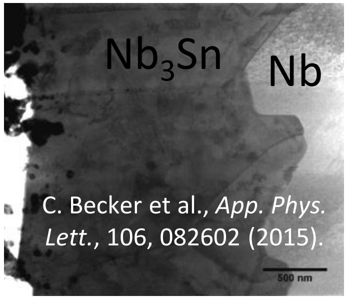
S. Posen, N. Valles, and M. Liepe, *Phys. Rev. Lett.*, 115, 047001 (2015).

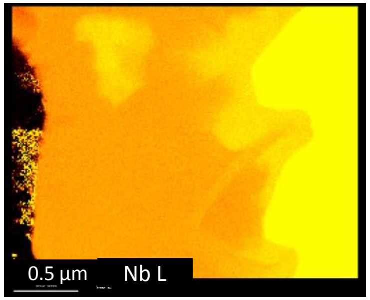


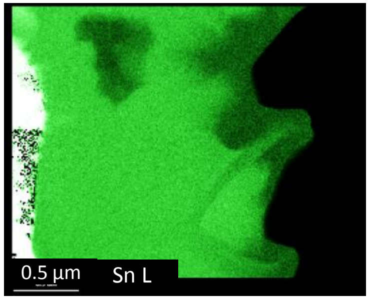

Extrapolation suggests 350 mT ~ 80 MV/m possible if defects can be mitigated



Largest-ever $Nb_3Sn$ SRF cavity coating chamber in fabrication: coatings for 9-cell 1.3 GHz cavities and 650 MHz 5-cell cavities



# A Perfect Storm of Opportunities?

- US Plan to use MOX plant and LWRs not working
  - SRS Plant overspent: $2B -> $5B -> asking for $2B more,
  - No LWR ready to accept W-Pu MOX fuel =>
  - Obama MOX budget on hold while alternatives examined
  - DOE preferred alternative – Downblend and Burial at WIPP
    - Waste Isolation Pilot Plant in Carlsbad, NM
    - Unlikely for several reasons, e.g. work by Bowman
- Eliminate W-Pu (State Department-DOE/NNSA)
  - Opportunity for Lavrov and Kerry to extend cooperation
  - 2000 Plutonium Management and Disposition Agreement
    - (DOE Secretary Moniz was major proponent of PMDA)
  - Navy adds nuclear power expertise, and location for demo
  - Solves Navy long-range synthetic fuel need
  - Turn $30B liability into $40B Profit (Congress/OMB)

**From Proposal Cover Page**

The name of organization: GEM*STAR Consortium, directed by for-profit companies

Funding Opportunity Announcement Number: DE-FOA-0001313

**Advanced Reactor Industry Competition for Concept Development**

Project Manager: Dr. Rolland Johnson, Muons, Inc.

Chief Scientist: Dr. Charles Bowman, ADNA Corp., BCLF Corp.

Estimated Cost: $50,000,000 over 5 years or less, including $10,000,000 cost share.

FY 2016 Proposed Cost: $7,500,000; with $4,100,000 to industry (including $1,500,000 cost-share), $2,400,000 to FFRDC national labs, and $1,000,000 to universities.

Muons, Inc.

# GEM*STAR: ACCELERATOR-DRIVEN SUBCRITICAL REACTOR FOR IMPROVED SAFETY, WASTE MANAGEMENT, AND PLUTONIUM DISPOSITION

| Partners | year 1 | Primary Role | Point of Contact |
|---|---|---|---|
| Muons/ADNA | 2.6 | Project direction, integration | Dr. Rolland Johnson |
| | | Scientific oversight, Fischer-Tropsch | Dr. Charles Bowman |
| Niowave, Inc. | 1.0 | Commercial Accelerator Manufacturer | Dr. Terry Grimm |
| Newport News Shipbuilding | 0.5 | Commercial Manufacturer of Nuclear Reactors (for Aircraft Carriers and Subs) | Mr. Phillip Mills<br>Mr. Neil Moravek |
| ORNL | 2.0 | Reactor Design | Dr. Lou Qualls |
| | | Accelerator Operations (SNS) | Dr. John Galambos |
| TJNAF | 0.4 | Accelerator Design | Dr. Andrew Hutton |
| VT | 0.5 | Reactor Design, Simulations | Prof. Alireza Haghighat |
| | | Internal Target Design | Prof. R. Bruce Vogelaar |
| GWU | 0.5 | Policy Issues, Systems Integration | Prof. Andrei Afanasev |
| | | Simulations, Material Studies | Prof. Philippe Bardet |

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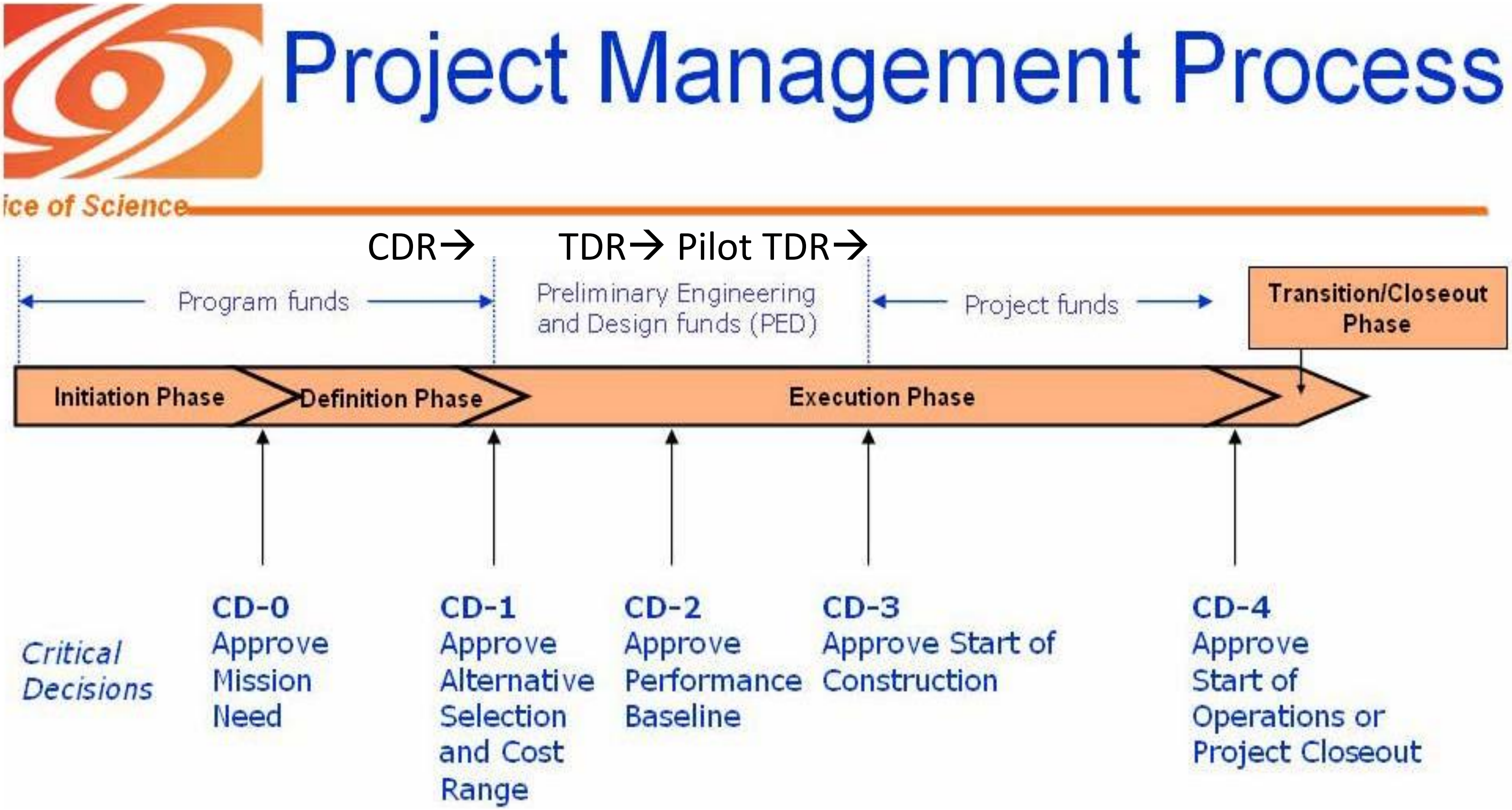


Conceptual Design Report (CDR), Technical Design Report (TDR), and Site Specific Pilot TDR are needed for the DOE/NNSA Critical Decision Management Process. CD-0 follows from stated need for alternatives to MOX solution at Savannah River.

# Technology Readiness Review - GEM*STAR needs engineering to merge known technologies (no additional Research needed)

**DOE's Technology Readiness Scorecard (Levels 1 – 9):**

1. Basic principles observed and reported.
2. Technology concept application formulated.
3. Analytical and experimental critical function and/or characteristic proof of concept.
4. Component and/or breadboard validation in a laboratory environment.
5. Component and/or breadboard validation in a relevant environment.
6. System/subsystem model or prototype demonstration in a relevant environment.
7. System prototype demonstration in an operational environment.
8. Actual system completed and qualified through test and demonstration.
9. Actual system proven through mission operations.

Table 1: Component Technology Readiness

| Component | Level | Comment / Example |
| --- | --- | --- |
| Accelerator – 1 MW | 9 | SNS at ORNL |
| Accelerator – 10 MW | 7 | SNS is a "prototype": 1 MW with < 10% duty factor |
| Molten-Salt Reactor | 6 | Molten Salt Reactor Experiment at ORNL |
| Spallation Target | 6 | Other designs (in many places) are level 9 |
| Fischer-Tropsch | 9 | Numerous operational plants e.g. SASOL in South Africa |
| MS Heat transfer to F-T | 4 | Prototype at BCLF Corp. (C. D. Bowman) |

*Detailed lists of year-by-year tasks and deliverables are available*

- MuSTAR proposes a profitable pilot plant demo of a subcritical molten-salt fueled nuclear reactor driven by a superconducting RF proton linac.
- The GEM*STAR multipurpose reactor design features an internal spallation neutron target and high temperature molten-salt fuel with continuous purging of volatile radioactive fission products.
- GEM*STAR is a reactor that without redesign will burn spent nuclear fuel, natural uranium, thorium, or surplus weapons material.
- The reactor itself, by virtue of its simple modular design and intrinsic safety features, is less expensive than conventional reactors.
- While already sufficiently powerful, reliable, affordable, and efficient, SRF linacs are on a steep learning curve with new developments in magnetron power sources, cryostats, and cavity construction techniques that will make SRF systems even more compelling.
- We described the design and the proposal and discussed the prospects for funding a profitable pilot plant to burn weapons-grade plutonium.