Mu*STAR: A Modular Accelerator-Driven Subcritical Reactor Design

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Muons, Inc. - http://muonsinc.com/

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What is Muons, Inc.?

- Founded 2002, subsidiaries - MuPlus, MuSTAR - by Scientists from US National Labs – original mission to design a **Muon Collider**
- NEW tools and technology for particle accelerators
- Funded by DOE contracts and SBIR-STTR grants
  - total of ~$30M
- 9 US university and 11 national lab research partners
  - Broad, diverse and cutting edge scientific network
  - We are embedded in both worlds
- Supported 18 post-docs and 6 Ph.D. students
- Muons, Inc. software product **G4beamline** widely used in particle physics, **MuSim** being developed for more general use.
- Mu*STAR accelerator-driven molten-salt nuclear reactors
  - Major focus of our companies

Mu*STAR: Superconducting RF Linac Driving Molten-Salt Graphite-Moderated Subcritical Modular Reactors

- **Superconducting RF proton Linac**
  - ORNL SNS demo (1.4 MW, SC Linac proton beam)
  - Scales to 25 MW, 1 GeV, $800M (ANL Design)
  - Improved by Muons, Inc. inventions
- **Molten-Salt Graphite-Moderated**
  - ORNL MSRE 1965-69, 8 MWt demo
  - Add internal SNS target
  - Virtues described by Bowman, Vogelaar, et al., HBofNE 2010 [1]
- **Subcritical**
  - Additional neutrons by SC technology and spallation
- **Modular Reactors**
  - Built in factories (<500MWt)

Why isn't this already being done?

- **Economics:**
  - Used fuel is not a liability to the operating companies
  - By law, it is the responsibility of the U.S. government
  - The government pays the operating companies to store it

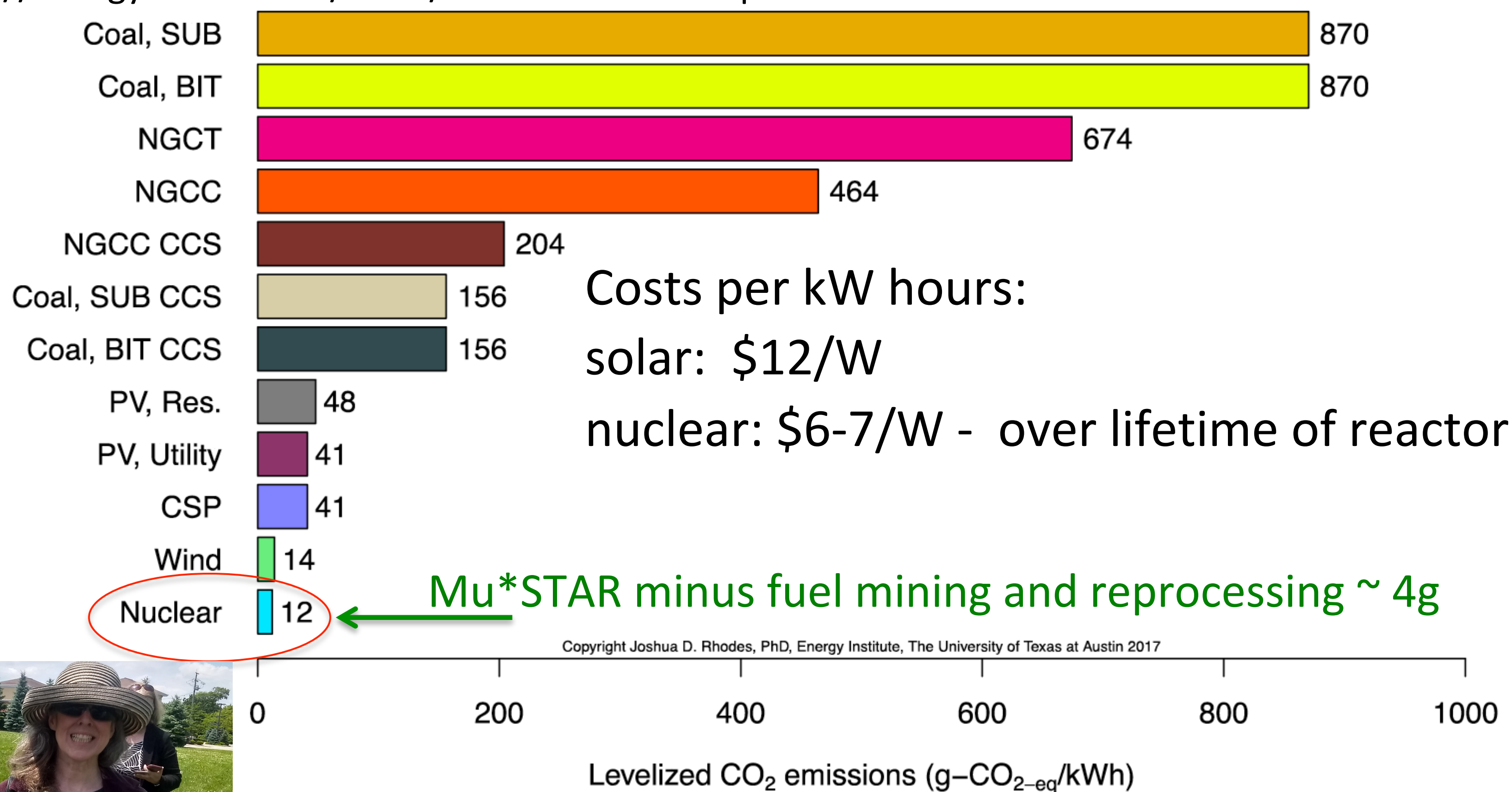
They have no incentive to deal with the used fuel.

- **Technology:**
  - The Department of Energy did a study in the 1990s that concluded ADSR is not viable because the accelerator is barely feasible and far too expensive
  - Today that no longer holds:

Superconducting Accelerators are now far more efficient and enormously less costly than the study considered.

What is Sustainable?

https://energy.utexas.edu/news/nuclear-and-wind-power-estimated-have-lowest-levelized-co2-emissions



Costs per kW hours:

solar: $12/W

nuclear: $6-7/W - over lifetime of reactor

Mu*STAR minus fuel mining and reprocessing ~ 4g

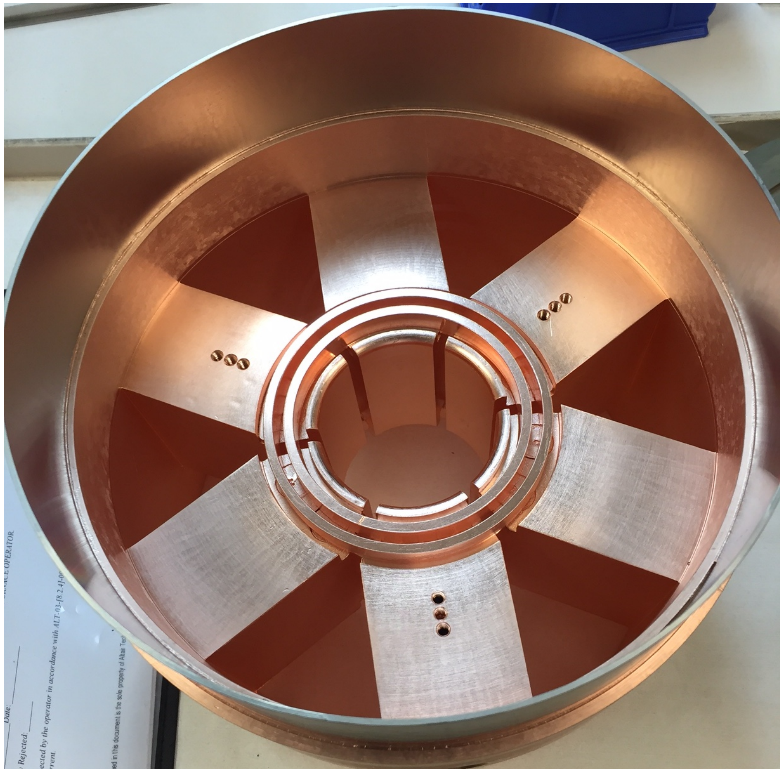
No long-term strategy for sustainable growth of nuclear power in the U.S.

ORNL Molten Salt Reactor Experiment

- Molten Salt Reactor Experiment operated at ORNL,1964-1969.
- Demonstrated the key aspects of using molten salt fuel.
- Critical reactor tested with three different fuels.
- Mu*STAR based on **MSRE parameters**-Temperature, graphite, Hastelloy-N
- Graphite MSRE core ¼ linear dimension of Mu*STAR, $4^3 = 64$ times Power

Example: 350 MHz, 140 kW DC Magnetron

- Muons, Inc. Invents Accelerator Technology
  - Magnetrons up to 90% efficient
  - Prototype for Niowave to make Mo-99 – replaces 30 kW tetrode
  - $2/W vs $10/W for klystrons



Superconducting RF Linacs

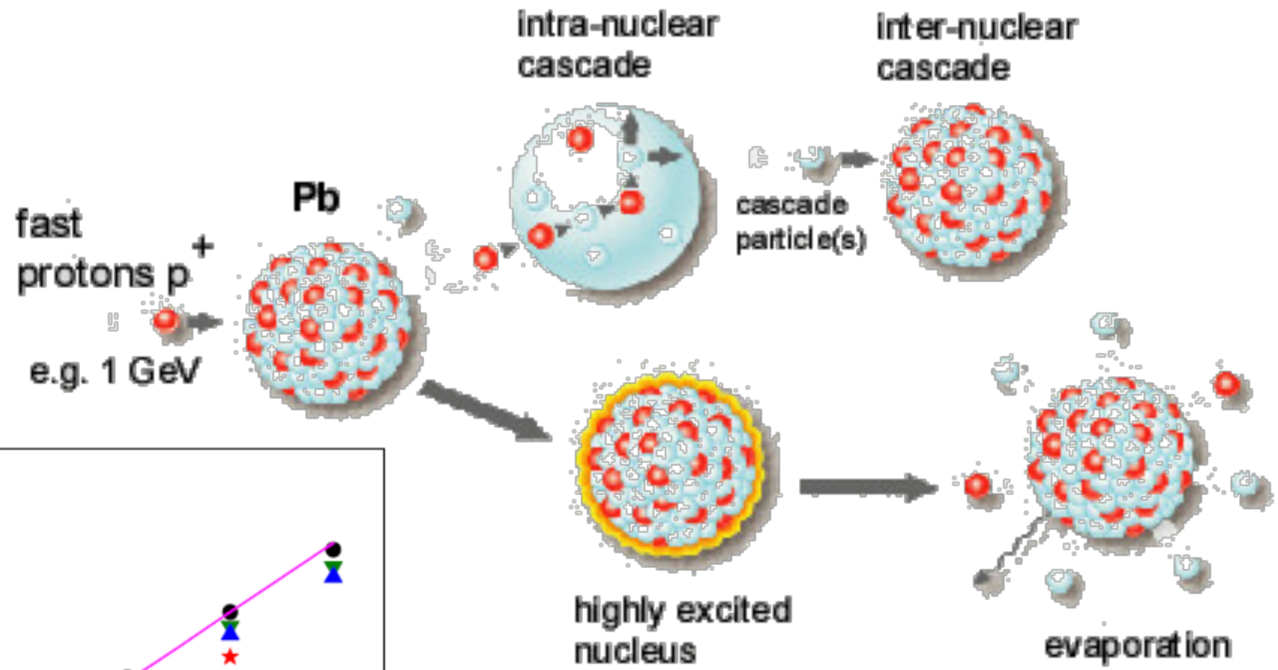
Breakthrough Technology – Superconducting RF Linac

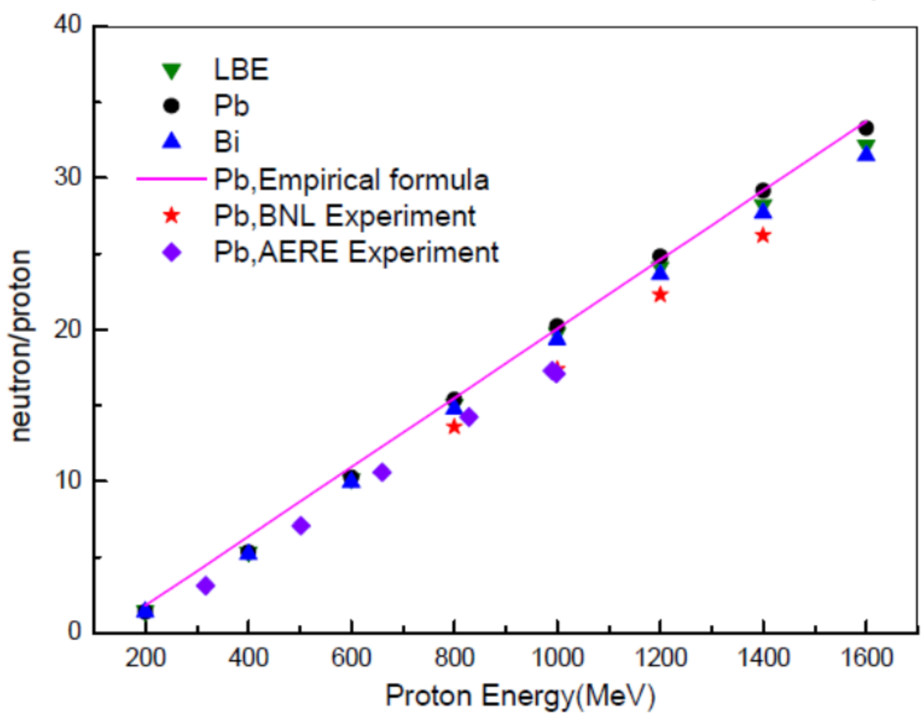
- Demonstrated at the ORNL Spallation* Neutron Source (SNS)
- Generates many neutrons to control reactor reactivity
- Powerful, efficient, affordable, reliable

*1 p produces > 30 n

Spallation requires Protons

Much higher neutron Amplification
1 p produces > 30 n

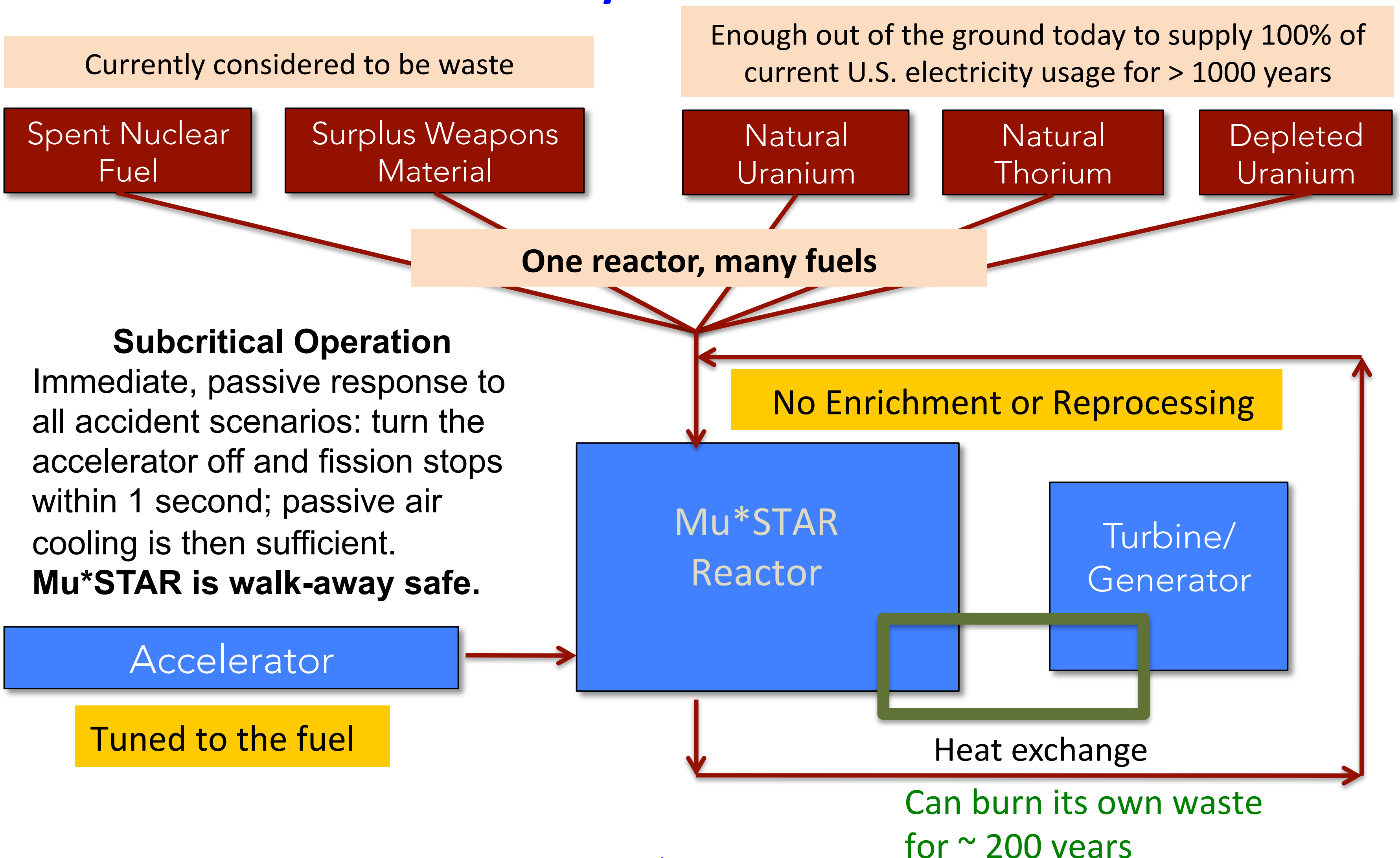




Target	600 MeV	800 MeV	1000 MeV
Fe	3.7	5.3	6.7
Pb	9.6	14.3	18.5
W	9.9	16.0	20.0
U	18.0	26.0	33.3

Universal Reactor Concept

Nuclear Power Reinvented by Mu*STAR



Subcritical Operation
Immediate, passive response to all accident scenarios: turn the accelerator off and fission stops within 1 second; passive air cooling is then sufficient.
Mu*STAR is walk-away safe.

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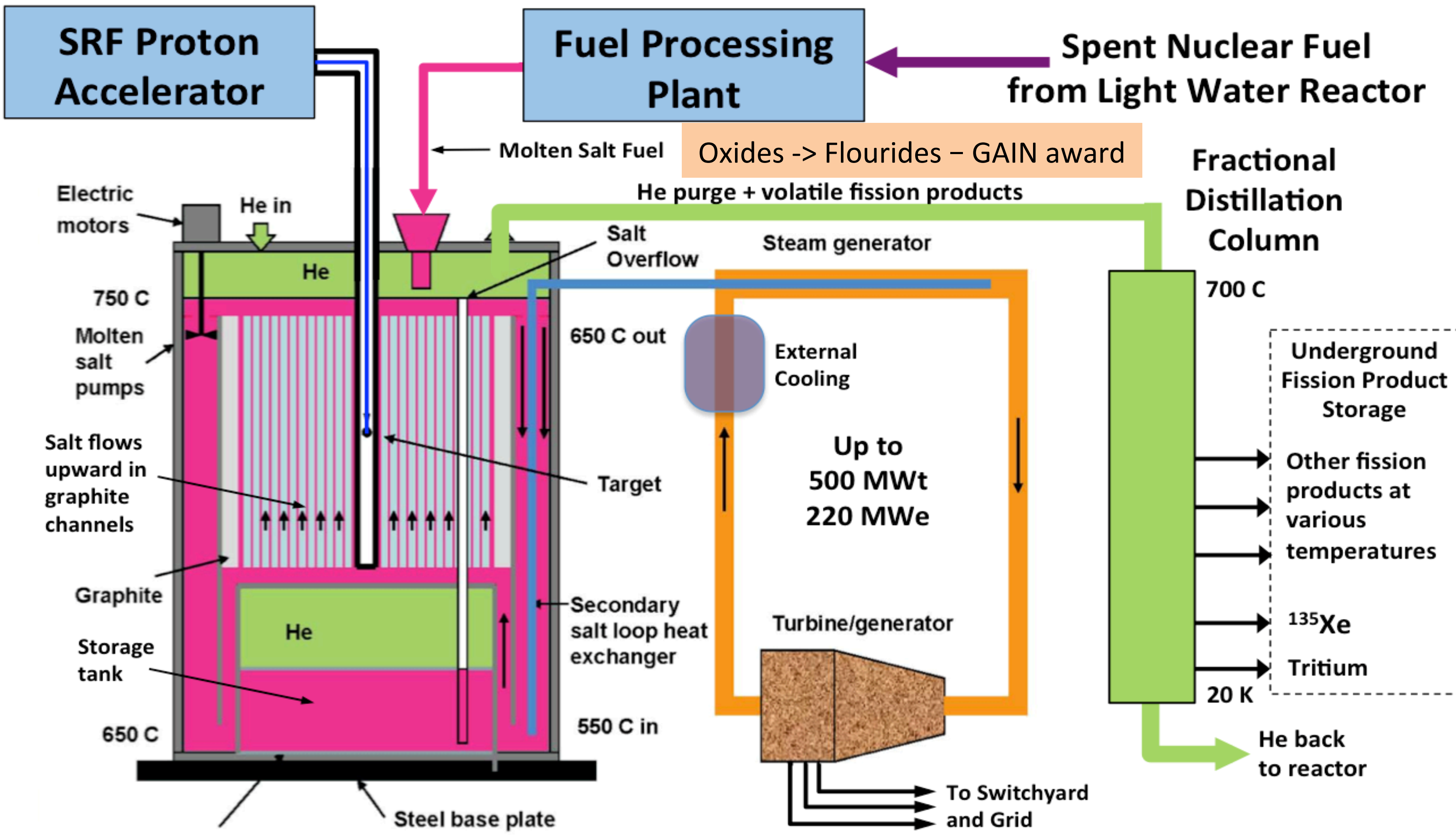
SNF Burning Concept



Reactor concept from C. D. Bowman, R.B. Vogelaar,
et al., 2010 HB of NE

SRF Linacs Driving Subcritical MS Reactors
Why This Approach is Superior

Deepest Burn – Unique to SC Linac & MS Reactors

- Driven by Superconducting RF Linacs
  - Newest technology for highest proton power (>25 MW)
- Molten Fluoride Salt Fuel Reactor (MSRE experience)
  - Accommodates short beam interruptions
  - Avoids issues of solid fuel rods
- Internal Spallation target
  - Amplifies neutron flux by factor of >30
- Graphite moderated thermal neutron spectrum
  - Less sensitivity to fission products

SRF Linacs Driving Subcritical MS Reactors
Why This Approach is Superior

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New Features

- Subcritical - defense in depth by controlling fuel reactivity (NRC – NOT a reactor, many licensing and import controls issues are avoided)
- Fission turned off by switching the accelerator off
- Continuous removal of volatile radioisotopes
- Versatile reactor design accommodates many fuels
- **Decouples nuclear energy from nuclear weapons**

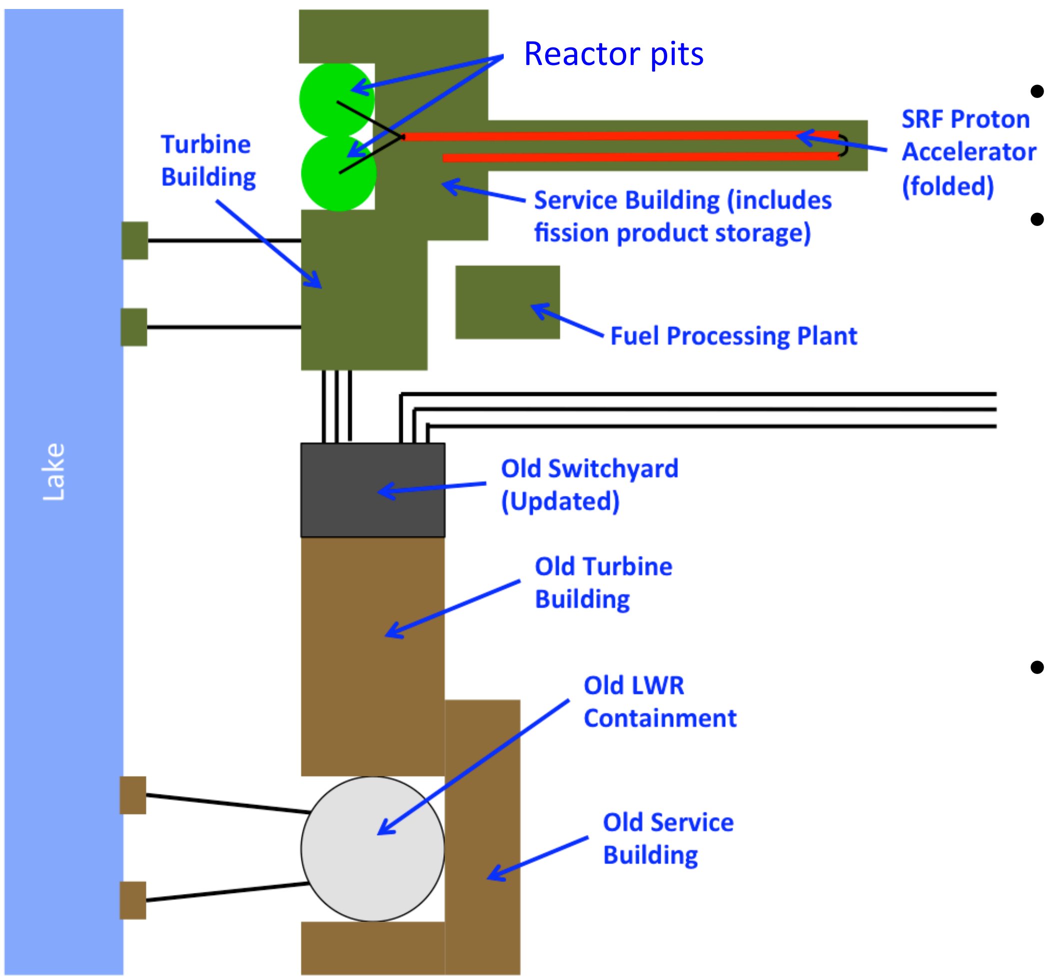
Mu*STAR Features

Additional Features/Advantages

- Tested technology put together in a new way
- The reactor operates underground at atmospheric pressure
  - no pressure vessel - eliminates many accident scenarios
- Volatile fission products are continuously removed
  - reactor contains almost a million times less than in a LWR
- No fuel rods/Zircaloy
  - no mechanical fatigue of UO_2 fuel rods from accelerator trips
- No critical mass is ever present, and cannot form
  - freeze plug as in all MS designs
- No chemical reprocessing or isotopic enrichment is needed
  - more proliferation resistant than other technologies
- Burns SNF, W-Pu, U233, natural uranium, thorium
  - without redesign –accelerator parameters match fuel
- Passive response to most accident scenarios
  - turn off the accelerator – passive air cooling is then sufficient

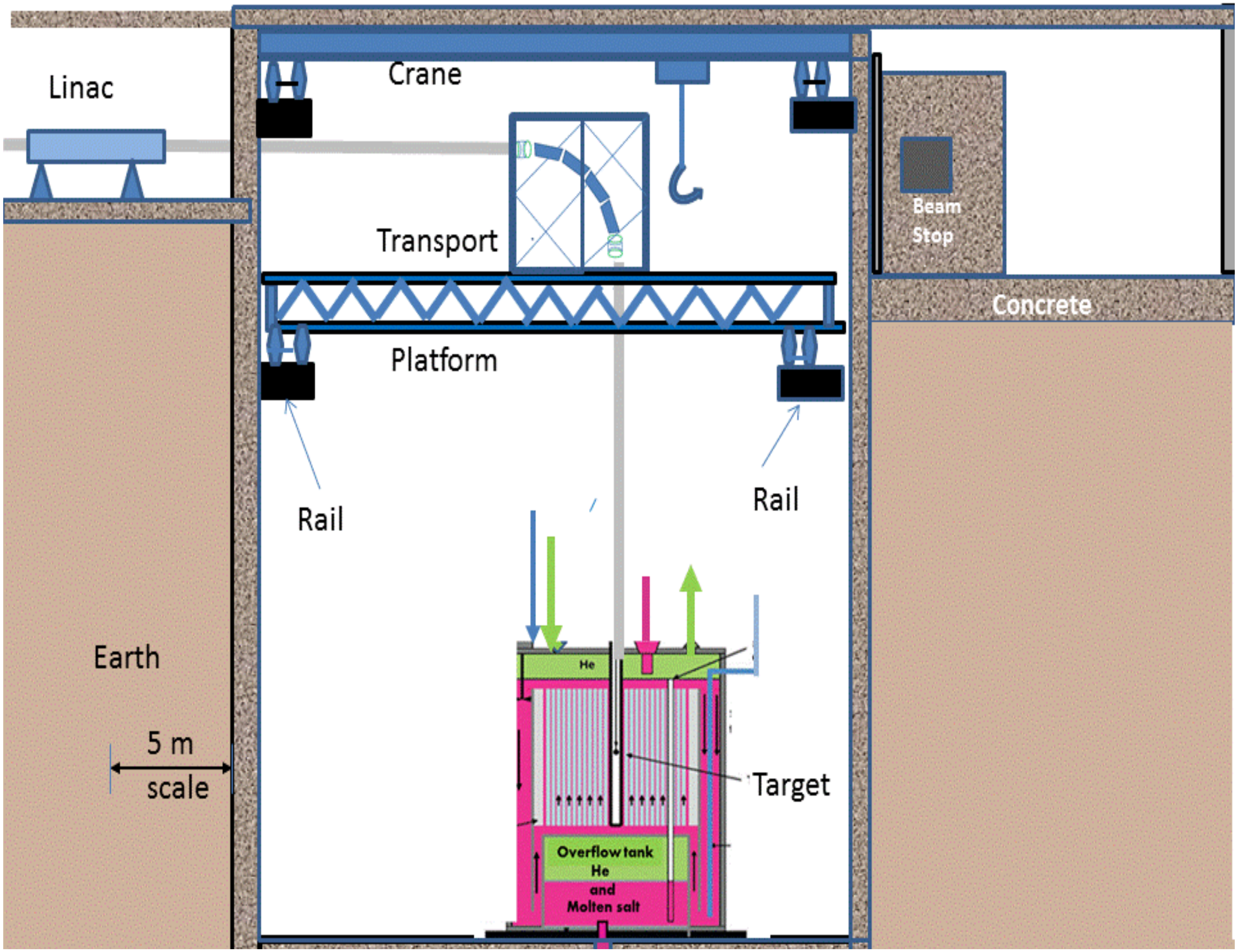
Mu*STAR SNF Concept

Build Mu*s at 60 existing LWR sites



- Convert SNF to fluoride MS fuel once
  - GAIN award with ORNL, SRNL, INL
- Burn to get 7 times as much energy
  - For 200 years
- Disruptive Technology
  - No uranium mining
  - No fuel enrichment
  - No fuel rod manufacture
  - No new SNF
  - No SNF transport
  - No SNF remote storage
- Consent based storage of SNF
  - Community support
  - Same amount of SNF as now
  - Fuel for their utility
  - Lots of jobs, economic stability
- Goal – electricity for less than gas

Underground Linac and Reactors



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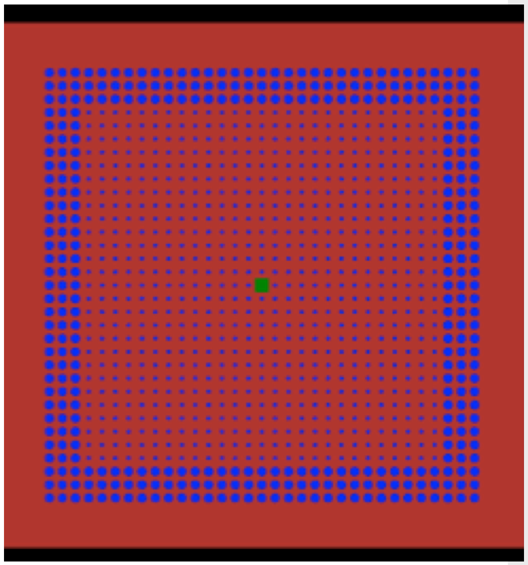
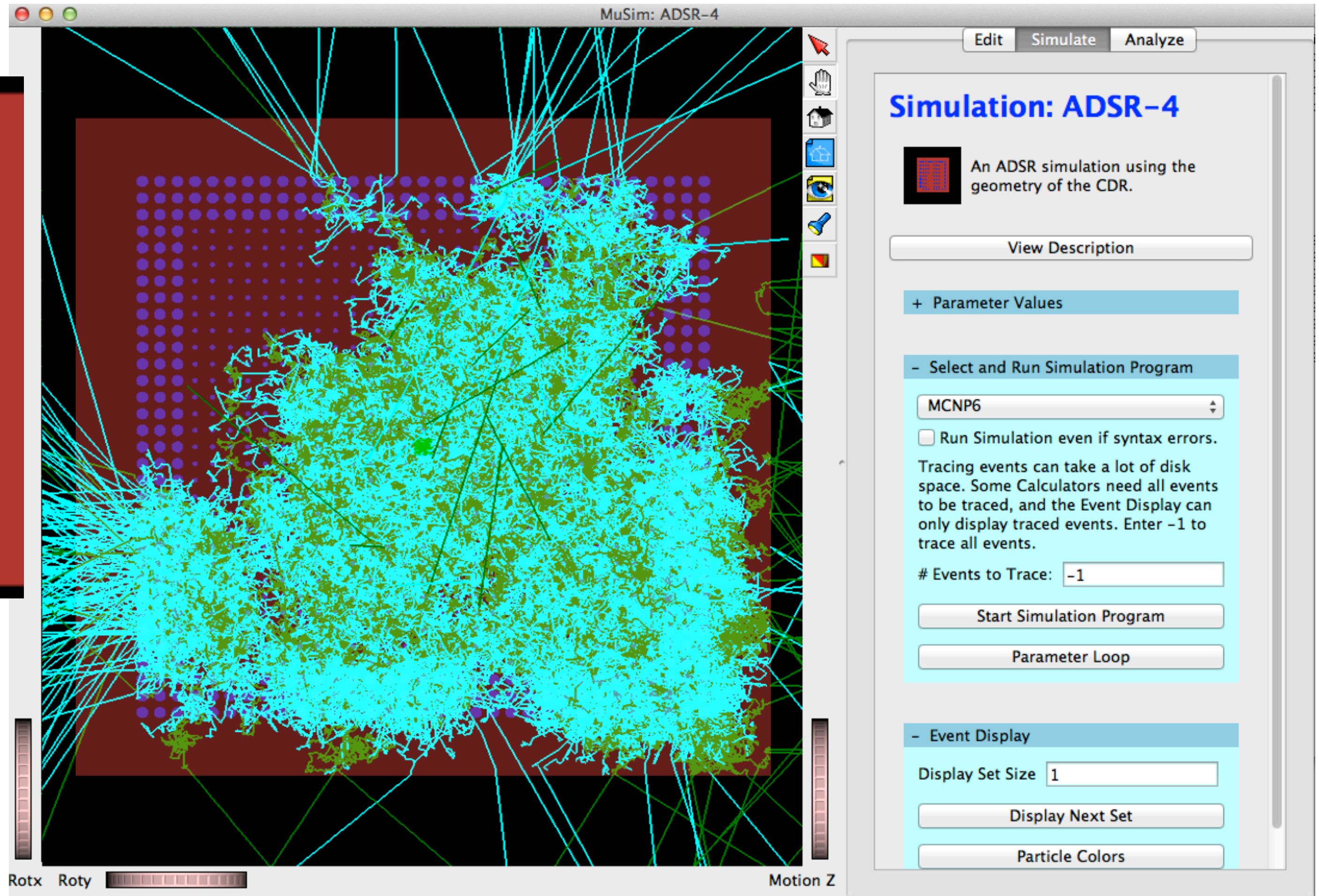
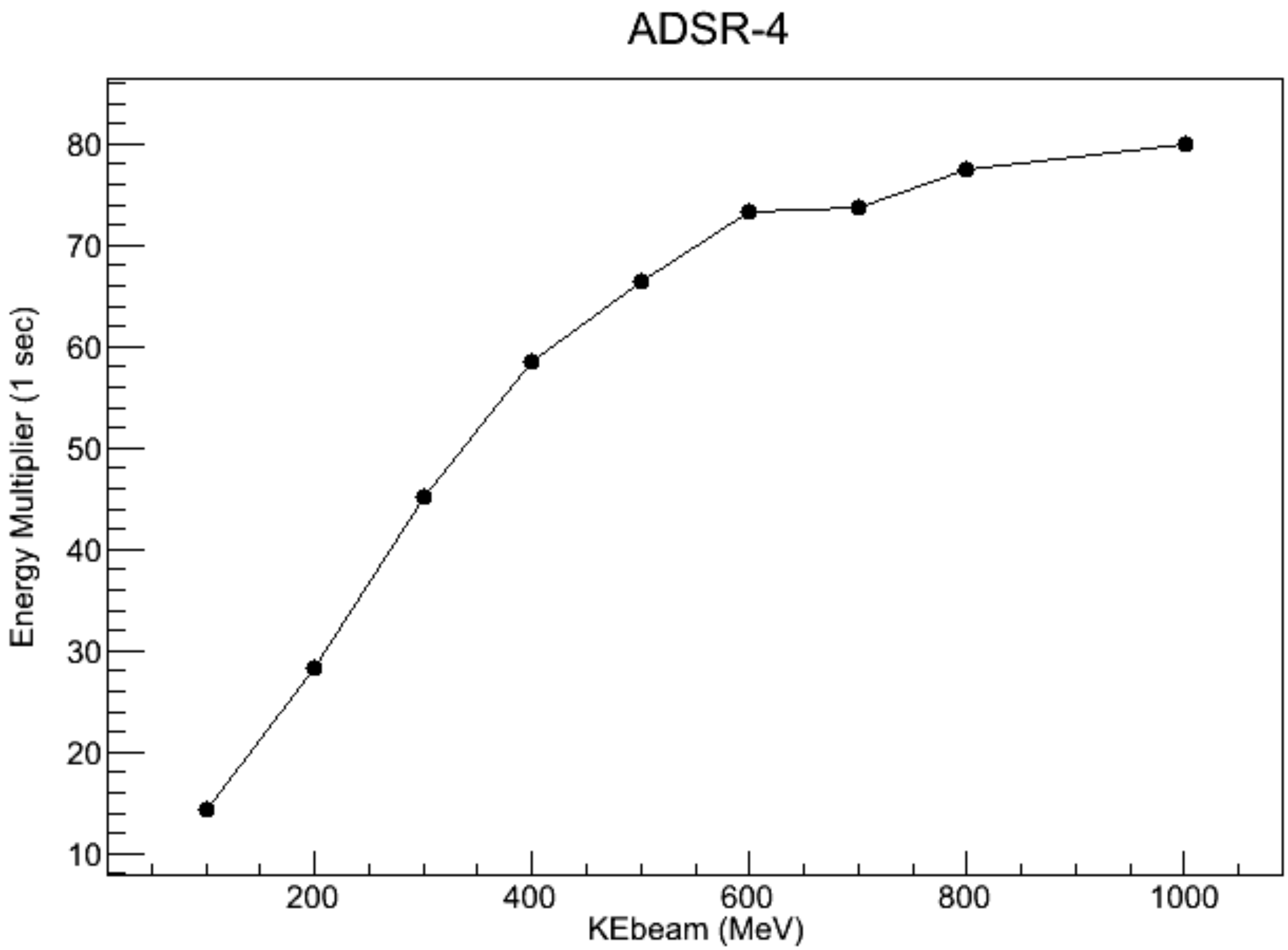
Mu*STAR
Using MuSim MCNP6 single event display





green=neutron, cyan=gamma, brown=graphite, purple=molten-salt fuel.
This single 1 GeV proton generated 402,138 tracks (not counting e^-).

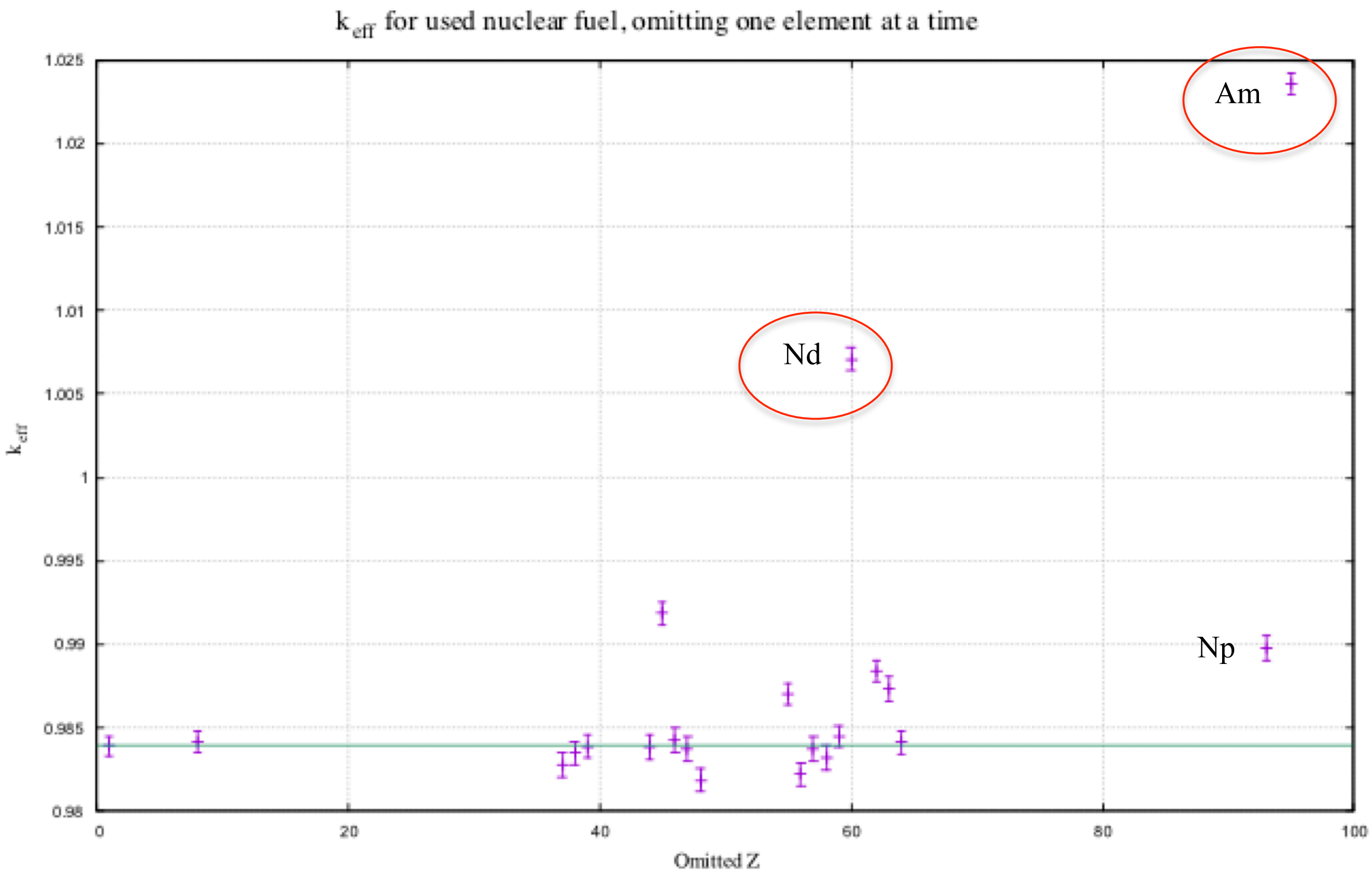
Mu*STAR
Energy Multiplier vs. Beam Energy



We can run much lower than 1 GeV energy ~ 600 MeV will be sufficient and be a significant cost saving on acceleration.

MuSim -Criticality Measurement

Burning used nuclear fuel (UNF) in Mu*STAR - neutron poisons build up in the fuel, reducing its reactivity and requiring increased accelerator power to maintain a constant thermal output. dentify the elements that are most responsible for reducing the reactivity, so we can concentrate on removing them.



Deep Burn Example #1
New Economics for SNF

- Convert LWR SNF into molten fluoride salt fuel
- Muons New DOE GAIN Award (with ORNL, SRNL, INL)
  - Gateway for Accelerated Innovation in Nuclear (GAIN)
- Example in Handbook of NE (Bowman et al) - Burns the M-S fuel for 200 years
  - In 5 passes in successive reactor units (fuel moved by He pressure)
  - Without chemical reprocessing
  - Only increasing the accelerator power each pass
  - Until it takes 15% of the reactor power to run the accelerator
  - Extract 7 times the energy as was generated by the original LWR
  - Energy normalized waste reduced by more than a factor of 7
  - Toxicity reduced – higher actinides burned
- SNF becomes a valuable commodity

Deep Burn Example #2
Making Tritium for the NNSA

The Vision –

-Mu*STARs at 60 US LWR sites
burning their existing stored SNF
for >200 years

How to get there?
Need to build a demo system

Get the NNSA to pay for it
Solve their problems
Save them money

NNSA Makes Tritium Now

- Tritium Production Burnable Absorbing Rods (TPBARS)
- National security function on commercial site
  - Subject to local, state, EPA, NRC regulation
  - Number of TPBARs limited – e.g. tritium in cooling water
  - NNSA pays TVA to use Watts-Bar ($?)
- Reactor fuel must be of national origin
  - Need US owned, US sited uranium enrichment facility (>$2B)
- ORNL (Y-12) Li-6 enrichment facility obsolete ($?)
- 2.8 kg/y of tritium needed after 2025
  - Weapon decommissioning ends
  - Additional reactor(s) needed
    - to be upgraded and certified for TPBARs ($?)
- Mu*STAR solves all these problems and saves money
  - Scaled back accelerator and only one Mu*STAR module
  - Essentially a Mu*STAR pilot plant (~$1B)

Mu*Star solution for Tritium at SRS

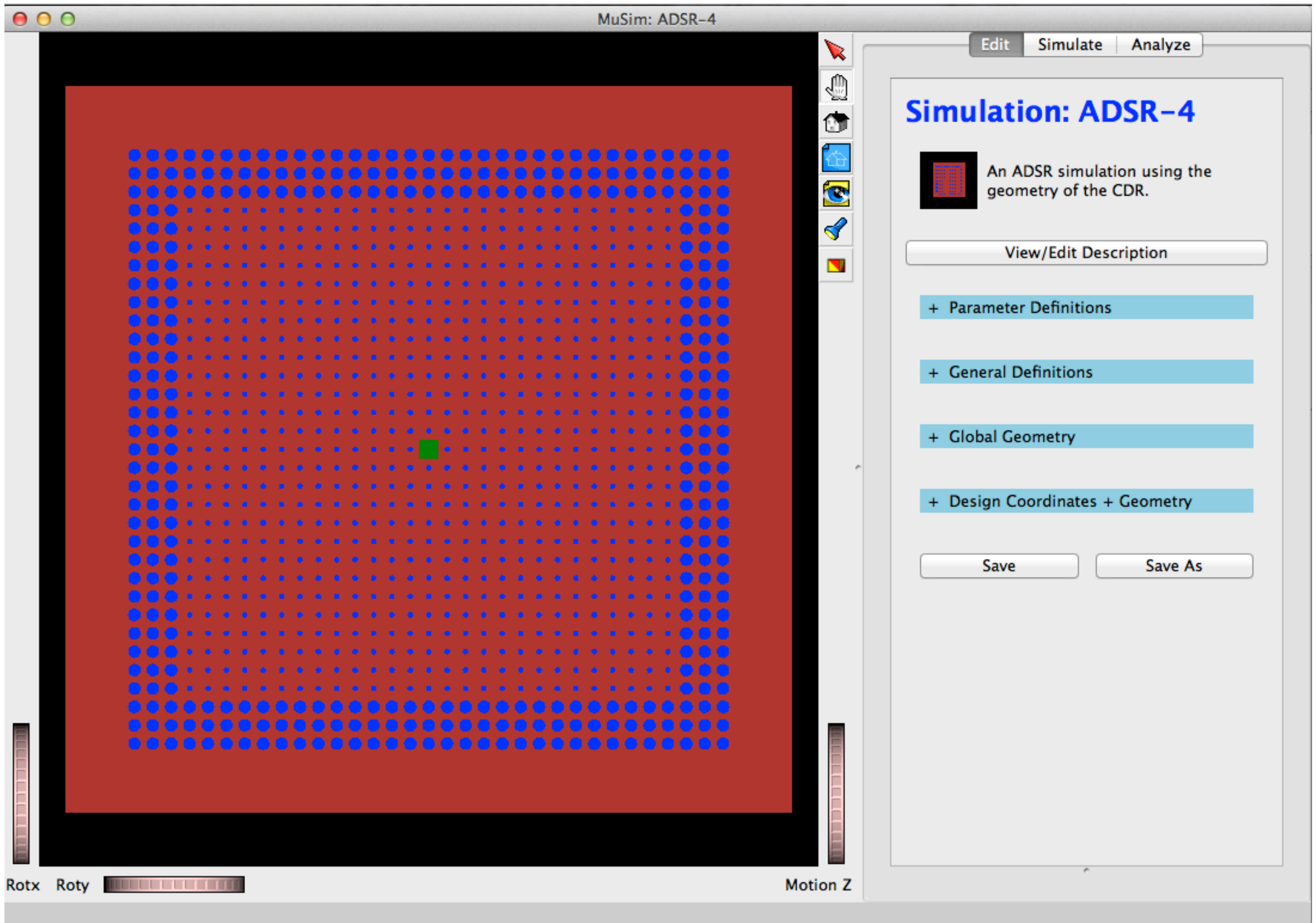
- Tritium contained in reactor, not TPBARs (saves $)
- Uses natural Li-6 component of the LF MS eutectic (saves $)
- Excess Pu at SRS as fuel (saves $)
- Pu burning easier
  - Subcritical operation
- Built on Savannah River Site (fewer uncertainties)
  - Some accelerator and reactor components from National Labs

- **Simulations already show 2.4 kg/y of tritium**
  - with 2.5 MW, 1 GeV proton beam
  - on an internal depleted uranium target burning 200kg/y of Pu

Conclusions

- **Mu*STAR is a solution to NE SNF problem**
  - Gets 7 times energy w/o reprocessing
  - Extends life of present reactor sites
  - Defers SNF transport/burial indefinitely
- **Mu*STAR pilot/demo funding**
  - Can solve tritium supply security for NNSA
  - Saves NNSA construction and operation costs

First MuSim Application - Mu*STAR



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.

Mu*Star solution for Tritium at SRS

- Tritium contained in reactor not TPBARs (saves $)
  - Removed continuously at low partial pressure
  - Reduced embrittlement and escape potential
- Uses natural Li-6 component of the LF MS eutectic
  - Upgrade of Y-12 enrichment plant not needed (saves $)
- Excess Pu at SRS as fuel
  - Environmental Management (EM) operates SRS
    - wants to get rid of many tons of it
  - No enriched uranium needed (saves >$2B)
- Pu burning easier
  - Subcritical operation overcomes PuF3 solubility limitations
  - Pu has fewer delayed neutrons than U235
  - U238 Doppler broadening not available or needed
- Built on Savannah River Site (fewer uncertainties)
  - Some accelerator and reactor components from National Labs

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