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Accelerator Driven Subcritical Reactors

Introducing GEM*STAR – A Particularly Advantageous Example

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Technology to revitalize the nuclear power industry through improved safety, waste management, efficiency, and proliferation resistance.

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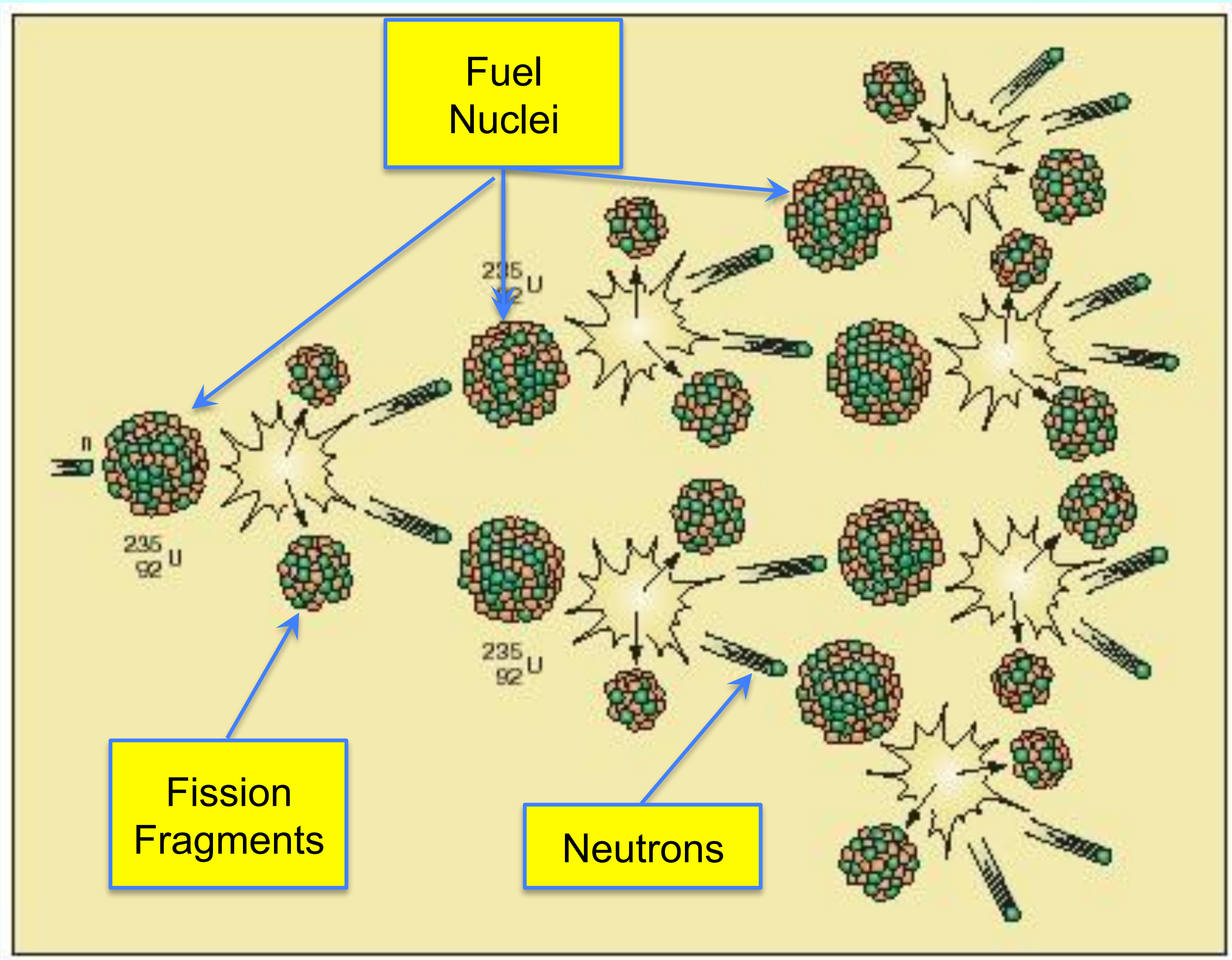
Outline

- "Nuclear Reactors 101" – how they work
- Subcritical operation – avoids many problems
- Why now? – answers to historical objections to ADSR
- GEM*STAR – specific example of ADSR
  - Passive safety
  - Burns all nuclear waste streams, *including its own*
  - Extracts most of the 94% energy left in spent nuclear fuel
  - Needs no isotope enrichment or reprocessing
- Summary

Nuclear Reactors 101
Fission Chain Reaction



http://www.scienceclarified.com

- Each fission yields:
  - 2-3 fragments
  - 2-3 neutrons
  - 1-3 gammas
  - Energy released ~ 200 MeV
- Some neutrons are lost, some are absorbed.
- Many fragments are radioactive – that is important.

Nuclear Reactors 101
Criticality Factor

- A key parameter of a nuclear reactor is the *criticality factor:*

$$k = \frac{(\#\ \text{neutrons that induce new fissions})}{(\#\ \text{fissions that created them})}$$

- k depends on the fuel mixture, the geometry, and the probability of a neutron inducing fission vs. being absorbed.
- If $k>1$ the reaction grows without bound until something stops it (typically the system exploding violently). **Bomb.**
- If $k<1$ the reaction stops, typically in less than 1 second. **Subcritical reactor.**
- All current reactors operate with $k=1$, maintained within about 1 part per million. **Critical reactor.**

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Nuclear Reactors 101

Neutron Moderation

- The neutrons emitted from a fission are *fast neutrons* with kinetic energies of 1-10 MeV.
- In a typical reactor fuel mixture, fast neutrons are more likely to be absorbed than to induce fission.
- That makes k=1 difficult to achieve with fast neutrons.
- A *moderator* is used to slow the neutrons down to become *thermal neutrons* (< 1 eV), via elastic collisions.
- Thermal neutrons are much more likely to induce fission.
- Moderators have low A and low neutron absorption.
- Typical moderators: water, heavy water, and graphite.
- The geometry is important.

Nuclear Reactors 101

Delayed Neutrons – Needed for Control

- Neutron-induced fission occurs within femtoseconds; neutron moderation and transport takes microseconds.
- That is too fast to be able to control the reaction.
- Fortunately many fission products are radioactive, and some of them emit neutrons with a delay from milliseconds to minutes– typically 0.6−0.8% of the neutron flux.
- The reactor operating point is set to be <u>subcritical</u> for the fission neutrons alone, but <u>critical</u> when the delayed neutrons are included.
- This is slow enough that control can be maintained.

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Nuclear Reactors 101

Cooling and Control

- The reactor must be maintained at k=1 to operate.
- *Control rods* are used, which are made of powerful neutron absorbers. With them fully inserted, k<<1.
- In operation, the control rods are partially withdrawn to set the operating point (where k=1).
- At the operating point, higher temperature will reduce k, while cooling down will increase it (combination of thermal expansion and moderation efficiency).
- Thus the reactor will automatically generate enough power to maintain its temperature – if you increase the cooling capacity it will increase power, etc.
- The control rods can be inserted at any time to shut down the reactor.

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Nuclear Reactors 101
Fuel Handling

- As a reactor operates, some of the fissionable portion of its fuel is burned, and fission fragments build up in the fuel rods.
- Some fission fragments are powerful neutron absorbers.
- So the control rods must be gradually withdrawn to maintain the operating point.
- Typically every 12-18 months, ¼-⅓ of the fuel rods are replaced. They still contain ~ 94% of their initial energy.
- The spent fuel rods are stored on-site, usually with water cooling to remove the decay heat from their residual radioactivity.
- That radioactivity remains dangerous for > 100,000 years.

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Nuclear Reactors 101
Summary

- Nuclear reactors depend on many details of nuclear physics. Fortunately that is now very well known.
- They must operate at $k=1.000000 \pm 0.000001$. Fortunately this is possible.
- They depend on ^{235}U, which is difficult to obtain and of limited supply on earth. Isotopic enrichment is required, which makes it intimately connected with concerns about nuclear weapons proliferation.
- There are significant concerns about safety.
- But the big problem is that the U.S. has no viable plan for the handling of nuclear waste.

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Subcritical Operation

- Subcritical operation cannot sustain itself, so an external source of neutrons is required.
- The most appropriate source is a proton accelerator generating spallation neutrons:
  - 600-1000 MeV
  - 1-10 MW
- Appropriate k values: $0.97<k<0.99$.
- k closer to 1 gives more output power for a given beam power. That power ratio can range up to 200 or so.
- As fission stops when the accelerator is turned off, this can provide significantly improved safety.
- The neutron source permits operation even with large amounts of fission fragments – **can burn waste**.

Why now?

Answers to Historical Objections to ADSR

- Doubt that a multi-MW accelerator could be built.
- Belief that such an accelerator would be too expensive and inefficient to operate.

Superconducting accelerators answer both.

- Expectation that frequent accelerator trips would cause mechanical fatigue in the reactor fuel rods.

Eliminated by using molten salt fuel, and by designing the accelerator for high availability.

- Doubt that the neutron economy would be viable.

Addressed with modern materials and simulations.

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GEM*STAR

- Our long-range goal is to sell intrinsically safe and versatile nuclear reactors to address world energy needs.
- GEM*STAR is an Accelerator-Driven Subcritical Reactor designed to burn nuclear waste, natural uranium, depleted uranium, thorium, and excess weapons-grade plutonium.
- It uses a superconducting accelerator and molten salt fuel to achieve greatly improved safety, address the issues of nuclear waste, and be both economically and politically feasible.
- Note these technologies <u>have already been demonstrated</u>.
- We believe that even in an era of cheap natural gas that GEM*STAR will be economically attractive.

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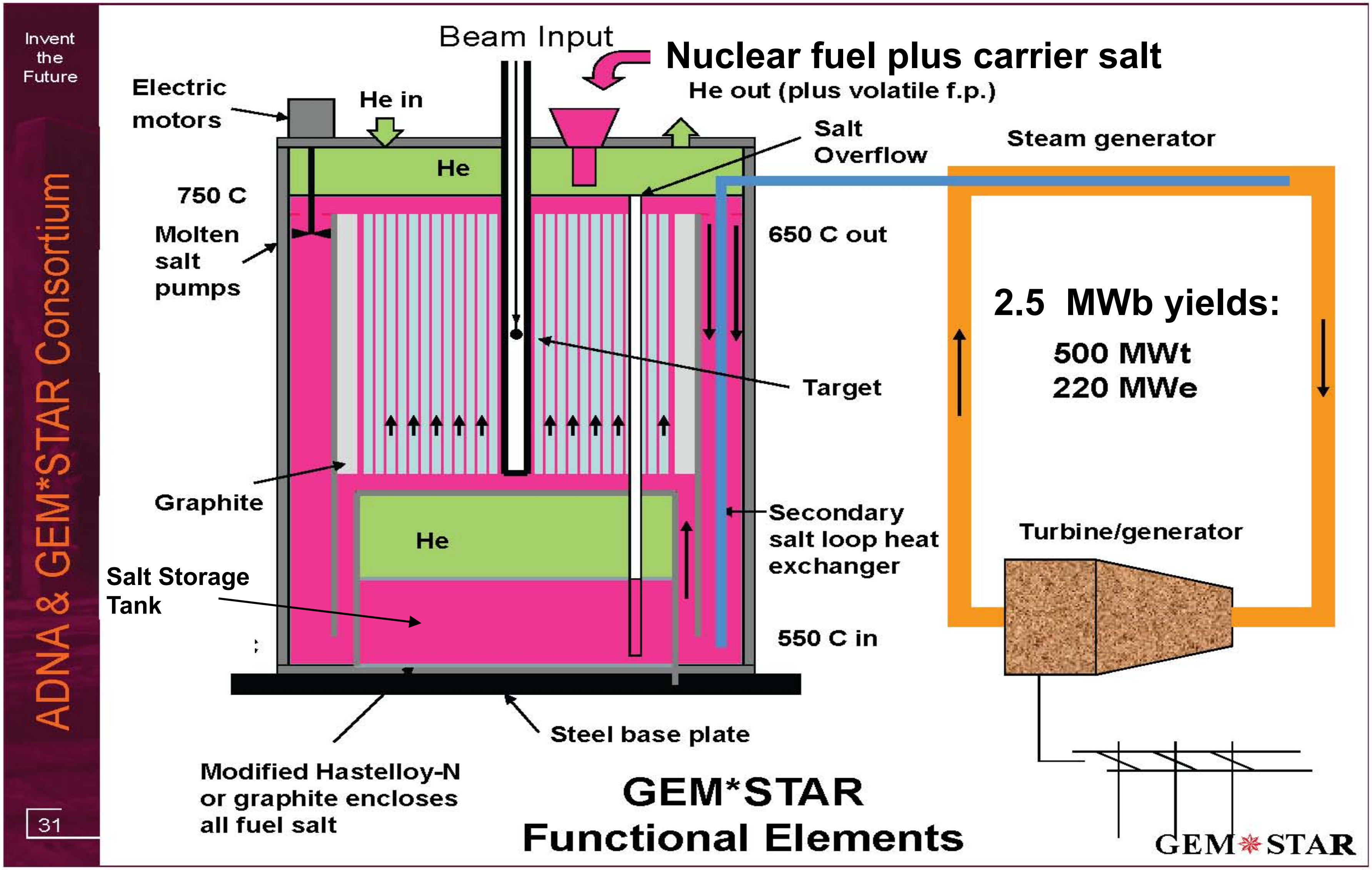
GEM*STAR
Molten Salt Fuel

- The Molten Salt Reactor Experiment operated at ORNL,1964-1969.
- It demonstrated the key aspects of using molten salt fuel.
- It was a critical reactor tested with several different fuels.
- They routinely powered it down for weekends, something no conventional reactor could do.

GEM*STAR


Invent
the
Future
ADNA & GEM*STAR Consortium
Beam Input
Nuclear fuel plus carrier salt
He out (plus volatile f.p.)
Electric
motors
He in
He
Salt
Overflow
Steam generator
750 C
Molten
salt
pumps
650 C out
2.5 MWb yields:
500 MWt
220 MWe
Target
Graphite
He
Secondary
salt loop heat
exchanger
Turbine/generator
Salt Storage
Tank
550 C in
Steel base plate
Modified Hastelloy-N
or graphite encloses
all fuel salt
GEM*STAR
Functional Elements
GEM*STAR
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GEM*STAR
Advantages

- Proven technology put together in a new way.
- The reactor operates at atmospheric pressure.
  - No pressure vessel.
  - Major design simplification, and eliminates many accident scenarios.
- Volatile fission products are continuously removed.
  - Avoids possibility of release (total ~ a million times lower).
- No fuel rods.
  - No Zircaloy that can instigate a hydrogen explosion (Fukishima).
  - No mechanical fatigue from accelerator trips.
- No critical mass is ever present, and cannot form.
- No reprocessing or isotopic enrichment is needed.
  - More proliferation resistant than other technologies.
- Passive response to most accident scenarios: turn off the accelerator – passive air cooling is then sufficient.

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GEM*STAR

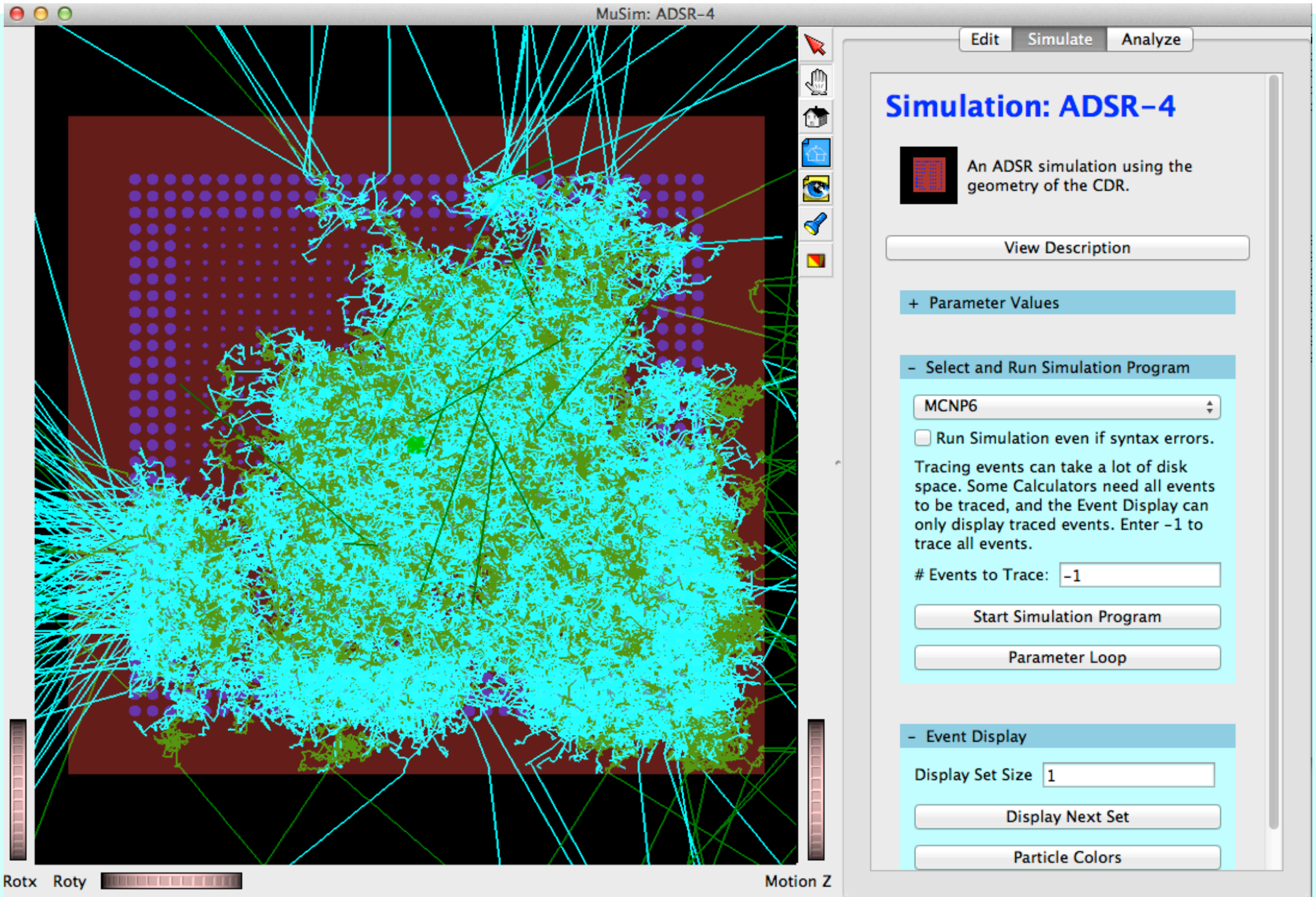
- One thing it does particularly well is to dispose of excess weapons-grade Plutonium.

  34 metric tons of excess weapons-grade plutonium is slated to be destroyed by the 2000 U.S.-Russian Plutonium Management and Disposition Agreement.

- GEM*STAR destroys it more completely than other approaches.
- The Pu is fed continuously into the reactor, and is immediately rendered not weapons-grade (even before burning is complete).

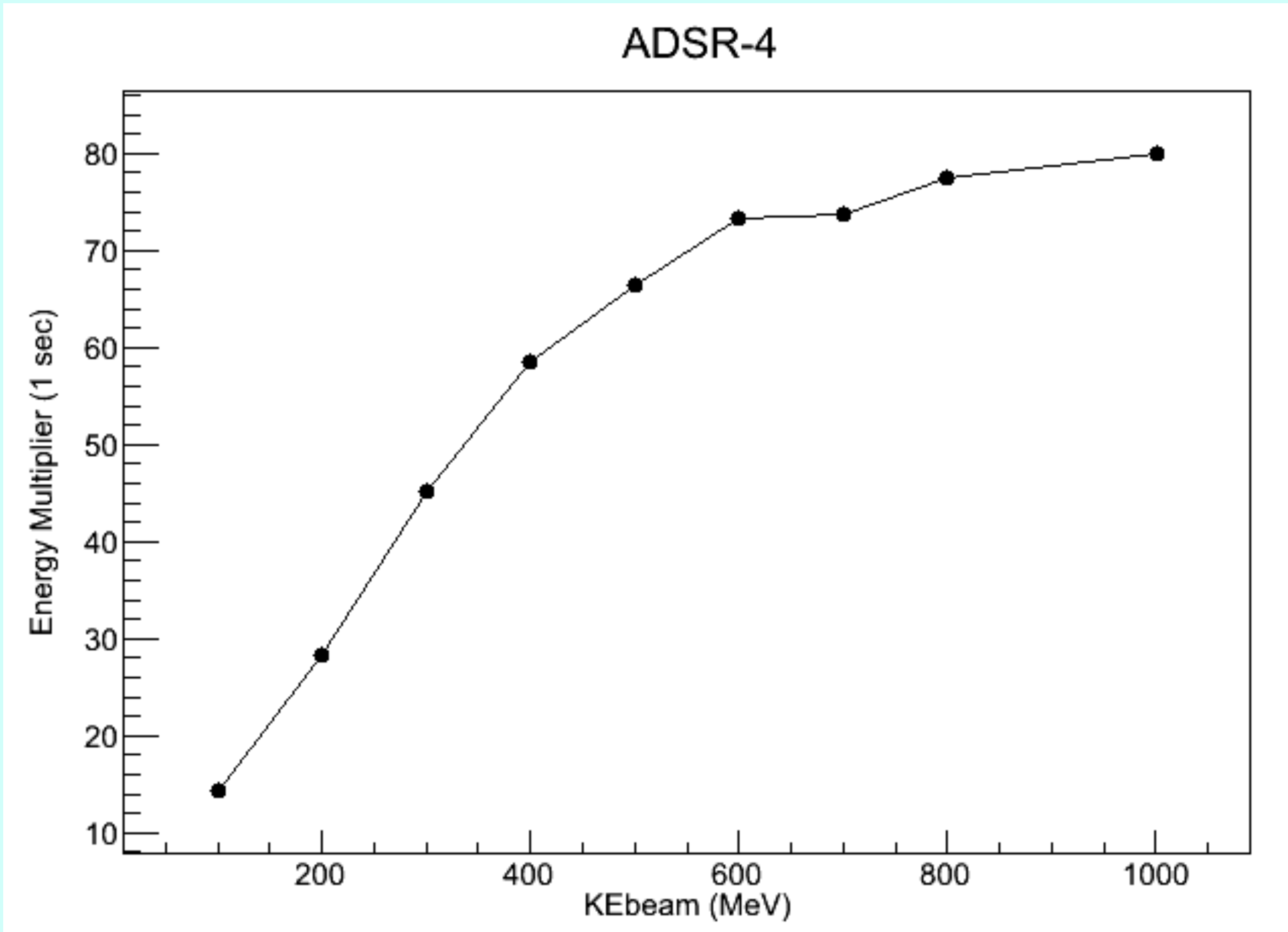
GEM*STAR

Simulation Using MuSim



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

GEM*STAR
Energy Multiplier vs. Beam Energy



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Summary

- Accelerator Driven Subcritical Reactors offer the promise to address the major problems associated with nuclear power – **both technical and political**.
- ADSR can be very flexible in fuel: spent nuclear fuel, natural uranium, depleted uranium, surplus weapons material, and thorium.
- Burning the waste from current reactors can potentially extend their lifetime and turn a huge liability into highly profitable use.
- Burning the spent nuclear fuel from the current fleet of nuclear reactors is vastly superior to throwing away its enormous internal energy and just piling it in a hole in the ground for 100,000 years.
- **With a fleet of systems like GEM*STAR there is enough uranium *out of the ground today* to supply the current U.S. electrical power usage for more than 1,000 years.**

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Summary – GEM*STAR

- **Safety:**
  - Fission stops when the accelerator is turned off.
  - Without fission, passive air cooling is sufficient.
  - Passive response to most accident scenarios.
  - Design avoids all historical reactor accident scenarios involving radioactive release.
- **Waste Management:**
  - Burns all nuclear waste streams, *including its own.*
  - Ultimate waste stream is > two orders of magnitude smaller.
- **Efficiency:**
  - Extracts most of the 94% energy left in spent nuclear fuel.
- **Proliferation Resistance:**
  - Needs neither isotopic enrichment nor reprocessing.
  - Waste stream is never useful to build weapons.

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Summary – Future

At the recent **White House Summit on Nuclear Energy** it was clear that nuclear energy is an important part of U.S. energy policy for the future.

That cannot happen without a sensible approach to the handling of nuclear waste#, which we don't have today.

ADSR is among the best approaches known.

E.g. Illinois has a moratorium on new nuclear facilities tied to a national policy on waste management.