Applications of Electron Linacs to ADS: One Potential Path Forward

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ADS, cast in its most general sense, is an accelerator driven system to produce photons, neutrons, fissions (nuclear reactions) and energy.

The (non-traditional) concept of ADS considered here is:

Zeroth Order	=	Accelerator-driven, high-brightness photon and fast neutron source (no fuel) for isotope production, burn up of nuclear waste, materials irradiations studies, with or without neutron moderation.
First Order	=	Accelerator-driven single-stage subcritical system with neutron multiplication for; isotope production, materials studies.
2nd Order	=	Accelerator-driven coupled-stages subcritical system with neutron multiplication for; power i.e. process heat etc.

ADS:
What are the applications of interest?

The applications where ADS has major potential and/or competitive advantage are:

“Standard” Applications:

1) Energy Production – either electrical or direct heat applications
2) Waste Transmutation
3) “Breed” ^{233}U, ^{3}H, etc.

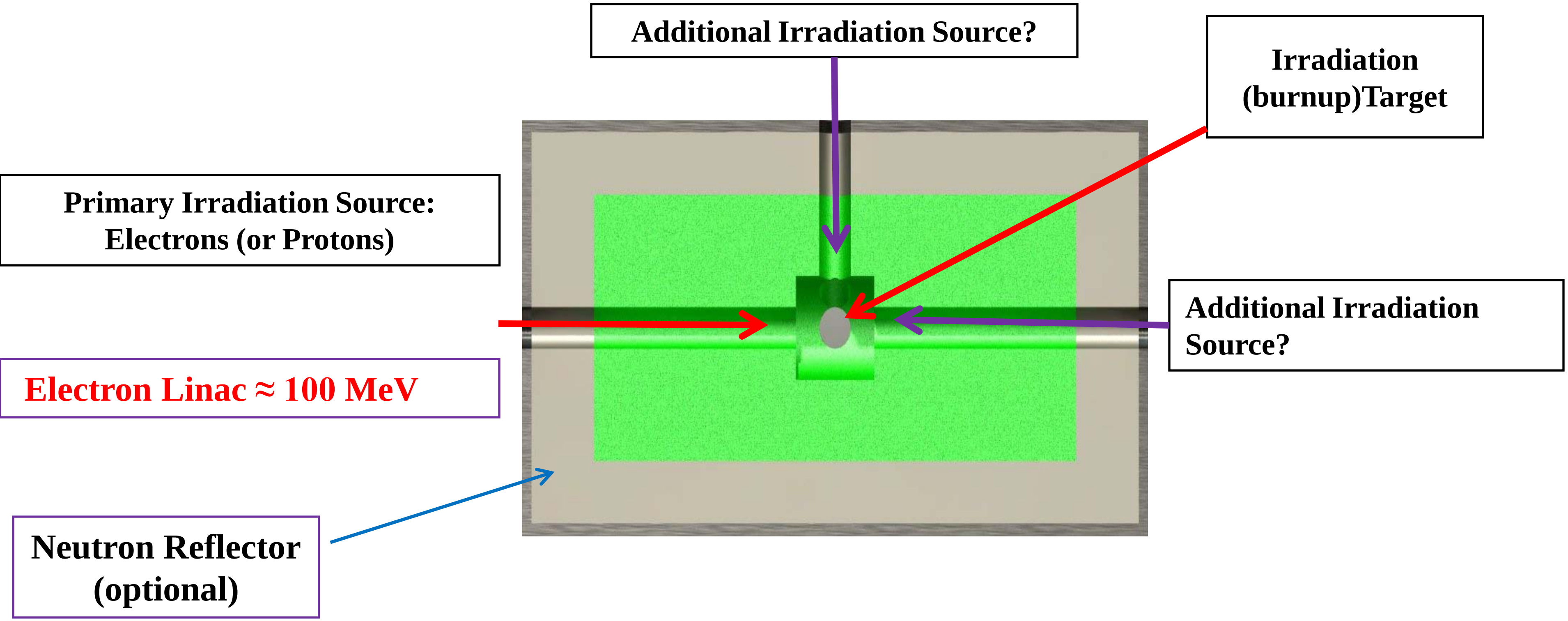
Non-standard Applications that may be entry-vehicle, low-hanging fruit for ADS:

4) Isotope Production (both neutron-rich, like a reactor AND proton-rich)
5) Radiation Damage of fuel-cycle materials, or other materials
6) Activation Analysis (photon and/or neutron) for a variety of applications

Primary Applications for each "Order" of ADS with **Electron Linacs**:

Zeroth Order	=	Isotope Production (photo-nuclear +/or n-capture), Radiation Damage (fission-spectrum fast neutrons) Waste Transmutation (^{99}Tc, ^{129}I)
First Order	=	Isotope Production, (esp. via n-capture and n-fission) "Breed" ^{233}U, ^{3}H, etc. Waste Transmutation
2nd Order	=	Energy/Power (direct heat or electrical) Isotope Production "Breed" ^{233}U, ^{3}H, etc. Waste Transmutation

Zeroth order ADS:
a bright neutron source for materials irradiation:

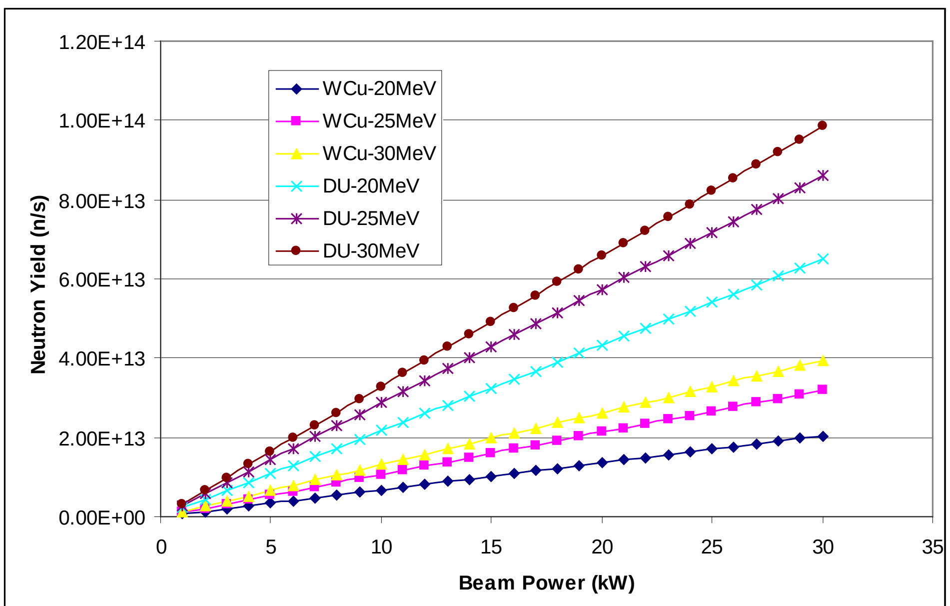


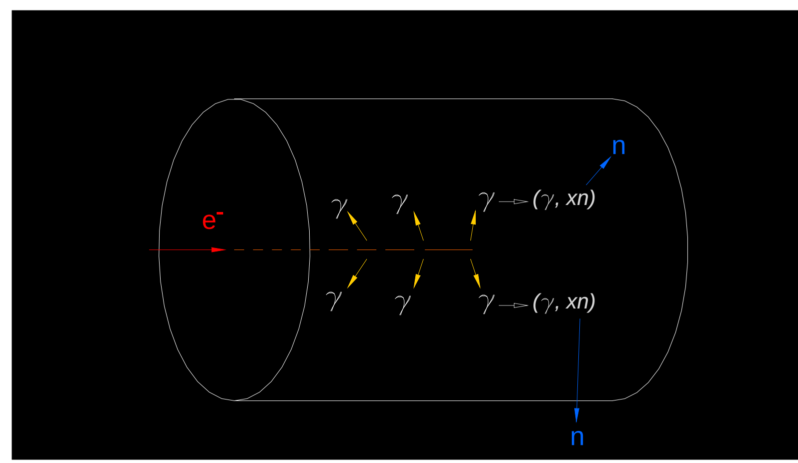
How intense can such an electron linac-driven source be, reliably?

100 kW?, 500 kW?

Zeroth order ADS: Neutron Source for Materials Irradiation

A relatively low-cost fast fission-spectrum neutron source for long term irradiation of <u>small samples</u> is possible. A 250 kW, 100 MeV electron source could provide an inexpensive domestic fast-neutron irradiation capability for small samples (~1 cm3) with a flux of up to ~10^{15} n/sec (~10^{14} n/cm^2-sec), to meet needs of fuel-cycle materials researchers





Zeroth order ADS:
a bright neutron/gamma source for waste transmutation

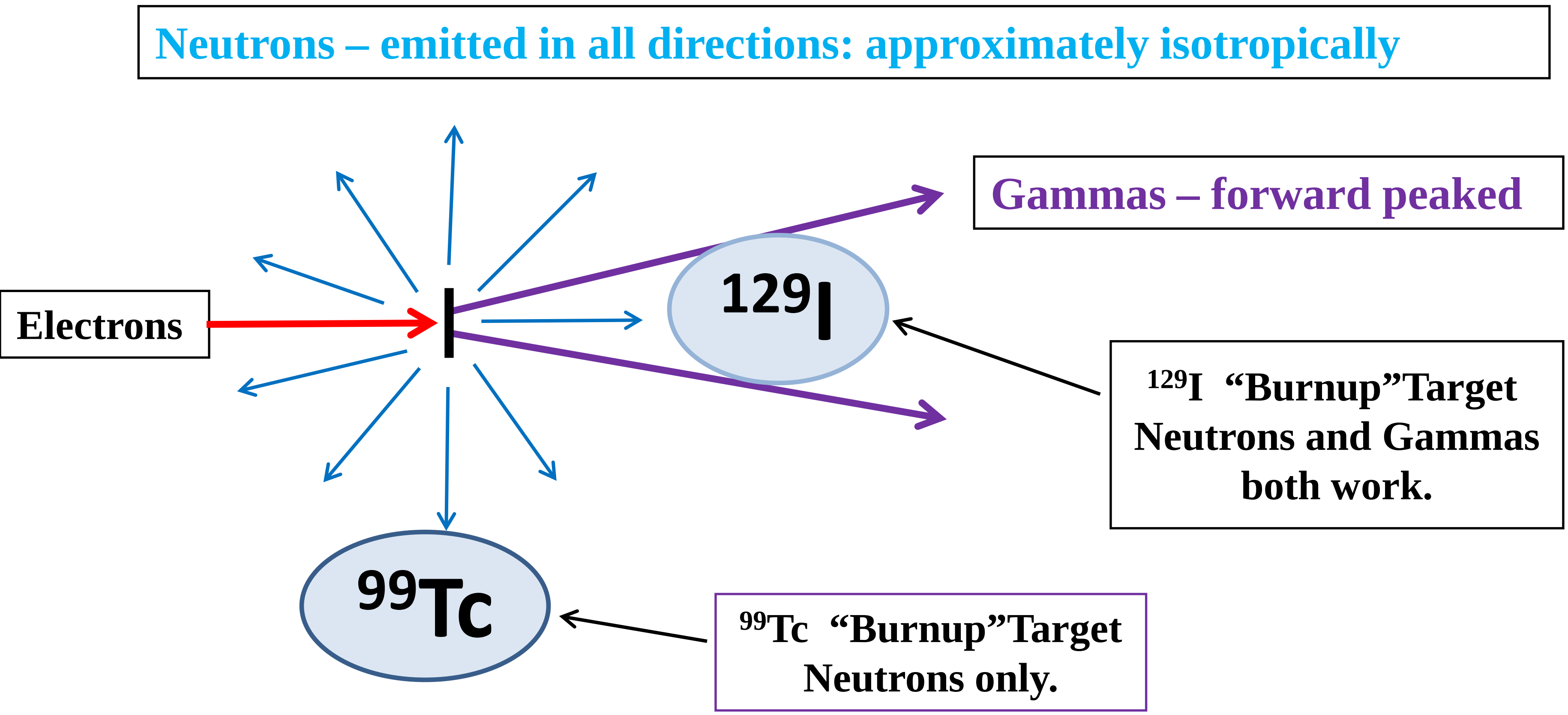
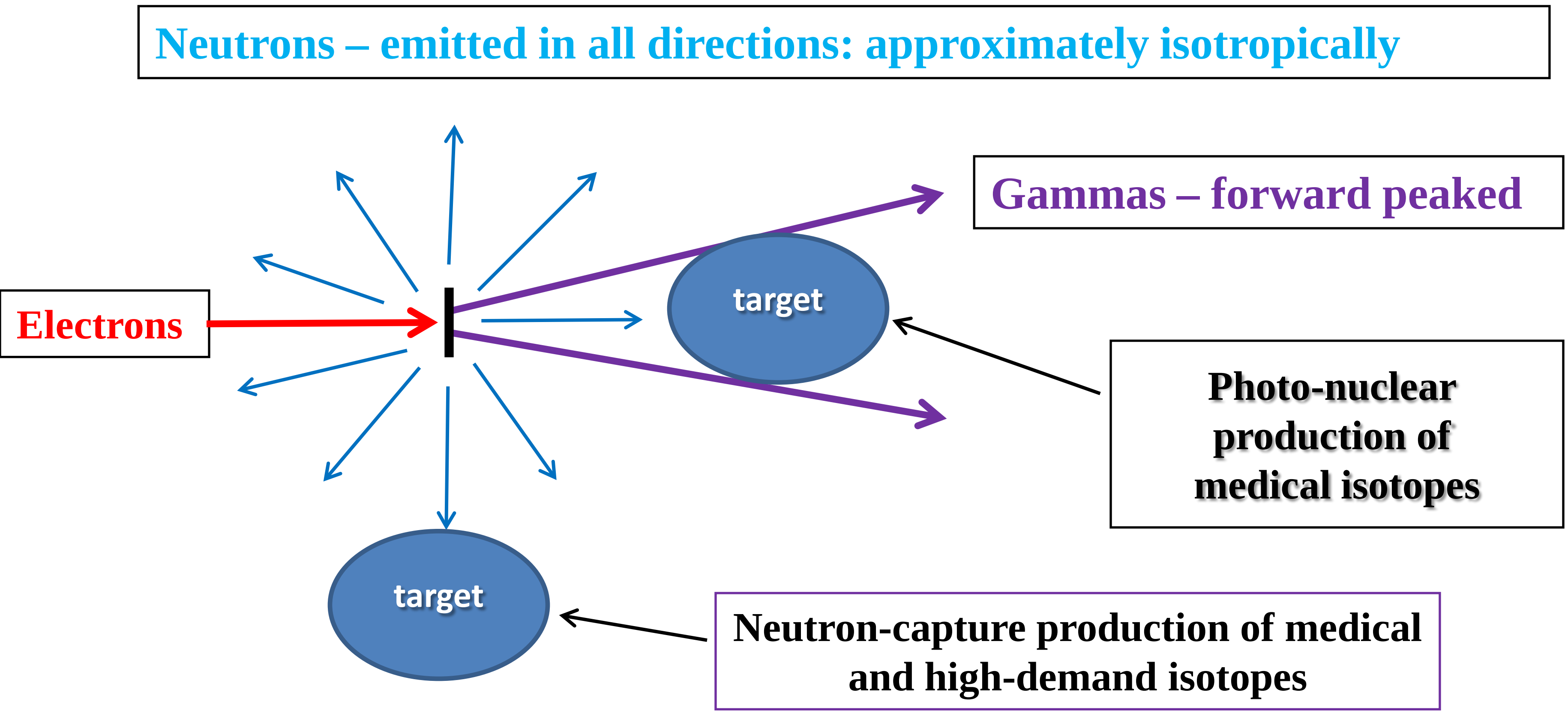


Photo-nuclear burnup of ^{129}I and ^{99}Tc with a 100 kW, 100 MeV e-beam can transmute these species (pure, separated targets) at a rate of approximately 25 kg/yr. U.S. spent fuel ^{129}I inventory is ~2,500 kg ➔ 10 such facilities could transmute this in 10 years. These rates can be boosted considerably with neutron production/reflectors (especially advisable for ^{99}Tc).

Zeroth order ADS:
a bright neutron/gamma source for isotope production



A 100 kW, 100 MeV electron linac is capable of producing 100% or the U.S. demand for many high-priority research isotopes for medical and other kinds of research. Such a device could also produce nearly 10% of the entire U.S. demand for ^{99}Mo.

First and higher-order ADS:
neutron multiplying assemblies with electron linacs

- If N/sec is the number of primary neutrons injected into a fissile assembly the total number of neutrons/sec after multiplication is

$$n = N/(1-k).$$

- The number of secondary neutrons produced by fissions/sec is n-N or

$$N\, k/(1-k).$$

- If N_f is the number of fissions/sec and v is the average number of neutrons released/fission (~2.3) then

$$vN_f = N\, k/(1-k)$$

and the number of fissions/sec is,

$$N_f = N\, k/v(1-k).$$

When the neutron source provides a large fraction of the system neutrons k no longer adequately describes the situation as to multiplication. Factors like source importance, boundary conditions, and neutron spectrum come in to play. A crude way to take these effects into account is to introduce a factor S (S~ 1.3) such that the number of fissions becomes:

$$\mathbf{N_f = S\, N\, k/v(1-k).}$$

<u>The ADS system provides power output that depends on S, N and k only.</u>

First Order ADS with an **Electron Linac:** Simple Example of Power Multiplication

- If $k=.95$ and a 100 MeV electron accelerator (N = 6x10e12 n/s/kWb, kWb is electron beam power) the number of fissions is related to a kW of input beam power as,

- $N_f = 6.4\text{x}10^{13}$ fiss/s/kWb.

- The fission power in this case is: P_{fiss} = 1.9 kW/kWb.

- If one operated at $k=0.98$, instead of $k=0.95$, the fission power is: P_{fiss} = 4.9 kW/kWb.

<u>Second Order</u> (2 coupled multiplying assemblies) ADS with an **<u>Electron Linac:</u>** Simple Example of Power Multiplication

Suppose two multiplying assembles (A1 and A2) are coupled so that some fraction (f) of the fast neutrons created in the first assembly were allowed to serve as the neutron source for the second one. The total number of fission neutrons created in assembly 2 is then: N2- fN/(1-k1), so that the number of fissions in assembly 2 is: $N_2 = fNk_2/v(1-k_1)(1-k_2)$

As an example if $f = 1/2$ and $k_1 = k_2 = 0.95$, fission power in the second assembly will be:

$P_2 = 9.9$ kW/kWb

And if k1 = 0.98, k2 = 0.95, then: $P_2 = 25$ kW/kWb

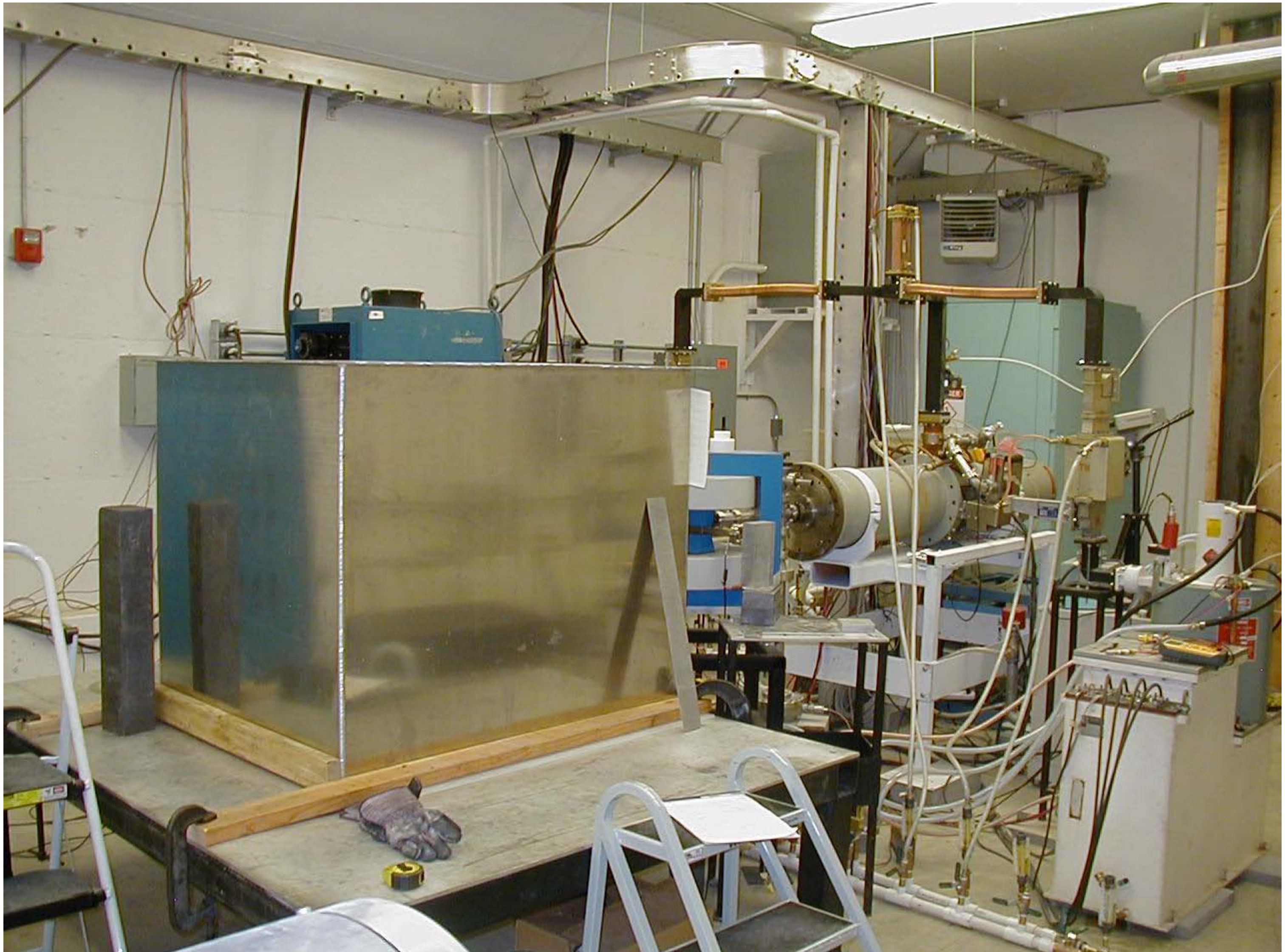
Such a gain would enable electron linac-driven ADS to provide net energy/power output, both electrical and heat, as well as waste transmutation, breeding ^{233}U, producing isotopes and, perhaps most importantly, serve as a U.S. test facility for further advancement of ADS. Further, more detailed analysis ought to be done, particularly regarding the 1-way mirror between the two assemblies that allows fast neutrons from A1 to escape into A2, but does not allow thermal neutrons from A2 to enter A1. Nevertheless, these crude results are very encouraging and suggest electron linac-driven ADS is an important path to pursue.

Work, on a small scale, could begin this winter – IAC is commissioning (to turn on February, 2012) a 10 kW, 50 MeV electron linac (upgradable to 40 kW) for high-power applications:

Follow-on work to U.S. Reactor-Accelerator Coupling Experiment is possible: (RACE, 2003 – 2006) was an ISU-led, DOE-funded research project (with U. Tex., TAMU, UNLV, U. Mich., INL, ANL, LANL, CEA, ECATS)

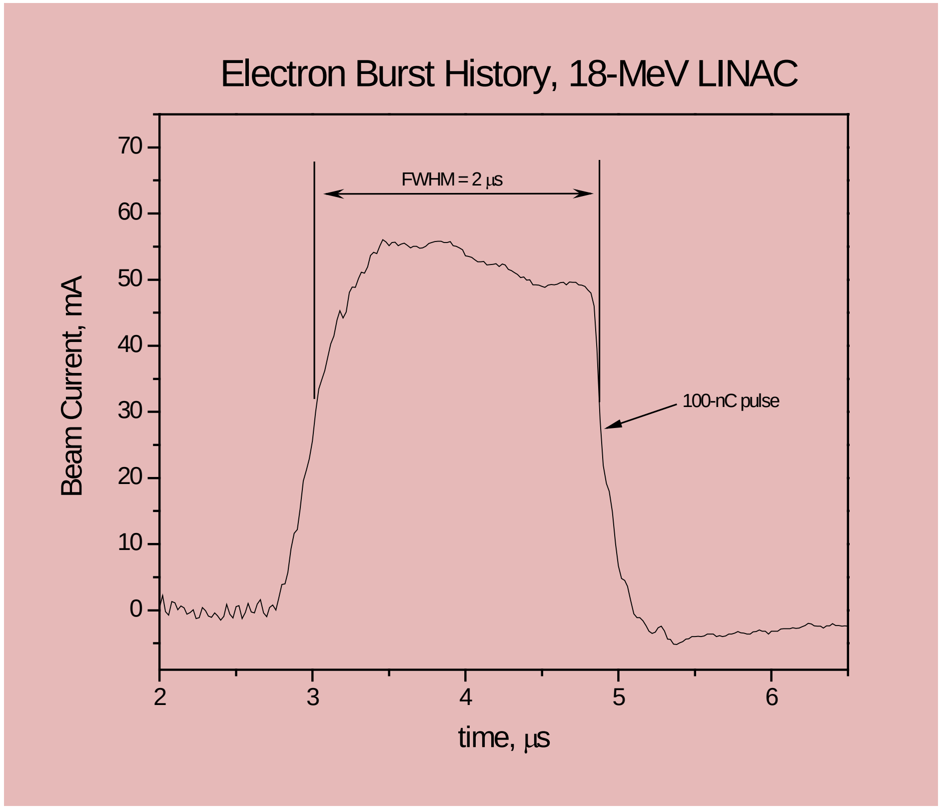
- Design, model, and conduct ADS experiments
- Predict and analyze subcritical multiplication and source-driven transients
- Map source importance & flux
- Study ADS startup and shutdown
- Study dynamic effects of power at different sub-criticality levels (feedback vs. source effects)
- Study start-up/shut-down scenarios
- In general, study all relevant aspects of current/power/importance/control rod relations

Original ISU RACE:
ISU Accelerator and Sub-Critical Assembly:



Original ISU RACE:

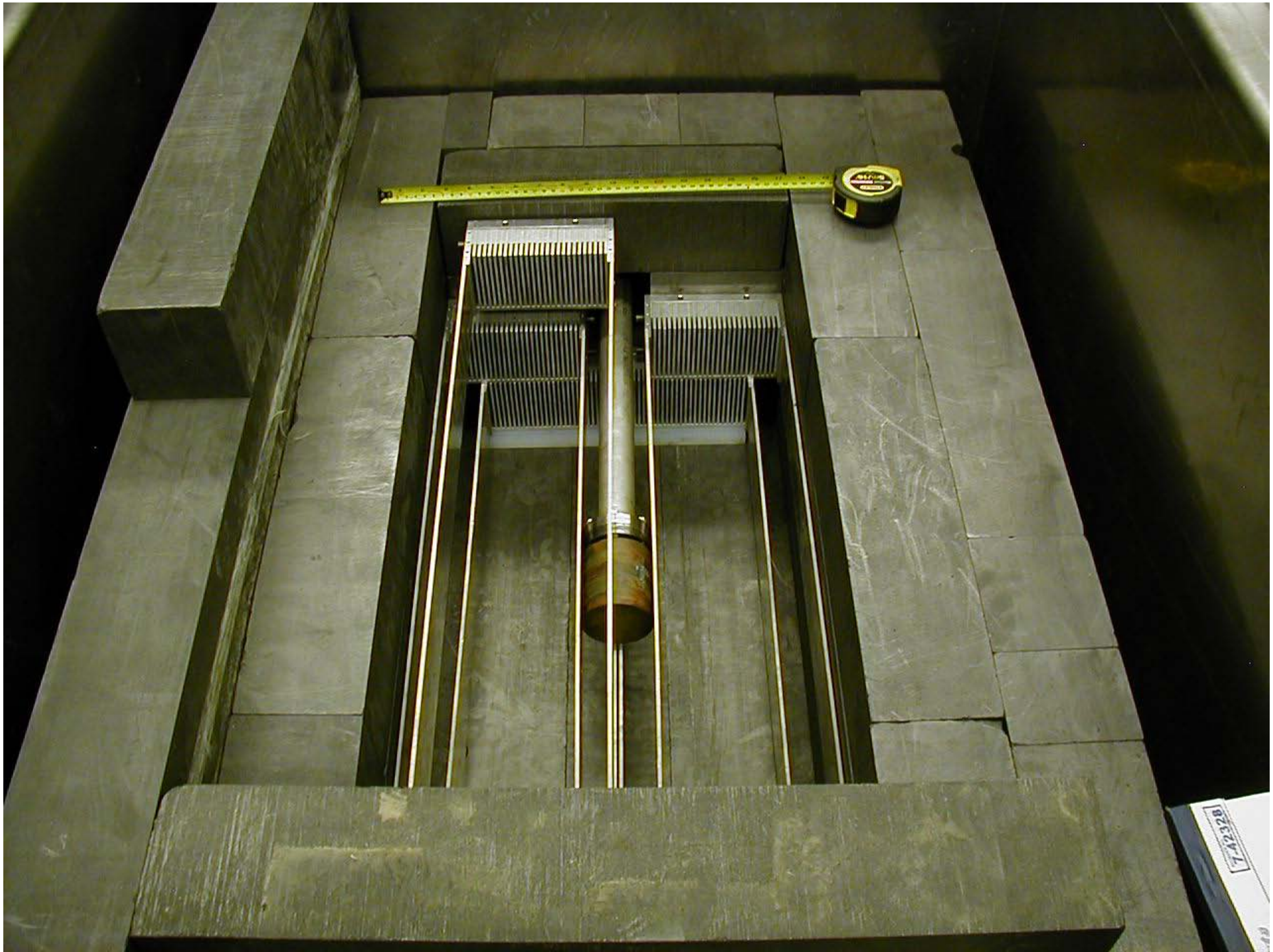
ISU Electron Linac



- Characteristics:
  - 25 MeV
  - 80-100 mA peak
  - 2-5 μs pulsewidth
  - 0 to 100 Hz
- 25 MeV * 80 mA * 5 μs * 100 Hz = <u>1 kW</u>

  → ~1 x 10^{12} n/s

Original ISU RACE fuel trays and target inside the graphite reflector

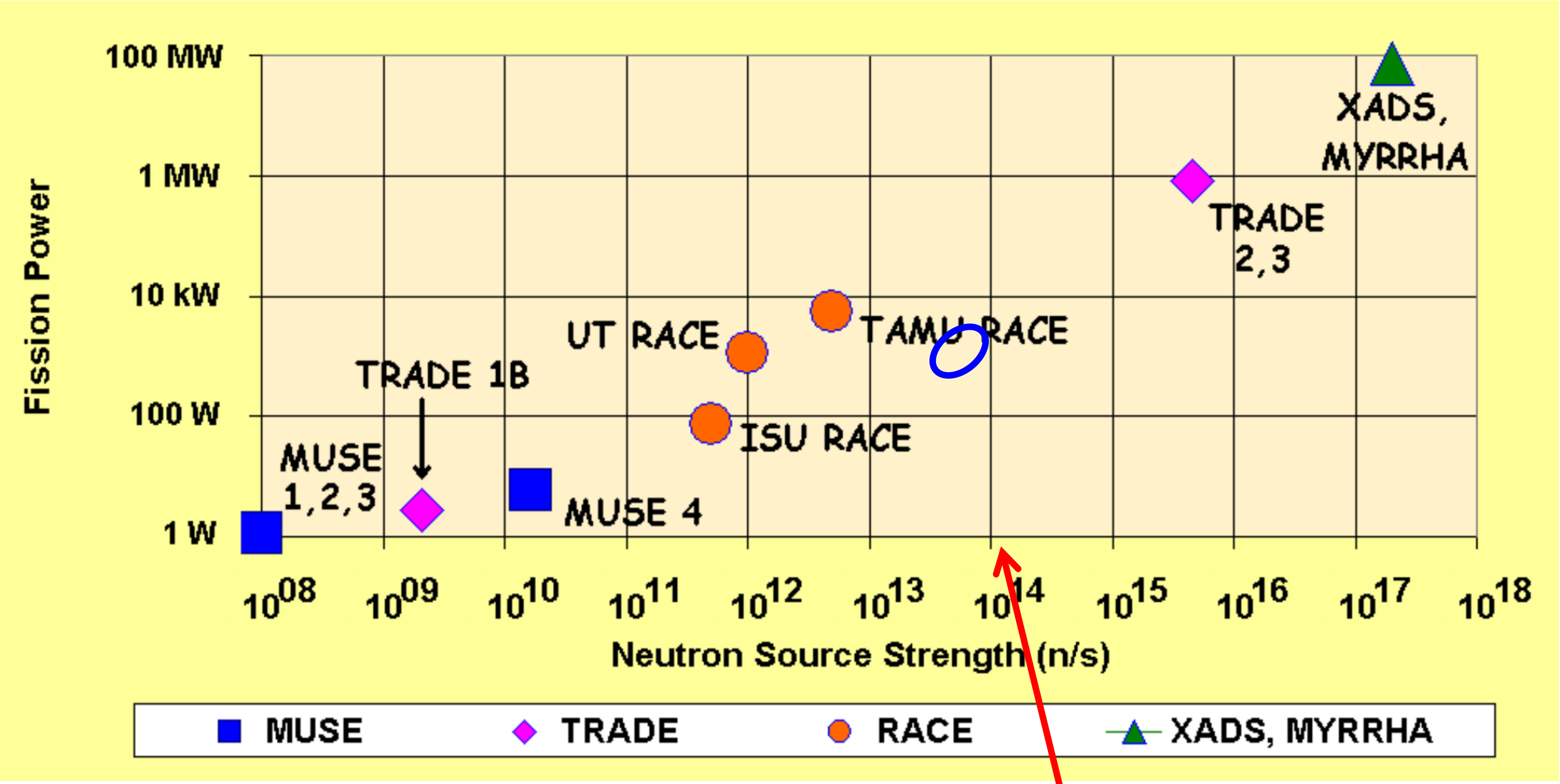


RACE+, the Driving neutron source:

- Original RACE linear electron accelerator:
  - ~10^{12} n/s/kW e-beam @ 25 MeV
  - Intermediate energy: spallation-like spectrum plus small tail up to 20-25 MeV

- Potential ISU high-power RACE+
  - 10-40 kW linac plus U target
  - Potential neutron production up to 10^{14} n/s

Source strength and reactor/fission power comparisons:



?Race+?

Conclusions and Questions

- The speed of advancement and private/governmental support of ADS systems may hinge on how soon practical applications are possible,
- Certain practical applications, such as isotope production and fuel-cycle materials irradiation are practical now,
- Should there be more effort placed in these areas?

Thank You!