Greetings, (from Bruce Vogelaar – September 30, 2010)

During the workshop, concerns arose about the efficiency of accelerators and the impact this could have on ADS systems. The 50% 'wall-plug to beam' efficiency used by GEM*STAR, was reported to be as low as 5% if beams of only a few megawatts were used. (The truth probably lies somewhere in between these extremes). In the GEM*STAR reference case having an overall system electrical multiplication factor of x30, a reduction in accelerator efficiency to 5% would reduce the overall system multiplication by a factor of 10 to an overall system multiplication of x3.

The reason for the low accelerator efficiencies was that while the cost of running the rf scaled with the beam power, the (substantial) cost of running the cryogenics was largely independent of the beam power. Thus, for high beam power the overall accelerator efficiency could be as high as 50%, but for low beam power it dropped very significantly. This prompted some to argue for a single, high-power, accelerator driving several cores, rather and one or two low-power accelerators driving a single core. I feel this argument is incorrect, since the impact of a lower-efficiency accelerator is actually very minimal (as I show below), whereas the reliability of having a high ratio of accelerators to cores is very significant. (Not to mention the advantages of several smaller facilities as opposed to a single monolithic one.)

When examining the overall system multiplication, one can break it into factors *before* beam power on target and those *after* beam power on target, since beam-power on target is likely to be the limiting engineering concern. Those '*after*' factors are the ones of critical concern. As long as there is a large amount of electrical power produced per power on target, one can always feed back a fraction of that electricity to run the accelerator (and doubling that small fraction to accommodate a lower efficiency accelerator is not a high price). The *only* impact 'choice of accelerator and beam energy' have *after beam-on-target* is the average energy-cost per neutron produced by a beam particle interacting in the target (10 MW of 50 MeV electrons is far less effective than 10 MW of 1 GeV protons). [Actual optimization must also take into account amortization of capital costs.]

Let me quantify the above arguments by first calculating the electrical power produced by a given beam power on target (including the thermal energy from the beam itself – although this is a small contribution), from which we then subtract the electrical power needed to run the accelerator (and finally normalize this *net* delivered output power to a unit power on target).

$\epsilon_n \equiv$ energy to create a neutron (about 19 MeV for a 1 GeV proton on Uranium)
$\epsilon_f \equiv$ energy per fission (about 200 MeV)
$n \equiv$ number of fissions per neutron (~3 to 60, depending on burn-up fraction)
$\eta_a \equiv$ efficiency of accelerator (somewhere between 0.05 and 0.50 ?)
$\eta_t \equiv$ efficiency converting thermal to electrical energy (0.44 for GEM*STAR – due to higher temperatures)

$$R = \frac{\text{Electric Power Produced – Power to run accelerator}}{\text{Power on target}} = \frac{\text{Net electrical energy output per proton}}{\text{Energy per proton}}$$

$$= \frac{\left(E_p + E_p \frac{\epsilon_f}{\epsilon_n} n\right)\eta_t - E_p/\eta_a}{E_p} = \left(1 + \frac{\epsilon_f}{\epsilon_n} n\right)\eta_t - \frac{1}{\eta_a} \equiv A - B$$

for a typical case at 50% accelerator efficiency, we would then have:

$R = \left(1 + \frac{200}{19} 15\right) 0.44 - \frac{1}{0.5} = 68$ (net MW electric output per MW beam on target) and at 10% accelerator efficiency we would have:

$R = \left(1 + \frac{200}{19} 15\right) 0.44 - \frac{1}{0.1} = 60$ (net MW electric output per MW beam on target)

Note that the 'beneficial' (resulting in output to the grid) use of the fuel burn-up fraction is no longer 1.0, since some of the produced electricity now is used to drive the accelerator. The percentage going to 'beneficial' use is given by: $P = 100(A - B)/A$ where A and B are defined above.

Here are the results for this scenario as a function of accelerator efficiency:

η_a (accelerator efficiency)	R (net MW electric output per MW beam on target)	P (% beneficial use of fissioned fraction)
0.05	49.9	71.4
0.10	59.9	85.7
0.15	63.2	90.5
0.20	64.9	92.8
0.25	65.9	94.3
0.30	66.6	95.2
0.35	67.1	95.9
0.40	67.4	96.4
0.45	67.7	96.8
0.50	67.9	97.1

You notice that even as you drop the accelerator efficiency from 50% to 20%, the final output of electrical power to the grid compared to the beam power on target only falls from 68 MW/MW to 65 MW/MW, while the beneficial use of burning the fuel falls from 97% to 93%. So while the 'Green' energy multiplication (using an *external* source of electricity for running the accelerator) falls by a factor of 2.5, the penalty for using self-generated electricity to run the accelerators is truly insignificant.

From a 'marketing' perspective, one could view GEM*STAR as a 'black-box', where the required cryogenic power (which does not scale with beam power) is simply an intrinsic, self-satisfied, load on the GEM*STAR system (as would be its circulation pumps, etc). In this case, the 'input' to the 'Green Energy Multiplier' would be the power needed to run the accelerator ***rf*** and the 'output' would be the net electrical power out. This would result in a large 'multiplication' factor. (Completely legitimate – just better packaging.) Obviously, the rf power could also be provided internally (reducing the net output a small amount), should no green energy source be available.

Coming back to the original question – the arguments presented above indicate there is no need to have a high-powered accelerator driving several reactor cores due to accelerator efficiency concerns. In fact, having one or two low-power accelerators driving a single core is much more reliable, and the final accelerator selection will be a balance between capital plus operation costs versus the value of net electricity output. Accelerators have just gotten *so* good that a factor of two in their efficiency is not determinative in the GEM*STAR context where the electricity produced by beam-on-target is so high. This is *not* the case for most transmutation schemes, which do not produce significant electrical energy, and where accelerator efficiency has a linear impact on their efficacy.