Background information on the HIF program requested by LBNL Director Chu

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Synopsis of history, motivations, and criticisms (and responses) July 22, 2005

<u>Perceptions of the heavy ion program are shaped in part by its history.</u>
($ and dates approximate. $ = then-current $)

- Al Maschke (BNL) proposed heavy ion fusion (HIF) around 1973, a few years after John Nuckolls/Lowell Wood paper proposed inertial fusion with lasers. Premise: high energy particle accelerators had the energy, beam quality (emittance), durability, pulse rate and efficiency desired for inertial fusion energy (IFE), but not the >100 TW of peak beam power on target. *R&D needed to address cost, beam compression and focusing with space charge.*
- LBNL began its HIF program around 1976 with a BES budget around $1-2 M/yr. Technical focus was on developing multiple beam induction linacs.
- Several HIF reactor design studies published in 1982 indicated $1 B direct cost accelerator drivers ($2B total capital cost), thought to be OK at the time (competitive with then-current "competition" of 1 GWe nuclear plants).
- During the energy crisis years the LBNL HIF program grew to about 8M/yr.
- In 1990, the Fusion Policy Advisory Committee recommended the HIF program and $8M/yr transfer to the Office of Fusion Energy from BES, *recommended HIF as more durable, efficient, and higher pulse rate vis-à-vis lasers, and recommended the HIF budget grow to $25M/yr.* LBNL proposed the 45M TEC Induction Linac Systems Experiment (ILSE), a four beam induction linac with10 MeV, 5 J energy for 1 μs pulses. Also around 1990, LLNL developed targets, chambers, and novel accelerators for HIF with LDRD funding. *The fusion budget was declining year-to-year, the HIF budget never grew, and ILSE was never funded despite favorable reviews.*
- While ITER (first conceptual design phases and R&D) funding grew to > $60 M/yr by 1994, (out of a total fusion budget of 340 M/yr), the HIF budget dwindled to $4M/yr, and was marked for closeout in 95. *HIF closeout was avoided because a 1993 FESAC panel had strongly supported the program, and because the Congress ordered US participation in ITER to stop completely (due to its killing off domestic fusion science).*
- 1997 First US-Japan exchange in inertial fusion was approved because heavy ion fusion was DOE civilian science-funded, not DOE weapons-funded.
- In 1999 Mike Campbell (LLNL) and Rob Goldston (PPPL) proposed a joint MFE-IFE program of research. Congress appropriated a $36M fusion budget increase for OFES (the first increase after a decade), a third of which went to IFE the next year. *In Dec 1998 Mike Campbell also arranged a MOA between LLNL and LBNL HIF research programs to form the HIF-VNL.PPPL joined a year later.*
- HIF funding grew to $11.3 M/yr in 2000, applied to development aspects for a proposed $300 M Integrated Research Experiment, a 32 beam, 200 MeV induction linac prototype.
- March 2001. OFES (Davies) tells the new HIF-VNL Director Logan "Forget the IRE. Fusion funding and your budget is unlikely to grow. Tell me what important science you can do for flat funding". The HIF-VNL proposed a new three year plan (2002-04) focused on beam physics in injection, high current transport, and neutralized beam focusing. *Science goals in that three year plan were successfully completed in 04 despite 13% budget erosion.*
- Fusion Snowmass Workshop 2002: We proposed the Integrated Beam Experiment, a single beam, 5 MeV induction linac designed to test the beam physics of acceleration, compression

and focusing for $50M TEC. *We found favorable fusion community support, and this led to IBX being included in the DOE 20-year facilities list.*

- May 2003. Orbach visits LBNL, tells Shank/Barletta that IFE will not be supported by SC until NIF gets ignition, but what could LBNL do for High Energy Density Physics? *We invented neutralized drift compression and focusing concept to meet this challenge.*
- March 2004. The HIF-VNL was ordered to redirect effort towards near term goal of HEDP (1 eV threshold in targets). *We proposed the Neutralized Drift Compression Experiment to meet this goal in five years with current funding of $10M/yr plus $5 M in new hardware.*
- July 2004 The National Task Force on HEDP identified heavy-ion beams as one of 15 major opportunities for discovery in HEDP. (*See Task Force Report attached*)
- February 2005: *We exceeded our two year goal of 10 X compression after only two months of operation of NDCX.* The President FY06 request reduced HIF by >60 % due to ITER.

<u>Motivations for heavy ion fusion</u> (in context of inertial fusion energy IFE):

(a) High energy particle accelerators of MJ-beam energy scale have separately exhibited intrinsic efficiencies, pulse-rates, average power levels, and durability required for IFE. *Advantage of being able to build upon a credible HEP accelerator experience base.*

(b) Thick-liquid protected target chambers with 30 year plant lifetimes, compatible with indirect-drive target illumination geometry to be tested in the National Ignition Facility. See Snowmass 2002 white paper reference. *Avoids the need for a long materials development program (that doesn't currently exist in the world) to qualify fusion structures that would otherwise have to suffer > 100 displacements per atom per year due to fast 14 MeV neutrons. The toroidal geometry of Tokamaks and the required spherically-distributed beam illumination for laser driven direct drive are both incompatible with cylindrical liquid protected cavities.*

(c) Focusing magnets for ion beams avoid direct line-of-sight damage from target debris, neutron and gamma radiation. *In contrast, solid final optics in laser systems are highly vulnerable to intense laser damage after micron-size debris contamination from the target chamber.* NIF plans to replace final optic debris shields (sacrificial glass covers) every shot if necessary. Unlike MFE, accelerator as well as laser drivers are well separated from fusion chamber neutrons.

(d) Several heavy ion power plant studies have shown attractive economics (competitive CoE with nuclear plants) and environmental characteristics (no high level waste; only class-C low level waste). *Advanced deuterium targets based on ion fast ignition with liquid boron-oxide vortex blankets may virtually eliminate tritium and other radioactive inventories.*

(e) HIF targets driven indirectly by x-rays within hohlraums can utilize much of the same target physics data to be generated by the NNSA ICF program. *Leverages large NNSA supported target physics effort, so OFES can concentrate on driver beam R&D.*

(f) Cryogenic-DT fuel capsules in HIF targets would be protected by the surrounding hohlraum when injected into hot IFE chambers. *Laser direct drive capsule survival in a hot IFE chamber has been likened to "snowballs in hell".*

(g) HIF plays to US strengths. In contrast to magnetic fusion, the US is the clear world leader in inertial fusion. Diversity of domestic fusion research, as you have argued for, should make IFE THE leading alternative to the Tokamak in the US program.

<u>Long time criticisms of heavy ion fusion</u> *(& and what we are doing about it)*

(1) You've have never hit a target! (with IFE relevant peak power and range ions).
True. GSI had focused 40 GeV heavy ions into mm targets, but with negligible space charge (not considered IFE-relevant). We had higher current beams but at too low an energy to compress and focus against space charge. We proposed facilities to increase the beam ion energy, but never got the funding for ILSE, IRE, or IBX to allow us to try to hit a target.

When Orbach challenged us to do HEDP, we knew we had an even greater challenge to compress ion bunches down to 1 ns. We invented plasma neutralized beam drift compression and focusing (NDC). We have demonstrated > 50 X bunch compression down to 3 ns so far, compressing 20 mA beams to ~ 1 A, and we plan to repeat that in NDCX-II starting with 20 X higher beam current. If successful, a $5M hardware upgrade to NDCX-II should deliver 1 eV high energy density physics threshold conditions in targets in 5 years.

(2) <u>Large Projected Power Plant Cost</u> Perception: Advocates familiar with large HEP-size accelerators were comfortable with HIF accelerator driver designs dwarfing the target chamber, but utility execs were incredulous. Advocates pointed out power plant studies showing HIF CoE competitive with GWe nuclear plants and Tokamaks. Critics answered "We don't need more multi-billion-dollar power plants of *any* kind- the future electricity market will need small modular 100MWe units."

We have looked at future needs for transportation fuel (hydrogen) instead of the current electricity market, recognizing the 10 X larger scale of the fuel market could better utilize IFE with strong economy-of-scale. We performed NREL-type energy pathway analysis to show that refinery-output scale (10 to 20 GWe size equivalent) multi-chamber HIF-IFE plants could produce electricity and hydrogen by electrolysis for transportation competitive with current gas turbine generators and gasoline from 20 $/bbl oil. We are also evaluating how to apply neutralized drift compression to HIF-IFE, and if successful, the technique should lower the cost of HIF-IFE as well as expedite HEDP.

(3)<u>Too expensive development path with insufficient science payoff along the way</u>
The defining heavy-ion driver IFE prototype was to have been the $300 M Integrated Research Experiment (IRE), a bundle of 32 beams inside a large common induction accelerator bore. DOE-OFES does not want to consider any HIF development step of that scale. Because of projected funding constraints in SC, even the $50M Integrated Beam Experiment (IBX) is placed beyond 2014 in the DOE Future Facilities Plan.

We are looking at the possibility of a more affordable modular development path, accepting new risks and opportunities in doing do: a new IRE design might become a single beam linac like NDCX-II using lower mass ions to reduce linac voltage, length and cost. Neutralized drift *compression and focusing might allow focusing to the target with lower kinetic energy ions. A single module might validate a full driver consisting of 20 to 40 such linacs in parallel. We have also invented (August 2004 LBNL Patent Disclosure) a unique new, high gradient linac using a co-axial architecture with a helical central conductor, called the Pulsed Line Ion Accelerator (PLIA), which may allow multiple pulses of short ion bunches accelerated at high gradient. Along this new development path, we plan to offer science users access to our facilities High Energy Density Physics, beam physics, plasma physics, and surface physics experiments. The cost and schedule for this approach is reasonable and affordable-see Figure below from the National Task Force report of July 2004, section 3.2:*

Figure 3.1: Timeline and Resource Requirements for Heavy-Ion Driven HEDP/fusion

Science Areas	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15
High Brightness Beam Transport	4 quadrupoles 4 solenoids		Upgrades (larger and more magnets)			Upgrades of injectors and diagnostics to further reduce beam temperature					
Longitudinal Beam Compression	10x compression		100x compression with 10x focusing			Active beam correction experiments to explore potential 1000x compressions					
Focusing onto Targets	Large plasma source		Plasma lens and time dependent corrections			Advanced focusing experiments e.g., induced self-pinching					
Beam-Target Interactions			Target design and fast beam diagnostics			Beam energy loss and deposition profiles, target $T_e(t)$ $n_e(t)$ diagnostics and modeling					
Advanced Theory and Simulations	Source to target models					Source through target models					
Estimated resource needs	$12 M/yr		$14M/yr			$16M/yr					

2yr Milestones:
A2: 10x neutralized compression
B2: Gas/electron limits in 4 magnets

5yr Milestones
A5: 100x neutralized compression and focusing
B5: Gas/electron predictive capability for HEDP accelerators

10yr Objective:
Beam and target physics knowledge base for heavy-ion-driven HEDP user facility

(4) Why is the US the only country interested in HIF? Most people are unaware that GSI has also pursued HIF over 2 decades. The GSI group and HIF advocacy is still there, although not so visible, because 6 years ago the German Government told the GSI group IFE was not allowed, only basic research (dense plasma science). This was the result of the European magnetic fusion mafia telling Bonn that inertial fusion was a US weapons program, even while they knew it had already been declassified by DOE Secretary Watkins. The real reason was European fusion program was not then and still not interested in supporting any alternatives to the Tokamak. There is a similar tendency going on now here in the US because of financial stresses created by the US trying to re-enter ITER. Meanwhile, over the past 6 years, significant new heavy-ion research activities have built up at ITEP in Moscow, and at TIT and RIKEN in Japan, although those are not yet as large as the US program. There is now US-Japan exchanges in heavy-ion fusion.