INDUSTRY ROLE FOR ADVANCED ACCELERATOR R&D

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Abstract

Besides large research institutes which typically focus on fundamental research, industrial companies can also contribute to the development of advanced applications of accelerators as well as to fundamental accelerator technology. The funding of advanced or fundamental R&D, which is usually high-risk but potentially high-reward, is difficult to obtain for any organization, especially smaller industrial companies. As an example of one funding approach, I discuss the role of industrial companies in the field of accelerators and present several examples from my own experience of advanced R&D performed by industry under the United States Department of Energy Small Business Innovation and Small Business Technology Transfer Research (SBIR-STTR) Grant programs.

SBIR-STTR GRANTS

Starting in 1982, the United States Congress has passed legislation that taxes part of the budgets of larger cabinet-level Departments (e.g. Energy, Transportation, Homeland Security, Defense, etc.) at about 3% to fund Small Business Innovation & Technology Transfer Research (SBIR-STTR) Grants [1].

SBIR-STTR programs have had evolving goals that were inspired originally because small businesses were considered more innovative than government laboratories judging by Intellectual Property (IP) generation per employee and inspired more recently because small businesses are thought to be drivers of job growth.

Original Charter:

- Stimulate technological innovation
- Use small business to meet Federal R/R&D needs
- Foster and encourage participation by the socially and economically disadvantaged small businesses, and those that are 51 percent owned and controlled by women, in technological innovation
- Increase private sector commercialization of innovations derived from Federal R/R&D, thereby increasing competition, productivity, and economic growth

Today the programs have evolved to have greater emphasis on commercialization and have added goals and requirements:

- Require evaluation of commercial potential in Phase I and Phase II proposal applications
- Like seed capital for early stage R&D
- Awards comparable to private angel investments
- Accept greater risk in support of agency missions

Each Department of the government has some flexibility in how they implement the legislation. The Department of Defense, for example, usually intends to buy the products that are developed by SBIR-STTR projects and they are usually interested to have the successful companies be long-term suppliers of equipment that they need.

The Department of Energy, where most particle accelerator R&D is done, does not now have that approach in that they rarely buy equipment and favor first-time applicants of the smallest companies.

Each year, each Department issues a Funding Opportunity Announcement (FOA) stating what topics small businesses should propose for grants according to the needs of the Department. In the Department of Energy, small companies (<500 employees) submit proposals for SBIR-STTR grants, which can have labs or universities as research partners. STTR grants require that >30% of the R&D funds go to a lab or university research partner, while SBIR grants do not require a research partner or have subgrant funding limits.

These proposals are reviewed by 4 (3 technical + 1 commercialization) experts for 9 month Phase I grants for up to $150,000 to show the proposal is valid. On average, only one in five to ten Phase I proposals is granted. If the Phase I project shows that the concept is valid, you can then propose a 2-year Phase II project (up to $1 M) that is reviewed by (probably) the same 4 reviewers. One out of two Phase II proposals is granted, such that the total chance of getting both Phase I and Phase II funding is between one in ten to one in twenty.

Phase III corresponds to additional funding outside of the SBIR-STTR program for continuing work based on the output of the Phase I and II grants, independent of whether the funding goes to the company.

Since 2002, Muons, Inc. has been funded by DOE contracts and SBIR-STTR grants to invent and develop tools and technology for particle accelerators with eight different US universities and nine different national labs as research partners. In the following sections, several examples are discussed of the innovations that a small business can bring to important problems of accelerator technology and applications.

MUON BEAM COOLING

Ionization cooling [2] is the simple idea that was the inspiration for many SBIR-STTR projects described below.

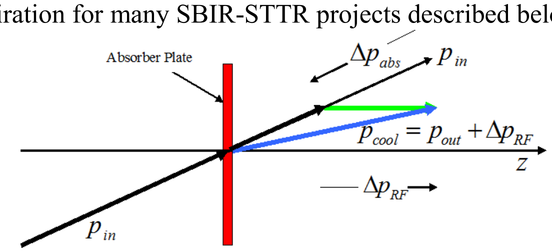

Figure 1: Principle of Ionization Cooling.

Figure 1 shows the momentum vector of a charged particle losing momentum by ionizing material in an absorber plate. After losing momentum in the absorber, an RF cavity restores only the longitudinal momentum, causing the angle of the particle trajectory relative to the Z axis of the closed orbit to be reduced. Thus ionization cooling

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only reduces the angular divergence of a beam. To also reduce the transverse size of the beam takes another absorber and RF cavity 90 degrees in betatron phase advance from the first absorber and cavity.

The expression for the rate of emittance reduction in each transverse plane is given by

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}$$

Here ε_n is the normalized emittance, E_μ is the muon energy in GeV, dE_μ/ds and X_0 are the energy loss and radiation length of the absorber medium, $\beta_\perp$ is the transverse beta-function of the magnetic channel, and β is the particle velocity. The cooling effect shown in Figure 1 is expressed mathematically by the first (negative) expression on the right side of the equation and the heating term is the positive expression on the right that is the usual expression for emittance growth due to multiple Coulomb scattering.

Table 1: Muon Beam Cooling and Applications

Year	Completed Project	Funds	Research Partner	Phase III
2002-5	High Pressure RF Cavity	\$600,000	IIT Kaplan	\$445,000
2003-7	Helical Cooling Channel	\$850,000	JLab Derbenev	\$3,100,000
2004-5	MANX demo experiment	\$95,000	FNAL Yarba	\$22,230
2004-7	Phase Ionization Cooling	\$745,000	JLab Derbenev	
2004-7	H2Cryostat - HTS Magnets	\$795,000	FNAL Yarba	\$1,400,000
2005-8	Reverse Emittance Exchange	\$850,000	JLab Derbenev	
2005-8	Capture, ph. Rotation	\$850,000	FNAL Neuffer	\$198,900
2006-9	G4BL Simulation Program	\$850,000	IIT Kaplan	\$8,732,479
2006-9	MANX 6D Cooling Demonstration Expt	\$850,000	FNAL Lamm	\$495,630
2007-10	Stopping Muon Beams	\$750,000	FNAL Ankebrandt	\$410,488
2007-10	HCC Magnets	\$750,000	FNAL Zlobin	\$255,000
	Completed Projects	\$7,985,000		\$15,059,727

H_2 Pressurized RF Cavities

The first Muons, Inc. STTR award [3] follows from the equation above with the idea that the best material for maximum cooling should have the largest dE_μ/ds and X_0 possible to maximize the cooling and minimize the heating terms. Since muons decay, to get the most compact cooling channel we proposed that the energy absorber and RF energy replenishment occupy the same real estate by using RF cavities filled with pressurized hydrogen gas, which has the highest dE_μ/ds times X_0 of all gases. An added bonus to those features is that the pressurized gas suppresses RF breakdown. As we showed later, pressurized cavities operate well in the very high magnetic fields that are needed to reduce $\beta_\perp$ in the equation above.

Table 1 shows the 8-year 11-grant funding history that followed from this innovative proposal. The research partner institution and subgrant Principal Investigator (PI) are also shown in Table 1 along with total Phase I and Phase II funding and Phase III funding. Since the Phase III funding was almost twice as much as the SBIR-STTR contribution for this period, we believe that this approach was a bargain from every point of view. The DOE leveraged their funds and, as we shall show, now have an innovative, affordable, solution to the problem of muon beam cooling that can be used for many applications including stopping muon beams for rare decay searches and muon colliders for Higgs factories and energy-frontier studies.

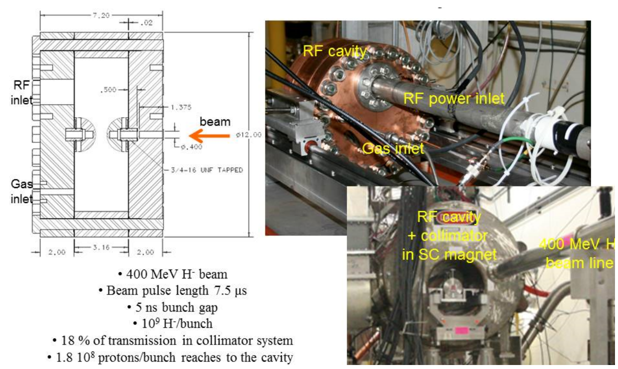

Figure 2: Beam tests of a GH2 pressurized RF cavity in a 5 T magnet at the Mucool Test Area at Fermilab.

Figure 2 shows the experimental set-up that was used to verify the operation of a high-pressure GH2 RF cavity in a strong magnetic field with the 400 MeV H-minus beam from the Fermilab linac [4]. It was shown that a small oxygen dopant in the hydrogen was enough to attach the ionization electrons created by the beam. Since the electrons become attached to the oxygen molecules, they are relatively immobile and do not move far enough in the RF field to collide with and lose energy to the hydrogen gas in the cavity. Without the dopant, the effective cavity quality factor becomes too low for efficient operation.

This experimental work was only possible for a small company through the cooperation of a national laboratory to allow the use of several million dollars of its equipment, beam time, and personnel. An unexpected beneficial outcome of this work to Fermilab was a new kind of radiation-tolerant beam profile monitor needed for its Long Baseline Neutrino Facility, also funded by an STTR grant reported at this conference [5].

Helical Cooling Channel

The second STTR grant was based on the innovation that is shown in Figure 3 that follows from the idea that filling the muon cooling channel with pressurized hydrogen allows a new way to exchange transverse and longitudinal emittances. In this figure, muons are dispersed by a dipole field and either pass through a wedge absorber shown on the left or lose energy by ionization of the gas

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as shown on the right. The longer path length and corresponding larger energy loss for the gas-filled cavity for higher momentum muons generates longitudinal cooling at the expense of transverse emittance growth, which can be cooled by ionization cooling.

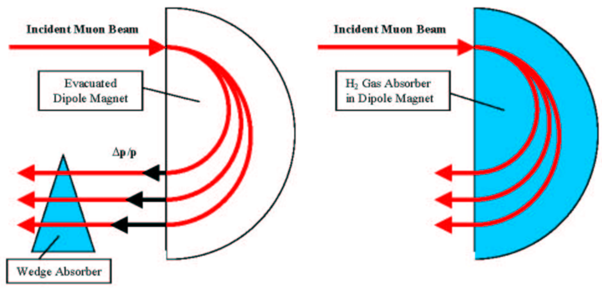

Figure 3: Old (left) and new (right) emittance exchange.

Slava Derbenev, one of the inventors of the Siberian Snake method that uses a helical dipole magnet to control the polarization of beams in an accelerator, had used helical dipole and solenoid fields to develop an elegant theory for a muon beam helical cooling channel (HCC). When we met at Jefferson Lab and he learned that pressurized RF cavities were possible, he suggested that we revisit his theory that was developed using wedge absorbers and consider a continuous energy absorber instead [6]. Figure 4 shows the HCC and indicates how the particle motion is described by a Hamiltonian that has two opposing radial forces. The expressions that follow from this approach allow one to optimize the parameters of a cooling channel analytically rather than by trial and error.

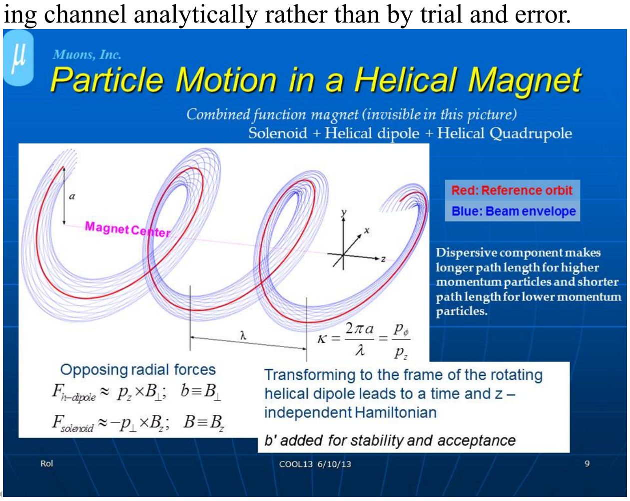

Figure 4: Particle motion in a Helical Cooling Channel.

Helical Solenoid

The HCC theory was developed using analytical expressions for the magnetic fields that contained solenoid, helical dipole and helical quadrupole fields. The concept of the helical solenoid, which can provide the needed magnetic fields in a very elegant and simple way, is shown in Figure 5. It was invented as part of an STTR project with the Fermilab Technical Division [7].

Unlike a bent solenoid, the almost circular coils shown in the figure are in parallel planes. The centers of the coils follow the closed orbit of the muon beam. Subsequent grants were used to design and build HCC helical solenoid section made from YBCO and Bi2212 high temperature superconductor that could provide extremely high fields when operated at low temperature [8]. STTR grants were used to develop concepts for fiber optic quench detection and protection systems for these expensive and easily damaged magnets [9].

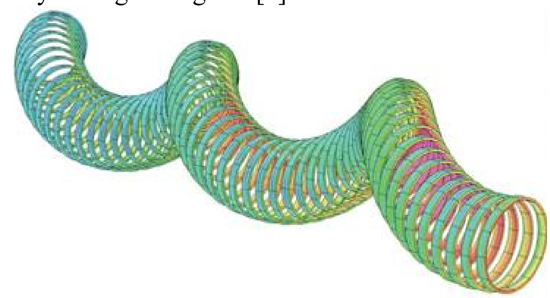

Figure 5: Helical Solenoid Magnet.

G4beamline Interface to GEANT4

Numerical simulations of muon beam cooling using GEANT4 [10] have been greatly expedited by our G4beamline [11] program as shown in Figure 6. This program was supported by an STTR project shown in Table 1. As such, the program can be freely downloaded from our web site. Many people have done this and have responded to surveys that show how useful it has been, especially for any accelerator problem that involves the passage of particles through matter. The surveys made a couple of years ago have been used to estimate the non-SBIR-STTR usage that we have claimed as Phase III effort that followed from this grant.

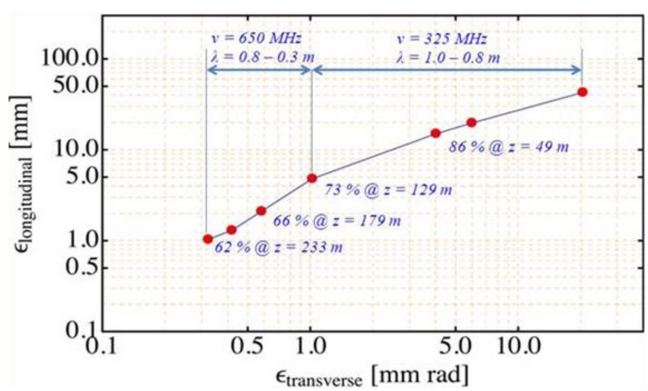

Figure 6: Muon beam emittance and survival evolution for a HCC as simulated using G4beamline.

The success of G4beamline and the need that we have for other simulation programs to develop concepts of accelerator-driven subcritical nuclear reactors have inspired a successor to G4beamline that is called MuSim. Figure 7 shows a screen shot of the MuSim interface and event display of a proton that enters the GEM*STAR reactor [12] and hits an internal spallation target to produce many neutrons and photons. MuSim can be downloaded from our website and has been tested as a useful interface to G4beamline and MCNP6.

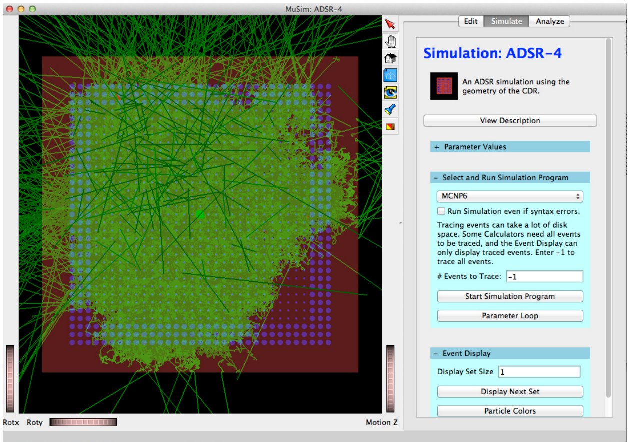

Figure 7: MuSim screen shot of an event in GEM*STAR.

Skew Parametric-resonance Ionization Cooling

The best HCC cooling simulation results using G4beamline indicate emittance reduction of almost 6 orders of magnitude. One interesting aspect of Figure 6 is that the final longitudinal emittance of 1 mm corresponds almost exactly to the 4 MeV expected width of the Higgs boson. This means that the Higgs particle can be made in a small muon collider by means of an s-channel resonance to test the theory in a unique and precise way.

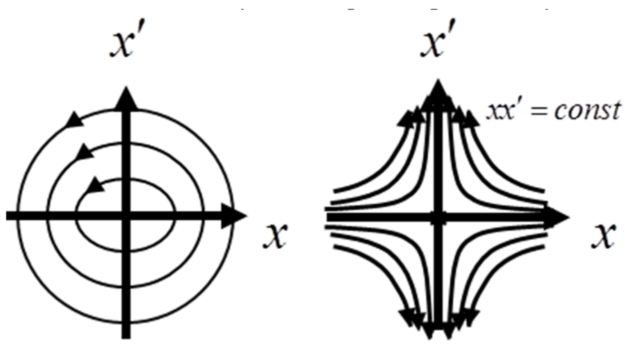

Figure 8: Parametric-resonance Ionization Cooling.

Figure 8 demonstrates the concept of Parametric-resonance Ionization Cooling (PIC), where the usual elliptical motion of particles in an accelerator or beam line (left) is changed to hyperbolic motion (right) under the influence of a parametric resonance [13]. Particles move to smaller position and larger angle; the growth to larger angle is constrained by ionization cooling as seen in Figure 1. When added to the cooling shown in Figure 6, PIC has the potential to reduce each transverse emittance an additional factor of 10. If we can accomplish this, a muon collider Higgs factory will become a compelling option for the next significant machine to be built. The aberration corrections needed to make a practical cooling channel are being studied under an STTR grant with Jefferson Lab using skew quadrupoles to reduce unwanted resonance driving terms by coupling transverse degrees of freedom [14].

COMPONENT AND DESIGN EXAMPLES

Magnetron Power Sources

Mu*STAR, Inc. [15] has been formed to support the development of GEM*STAR reactors that are driven by powerful superconducting RF linacs. One of the big cost-drivers of such linacs is the cost of RF power, which up to now has been from klystrons or IOTs. The magnetron power source was invented almost a century ago and is well-known as the most inexpensive (around $1/W), efficient (up to 90%), and convenient RF source (e.g. for popcorn).

However, magnetron power sources are effectively oscillators that typically cannot be controlled in phase, frequency, and amplitude with the precision required to power SRF cavities for most applications.

Figure 9 shows the 1497 MHz magnetron design [16] that is being built as a replacement for the CEBAF klystrons as part of an STTR project with Jefferson Lab. A large part of the project involves the innovative control system that deals with noise-induced microphonic distortions of the RF cavity shape that cause the resonant frequency of the cavities to change.

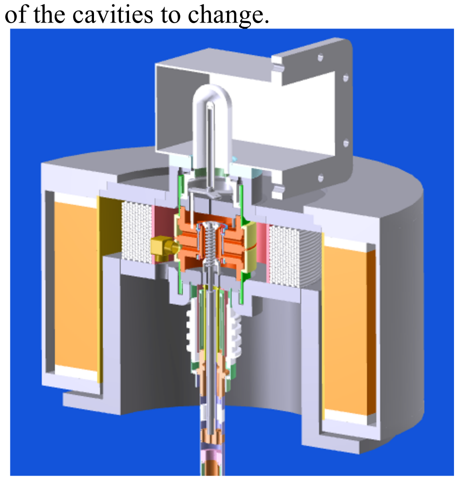

Figure 9: 1497 MHz klystron design.

Another magnetron project is under way for a replacement for 350 MHz tetrode power sources. Figure 10 shows the copper anode structure just after electrical discharge machining. While not directly supported by SBIR-STTR grants, the enthusiasm for this project was generated by an earlier grant to develop phase and frequency-locked magnetrons.

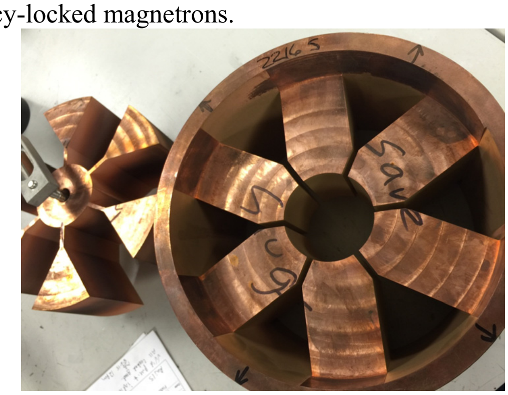

Figure 10: Anode structure for a 350 MHz magnetron.

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Ion Sources

Figure 11 compares the usual solenoid antenna RF source configuration with the saddle-antenna innovation that is the basis of an SBIR project [17] with ORNL to improve the H-minus source at the SNS. Not shown is an external magnetic field that is aligned with the axis of the cylindrical discharge chamber.

In the RF discharge with solenoidal antenna the plasma is generated near the coil and diffuses to the axis while creating a nearly uniform plasma density distribution in all cross sections of the discharge chamber as shown in Fig. 11a. In the RF discharge with the saddle antenna the plasma is generated near the axis and the magnetic field suppresses the plasma diffusion from the axis, creating a peaked plasma density distribution as shown in Fig. 11b. With the saddle antenna, the RF power needed is reduced because the volume of the plasma is reduced and plasma is more concentrated on the ion-forming metallic ring on the axis. This improved efficiency should increase the source lifetime by an order of magnitude.

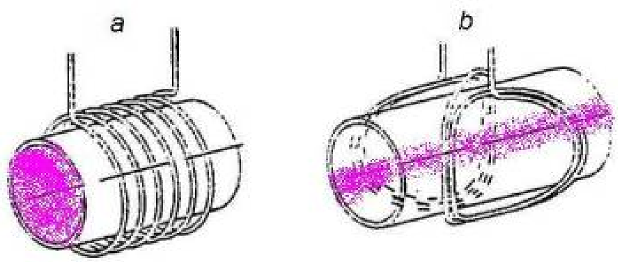

Figure 11: RF plasma generator antennae;
a- solenoid antenna; b- saddle antenna.

ERL for Radioisotope Production

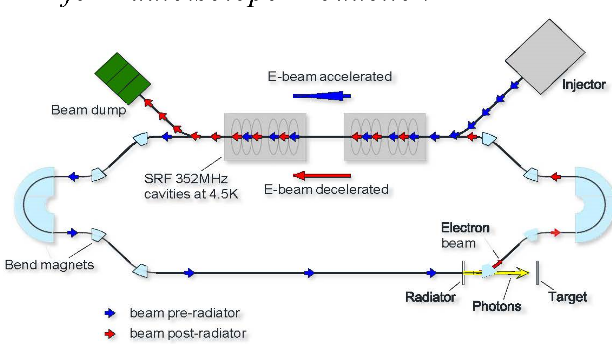

Figure 12: ERL to produce radioisotopes.

Superconducting Radio Frequency (SRF) Energy Recovery Linacs (ERL) are paths to a more diverse and reliable domestic supply of short-lived, high-value, high-demand isotopes at a cost lower than that of isotopes produced by reactors or positive-ion accelerators. Figure 12 shows the MuPlus-Jefferson Lab approach to this problem that was addressed in a Phase I STTR grant [18] using a thin photon production radiator. The thin radiator allows the electron beam to recirculate through RF cavities so the beam energy can be recovered while the spent electrons are extracted and absorbed at a low enough energy to minimize unwanted radioactivation.

In Phase I it was demonstrated that 1) the ERL advantage for producing radioisotopes is at high energies (~100 MeV), 2) the range of acceptable radiator thickness is narrow (too thin and there is no advantage relative to other methods and too thick means energy recovery is too difficult), 3) using optics techniques developed under an earlier STTR for collider low beta designs greatly improves the fraction of beam energy that can be recovered (patent pending), 4) the energy cost per gram of radioisotope using an ERL can be one third that of a conventional linac, and 5) many potentially useful radioisotopes can be made with this ERL technique that have never before been available in significant commercial quantities.

CONCLUSIONS

Over the last 14 years, Muons Inc. and its subsidiary MuPlus, Inc. have succeeded to be funded by the DOE SBIR-STTR program at a level totalling more than $25 M to use the innovative ideas of their staff and research partners to solve significant problems of national and global importance. These funds also supported 16 post-doctoral researchers and 4 Ph. D. students to work with the most creative accelerator scientists in the world.

The recent reauthorization bills of the SBIR and STTR programs have changed the emphasis of the programs to be on job creation. However, one can argue that the original idea of allowing industry to contribute to the goals of the government through SBIR-STTR grants was productive and a good model for funding industry collaborations with universities and national laboratories. Other countries may want to consider similar programs.

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