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# Industry Role for Advanced Accelerator R&D

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Muons, Inc. (http://www.muonsinc.com/)

- Besides the large research institutes that typically focus on fundamental research, industrial companies can also contribute to the development of advanced technology and applications of accelerators.
- This talk discusses the role of (smaller US) industrial companies in the field of accelerators and presents examples of advanced R&D.
- In 15 mintes, I can only describe what has been done in the USA
  - A funding model that may be unique among countries in the world
- But the bottom line is that there is no role if there is no funding

# SBIR-STTR Process

- US Congress taxes the operating budgets of all cabinet-level Departments (~3%) (Energy, Transportation , Homeland Security, Defense, etc.)
  - To fund Small Business Innovation & Tech Transfer Research (SBIR-STTR)
  - Originally, because small businesses were more innovative than gov orgs
  - More recently, because they want small businesses to help job growth
- Each year, each Department gives 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, where most accelerator R&D is done,
  - Small companies (<500 employees) submit proposals for SBIR-STTR grants
    - Which can have labs or universities as research partners
  - That get reviewed by 4 (3 technical + 1 commercialization) experts
  - For a 9 month $150,000 phase I grant to show the proposal is valid
    - 1 in 5 phase I proposals are granted
  - If it is valid, you can propose a 2-year project (up to $1M)
    - That is reviewed by (probably) the same 4 reviewers
    - 1 in 2 phase II proposals are granted

- For 14 years, Muons, Inc.
  - has been funded by DOE Contracts and SBIR-STTR grants
  - to invent and develop tools and technology for particle accelerators
  - with eight US university and nine national lab research partners
- Large US companies do little fundamental research on accelerator technology
  - Some larger companies work with small ones under SBIR-STTR grants
- Example 1 Muon beam cooling for a Muon Collider
  - next energy frontier machine to follow the LHC and Higgs boson factory
- Example 2 Designing a new Accelerator-Driven Subcritical Nuclear Reactor
  - Based on SRF proton accelerators and spallation
- Example 3 Designing an ERL to make commercial radioisotopes
  - Photoproduction using thin radiator and external target

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# Completed Muons, Inc. Projects

| Year | Completed Projects | SBIR-STTR Funds | Research Partner | Phase III |
|---|---|---|---|---|
| 2002 | Company founded | | | |
| 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 Exch. | $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 Demo | $850,000 | **FNAL (Lamm)** | $495,630 |
| 2007-10 | Stopping Muon Beams | $750,000 | **FNAL (Ankenbrandt)** | $410,488 |
| 2007-10 | HCC Magnets | $750,000 | **FNAL (Zlobin)** | $255,000 |
| 2007-8 | Compact, Tunable RF | $100,000 | **FNAL (Popovic)** | $23,400 |
| 2008-9 | Rugged RF Windows | $100,000 | **JLab (Rimmer)** | |
| 2008-9 | H2-filled RF Cavities | $100,000 | **FNAL (Yonehara)** | $23,400 |
| | Completed Projects | **$8,285,000** | | **$15,084,297** |

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# Completed Muons, Inc. Projects

| Year | More completed projects | Funds | Research Partner | Phase III |
|---|---|---|---|---|
| 2008-12 | Pulsed Quad RLAs (NFE) | $850,000 | **JLab (Bogacz)** | |
| 2008-12 | Fiber Optics for HTS (NFE) | $800,000 | **NCSU (Schwartz)** | |
| 2008-13 | RF Breakdown Studies | $850,000 | **LBNL (Li) ANL (Gai)** | |
| 2009-12 | HOM Absorbers | $850,000 | **Cornell (Hoffstaetter)** | |
| 2009-13 | Quasi Isochronous HCC | $850,000 | **FNAL (Neuffer)** | $198,900 |
| 2009-10 | DC Gun Insulator | $100,000 | **JLab (Poelker)** | |
| 2009-13 | H-minus Sources | $850,000 | **ORNL/SNS (Stockli)** | |
| 2009-13 | Hi Power Coax Coupler | $850,000 | **JLab (Rimmer)** | |
| 2009-10 | Hi Field YBCO Magnets | $100,000 | **NCSU (Schwartz)** | |
| 2009-13 | Φ & f–locked Magnetrons | $850,000 | **FNAL (Popovic)** | $198,900 |
| 2010-11 | ps detectors for MCDE | $100,000 | **U Chicago (Frisch)** | |
| 2010-11 | Crab Cavities | $100,000 | **JLab (Rimmer)** | |
| 2010-11 | MC detector bkgnds | $100,000 | **NIU (Hedin)** | |
| 2010-13 | Epicyclic PIC | $850,000 | **JLab (Derbenev)** | |
| | Projects In Progress | **$8,100,000** | | $397,800 |

## More Completed Muons Inc. Projects

| | | | | |
|---|---|---|---|---|
| 2011-12 | Adjustable Coax Coupler | $100,000 | **ANL (Nassiri)** | |
| 2011-12 | SAW Photoinjector | $100,000 | **JLab (Poelker)** | |
| 2011-12 | 2-Stage Magnetron | $100,000 | **FNAL (Yakovlev)** | $23,400 |
| 2011-12 | Efficient H-minus Source | $100,000 | **FNAL (Bollinger)** | $23,400 |
| 2011-12 | Achromatic Low Beta | $100,000 | **JLab (Derbenev)** | |
| 2011-14 | FiberOptic Quench Detection | $1,100,000 | **NCSU (Schwartz)** | |
| 2012-13 | Ribbon e Beam Monitor | $100,000 | **ORNL/SNS (Aleksandrov)** | |
| 2012-13 | RF Photoinjector Cavity | $100,000 | **JLab (Rimmer) LBL(Li)** | MuPlus |
| 2014 | Bi2212 30T Solenoid | $150,000 | **FNAL(Shen)** | |

## SBIR-STTR Projects in Progress

| | | | | |
|---|---|---|---|---|
| 2011-14 | FRIB Separator Magnet | $1,100,000 | **BNL (Gupta)** | |
| 2011-14 | HCC Engineering Design | $1,100,000 | **FNAL (Yonehara)** | $23,400 |
| 2012-15 | S-Band RF Load | $1,100,000 | **SLAC (Krasnykh)** | |
| 2012-15 | Complete Cooling Channel | $1,100,000 | **JLab (Derbenev)** | MuPlus |
| 2013-17 | High MTBF Magnetron | $1,150,000 | **JLab(Wang)** | |
| 2014-16 | H-minus source | $1,150,000 | **ORNL/SNS (Stockli)** | |
| | | **$8,150,000** | | |

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# Contracts with National Labs

| | | | Phase III |
|---|---|---|---|
| 2009-10 | Mono-E Photons | 2 contracts w **PNNL** | $172,588 |
| 2009-10 | Project-X and MC/NF | contract w **FNAL** | $260,000 |
| 2009-10 | MCP and ps timers | contract w **ANL** | $108,338 |
| 2010 | MAP - L2 mngr | 2 contracts w **FNAL** | $55,739 |
| 2010 | 805 MHz RF Cavity | contract w **LANL** | $230,000 |
| 2012 | MAP - L2 mngr | contract w **FNAL** | $40,000 |
| 2012 | PX cooling for Mu2e | contract w **FNAL** | $75,490 |
| 2012 | g-2 | contract w **FNAL** | $40,160 |
| 2012 | ACE3P 12 GeV Upgrade Studies | contract w **JLab** | $50,000 |
| 2013 | MAP, L2, MASS, G4beamline | contract w **FNAL** | $115,000 |
| 2014 | Parmela Simulations | contract w **Niowave** | $50,000 |
| 2014 | MAP, L2, MASS, G4beamline | contract w **FNAL** | $125,000 |
| 2015 | Mu2E MuSim Support | contract w **FNAL** | $230,000 |
| 2015 | Magnetron power source feasibility | contract w **Toshiba** | $30,000 |
| | | | $1,582,315 |

# More People

- Under SBIR-STTR grants, Muons, Inc. supported or is supporting 8 full-time junior Ph. D. accelerator scientists directly (Drs. Mohammad Alsharo'a, Kevin Beard, Gene Flanagan, Pierrick Hanlet, Masahiro Notani, David Newsham, Kevin Paul, and Cary Yoshikawa).

- and seven indirectly through subgrants, at Fermilab, JLab, IIT, NCSU, LBNL and ODU (Drs. Katsuya Yonehara, Shahid Ahmed, Guimei Wang, Vasiliy Morozov, Frank Hunte, Dan Bowring, Amy Sy).

- Muons, Inc. supports Ph. D. students working on our projects: Ms. Mahzad BastaniNejad and Ms. Ana Samolov at ODU, Ms. Melanie Turenne at NCSU, and Mr. James Maloney at NIU. Other potential Ph. D. students are considering working on our projects as thesis topics. Melanie and Ana completed all requirements and received their Ph.D.s in 2012! Jim defended his this thesis in 2014.

- Principal Investigator collaborators for our subgrants at national labs and universities amplify our company strengths:

(e. g. Derbenev-JLab, Yarba-FNAL, Schwartz-NCSU, Hoffstaetter-Cornell, Neuffer-FNAL, Kaplan-IIT, Rimmer-JLab, Li-LBNL, Gai-ANL, Stockli-ORNL, Frisch-Uchicago,…)

# Muon Collider Conceptual Layout

**Project X**
Accelerate hydrogen ions to 8 GeV using SRF technology.

**Compressor Ring**
Reduce size of beam.

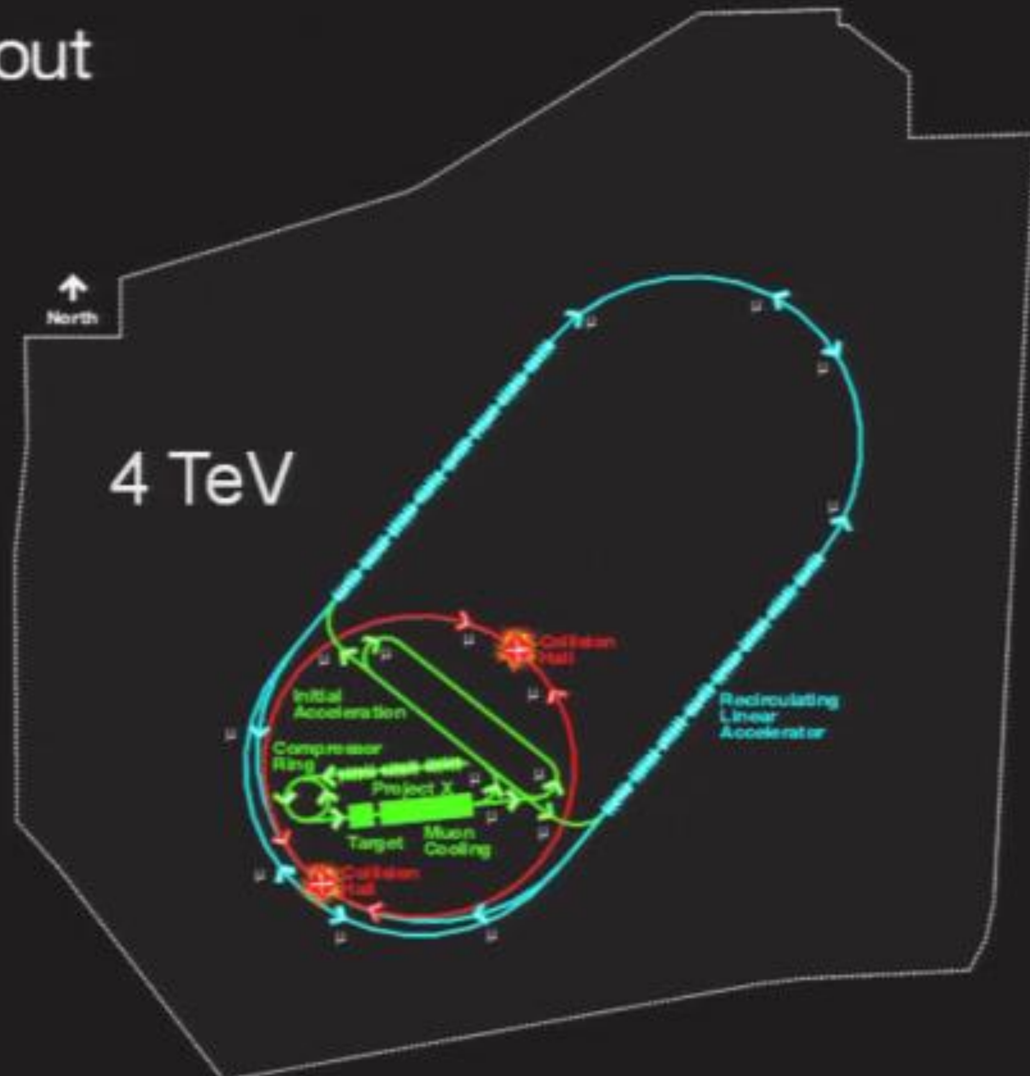
**Target**
Collisions lead to muons with energy of about 200 MeV.

**Muon Cooling**
Reduce the transverse motion of the muons and create a tight beam.

**Initial Acceleration**
In a dozen turns, accelerate muons to 20 GeV.

**Recirculating Linear Accelerator**
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

**Collider Ring**
Located 100 meters underground. Muons live long enough to make about 1000 turns.



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# Muon Beam Cooling

New concepts for muon ionization cooling,

Physical designs in progress

Sufficient beam cooling for a Higgs factory and

Energy Frontier Muon Collider that fits on Fermilab site

The ideas that are basic to the prototype being designed are <u>new for this millennium:</u>

Hydrogen-pressurized RF cavities,

doped with oxygen,

modified to fit inside strong superconducting magnet coils,

Helical Ionization Cooling theory using Siberian snake fields in

Helical Solenoid magnets, generating 6d cooling using

emittance exchange with a continuous homogeneous absorber

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# Ultimate Goal – after the LHC: High-Energy High-Luminosity Muon Colliders

- precision lepton machines at the energy frontier
- achieved in physics-motivated stages that require developing inventions and technology, e.g.
  - MANX (a new version is in the works)
    - demonstrate HCC, HS, & EEX concepts (based on a prototype HCC segment)
  - high-intensity proton driver <u>Needed for GEM*STAR</u>
    - simultaneous intense muon beams
  - stopping muon beams <u>Mu2E Contract w FNAL</u>
    - useful 6D cooling w HCC, EEX
  - neutrino factory
    - HCC with RF, RLA in CW Proj-X
  - Z′ factory
    - low Luminosity collider, HE RLA
  - <u>Higgs factory</u> ← (new ideas!)
    - extreme 6D cooling, low beta, super-detectors
  - energy-frontier muon collider
    - more cooling, lower beta

# A wedge or continuous absorber combined with magnetic dispersion can be used for emittance exchange

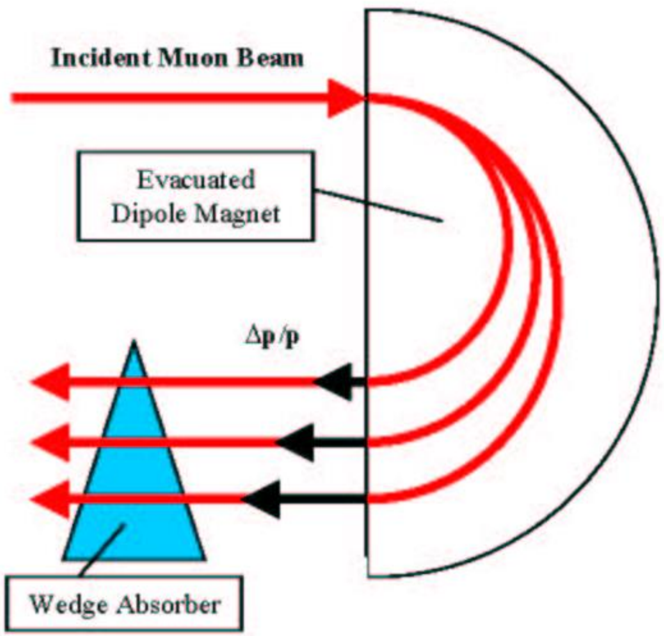


**Figure 1. Use of a Wedge Absorber for Emittance Exchange**

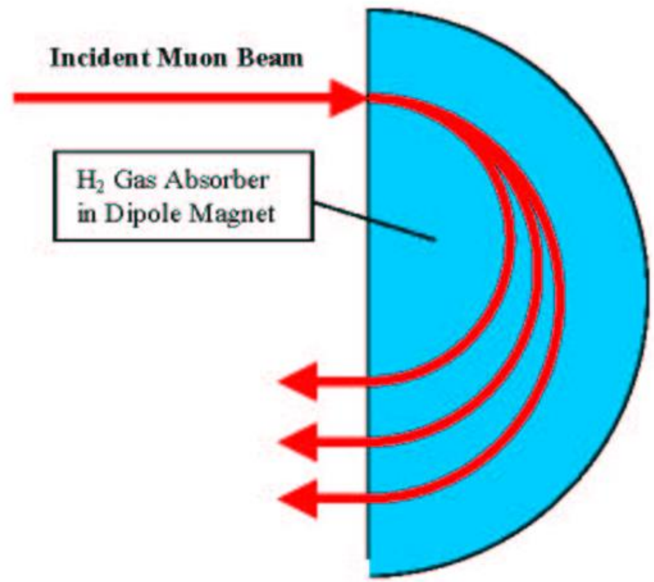


**Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange**

Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

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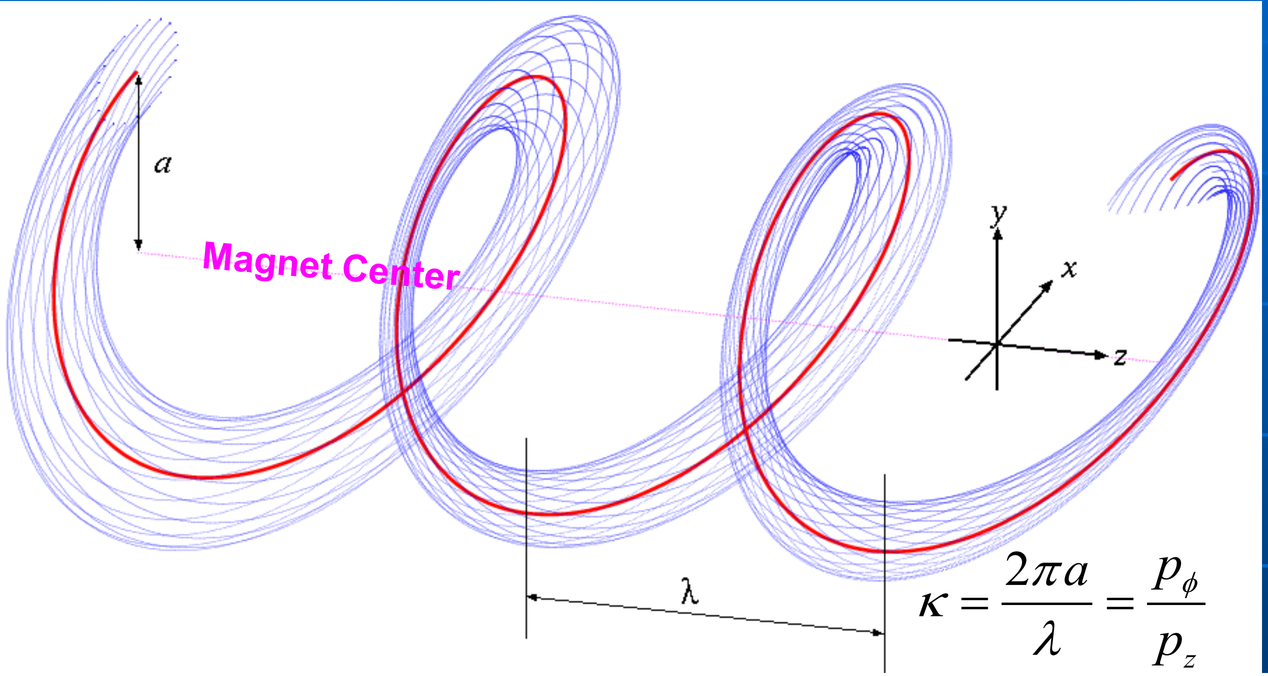
# Particle Motion in a Helical Magnet

*Combined function magnet (invisible in this picture)*

Solenoid + Helical dipole + Helical Quadrupole




$$\kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z}$$

**Red: Reference orbit**

**Blue: Beam envelope**

**Dispersive component makes longer path length for higher momentum particles and shorter path length for lower momentum particles.**

Opposing radial forces

$$F_{h-dipole} \approx \; p_z \times B_\perp; \quad b \equiv B_\perp$$

$$F_{solenoid} \approx -p_\perp \times B_z; \quad B \equiv B_z$$

Transforming to the frame of the rotating helical dipole leads to a time and z – independent Hamiltonian

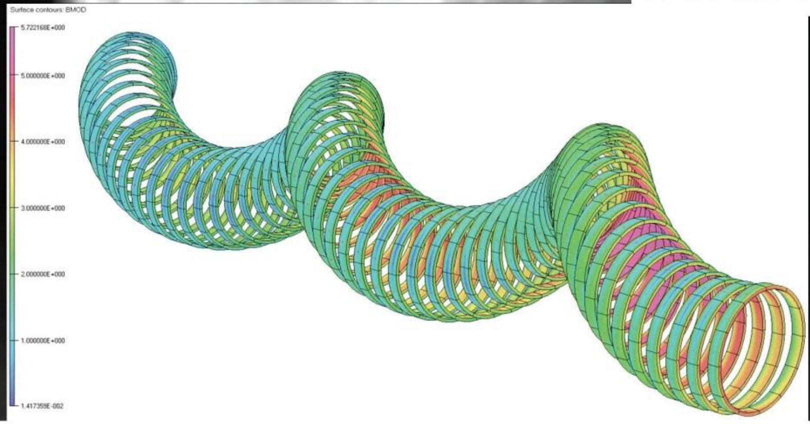
*b' added for stability and acceptance*

# Hardware Development

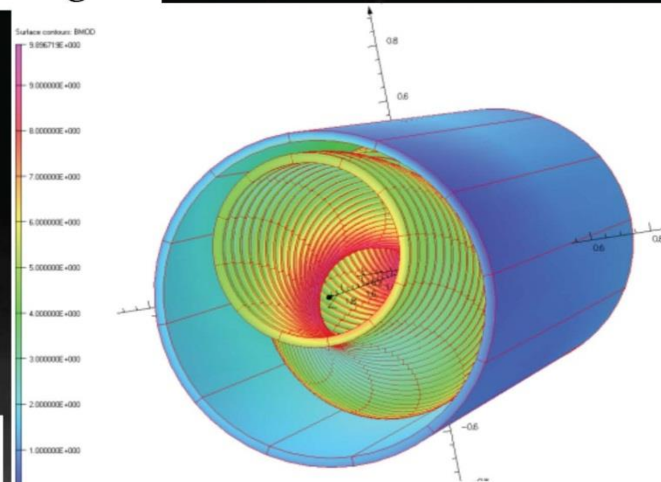
- Helical Solenoid invention to get HCC fields
  - 4-coil NbTi HS model tested ($1^{st}$ 6d HCC segment)
  - 6-coil YBCO HS model tested (last 6d HCC segment)
- High Pressure $H_2$ Cavity development
  - Test cell shows no HV max dependence on external B
  - First beam tests show agreement with models
    - No RF breakdown
    - Ionization electrons move far enough to heat $H_2$ – reduce Q
    - Mitigated with 0.01% $SF_6$ dopant
    - Oxygen shown to be a good dopant with less corrosion

# Helical Magnet

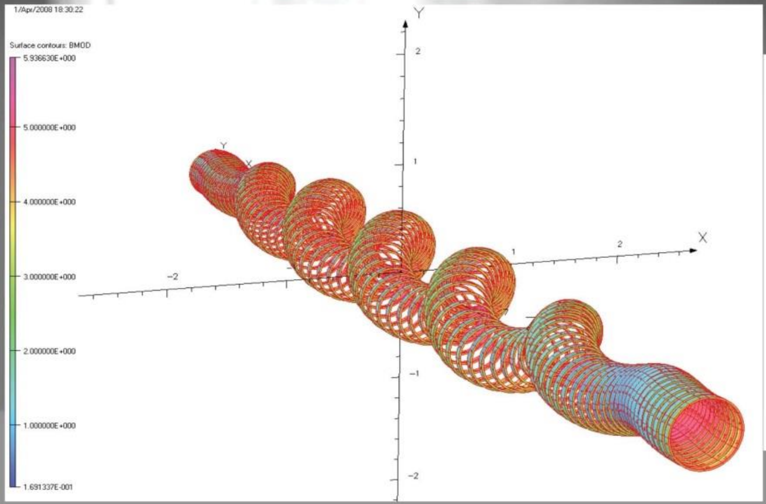
## Helical solenoid magnet



- Coil center follows on the helical reference track
- It generates proper helical dipole + field gradient



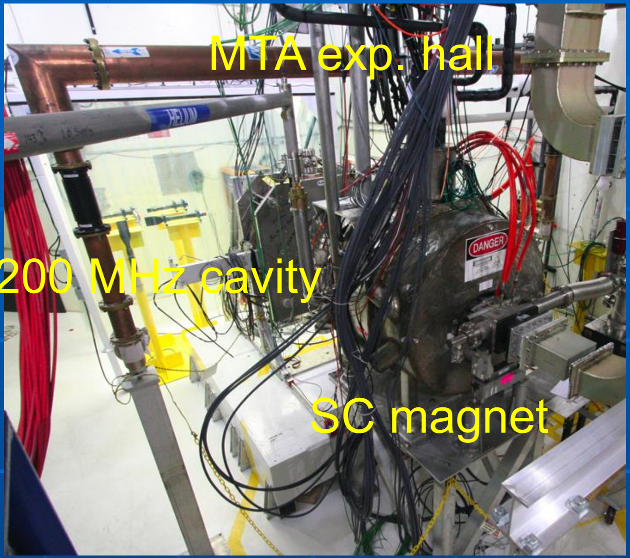
- By adding a solenoid coil, it tunes all three field components (b, b’, bz)



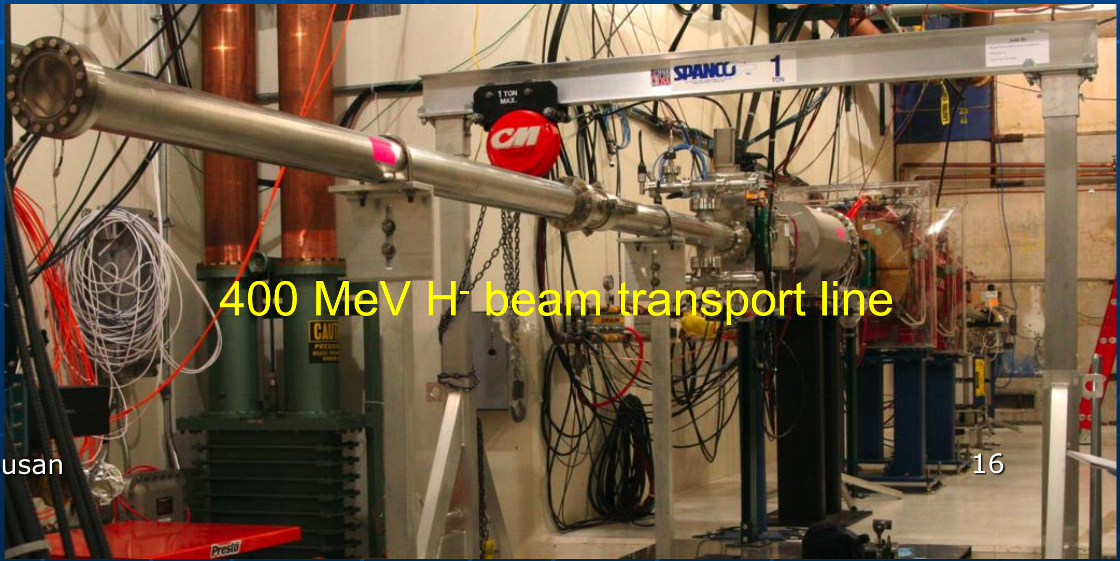
- By modulating the coil position, it can make a beam adapter to connect between straight and helical magnet sections.
- Helical solenoid magnet generates more uniform field than analytical field.
- It means that helical solenoid magnet has larger acceptance than analytical one.

# Mucool Test Area (MTA) at FNAL

Multitask work space to study RF cavity under strong magnetic fields
& by using intense $H^-$ beams from Linac





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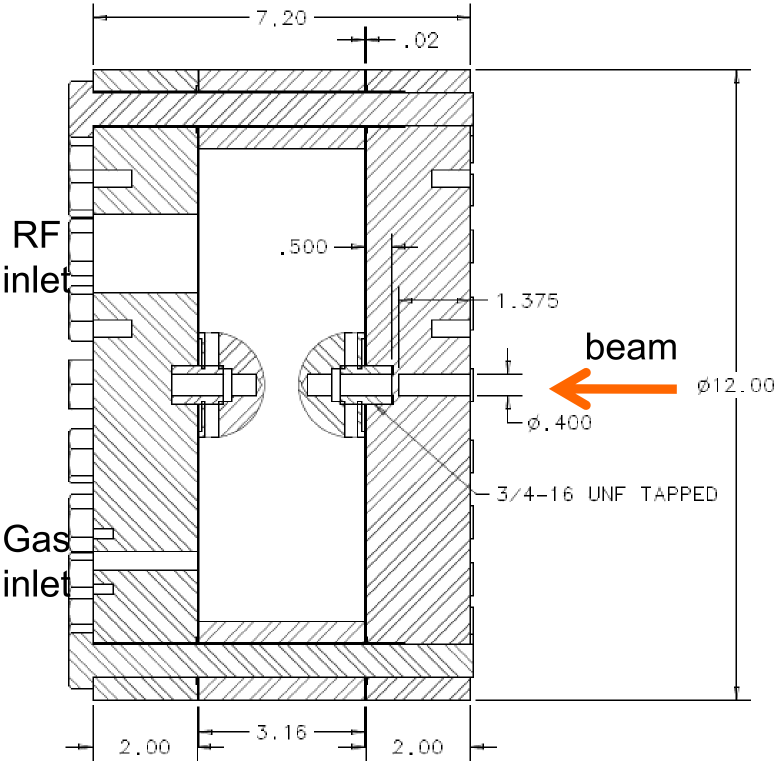
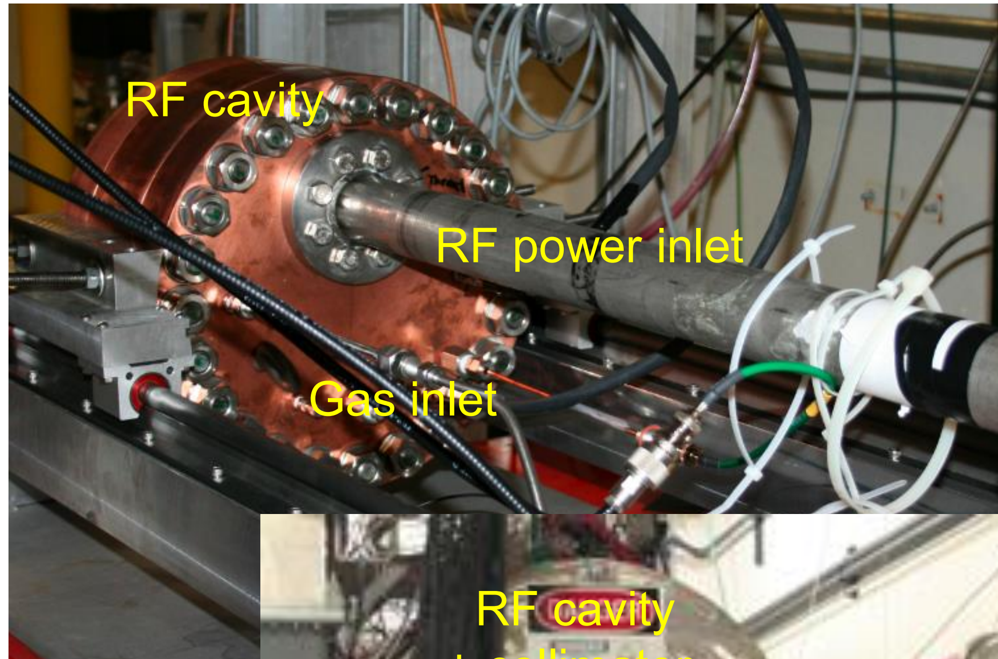
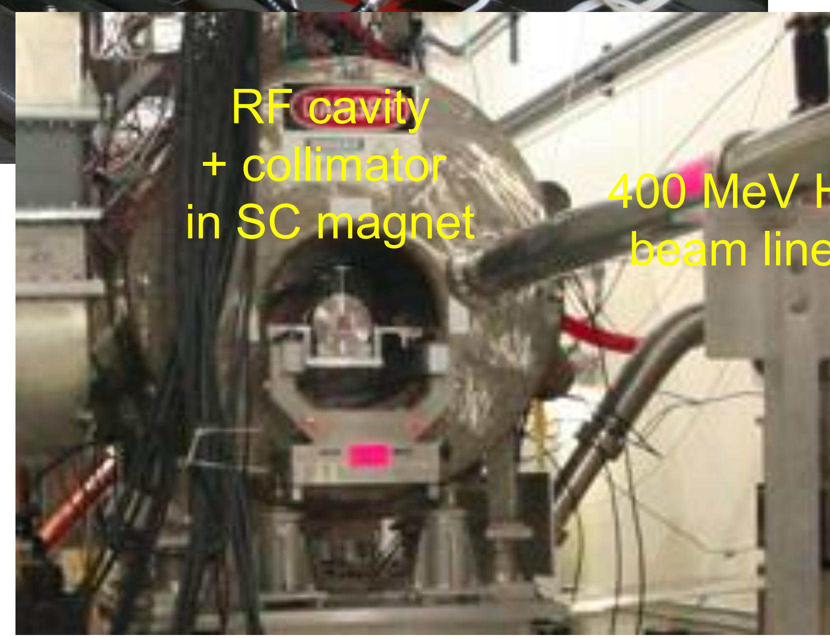
# First results HPRF cavity in beam




- 400 MeV $H^-$ beam
- Beam pulse length 7.5 μs
- 5 ns bunch gap
- $10^9$ $H^-$/bunch
- 18 % of transmission in collimator system
- 1.8 $10^8$ protons/bunch reaches to the cavity

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## Table I: 6-segment HCC as simulated by G4beamline

| segment | *z* | *b* | *db/da* | *B* | $\lambda$ | $\nu$ | $\varepsilon_T$ | $\varepsilon_L$ | $\varepsilon_{6D}$ | $\mu/\mu_\iota$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | m | T | T/m | T | m | MHz | mm | mm | $mm^3$ | % |
| start | 0 | 1.3 | -0.5 | -4.2 | 1 | 325 | 20.4 | 42.8 | 12,900 | 100 |
| 1 | 40 | 1.3 | -0.5 | -4.2 | 1 | 325 | 5.97 | 19.7 | 415.9 | 92 |
| 2 | 49 | 1.4 | -0.6 | -4.8 | 0.9 | 325 | 4.01 | 15 | 108 | 86 |
| 3 | 129 | 1.7 | -0.8 | -5.2 | 0.8 | 325 | 1.02 | 4.8 | 3.2 | 73 |
| 4 | 179 | 2.6 | -2 | -8.5 | 0.5 | 650 | 0.58 | 2.1 | 2 | 66 |
| 5 | 203 | 3.2 | -3.1 | -9.8 | 0.4 | 650 | 0.42 | 1.3 | 0.14 | 64 |
| 6 | 233 | 4.3 | -5.6 | -14.1 | 0.3 | 650 | 0.32 | 1 | 0.08 | 62 |

G4beamline is our program that interfaces to GEANT4. You can download it for free at muonsinc.com

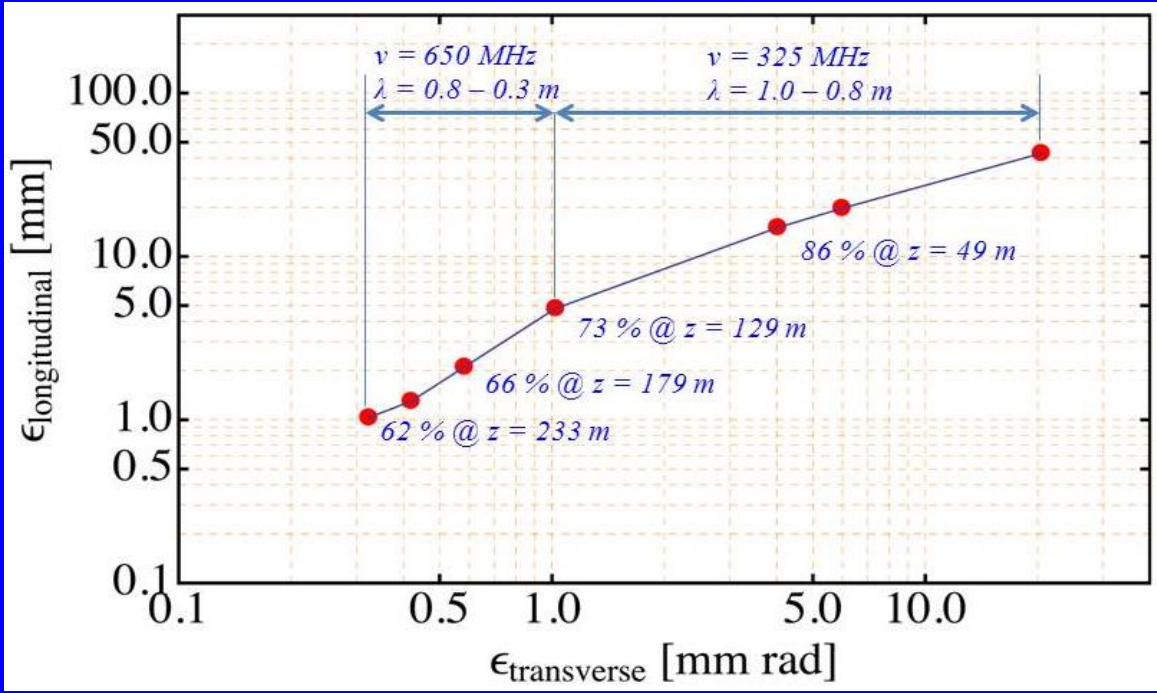


Figure 2: Emittance evolution and muon survival for the six HCC segments shown in Table I.

**1 mm = 4 MeV Higgs boson width**

# Magnetron Power Sources

- Magnetron is a good RF source for HCC RF
  - Inexpensive (<$2/W vs $5 to $10/W for klystron or IOT)
  - Efficient (~85% vs 50-60% for klystron or IOT)
  - Frequency and phase stabilization are an issue for accelerators
  - Muons, Inc. has several relevant projects underway that are relevant to muon cooling
    - 350 MHz CW 120 kW for radioisotope production
    - 650 MHz for medical application
    - 1500 MHz for CEBAF klystron replacement

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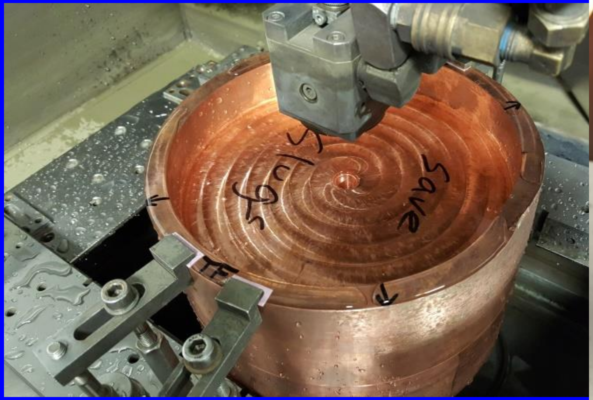
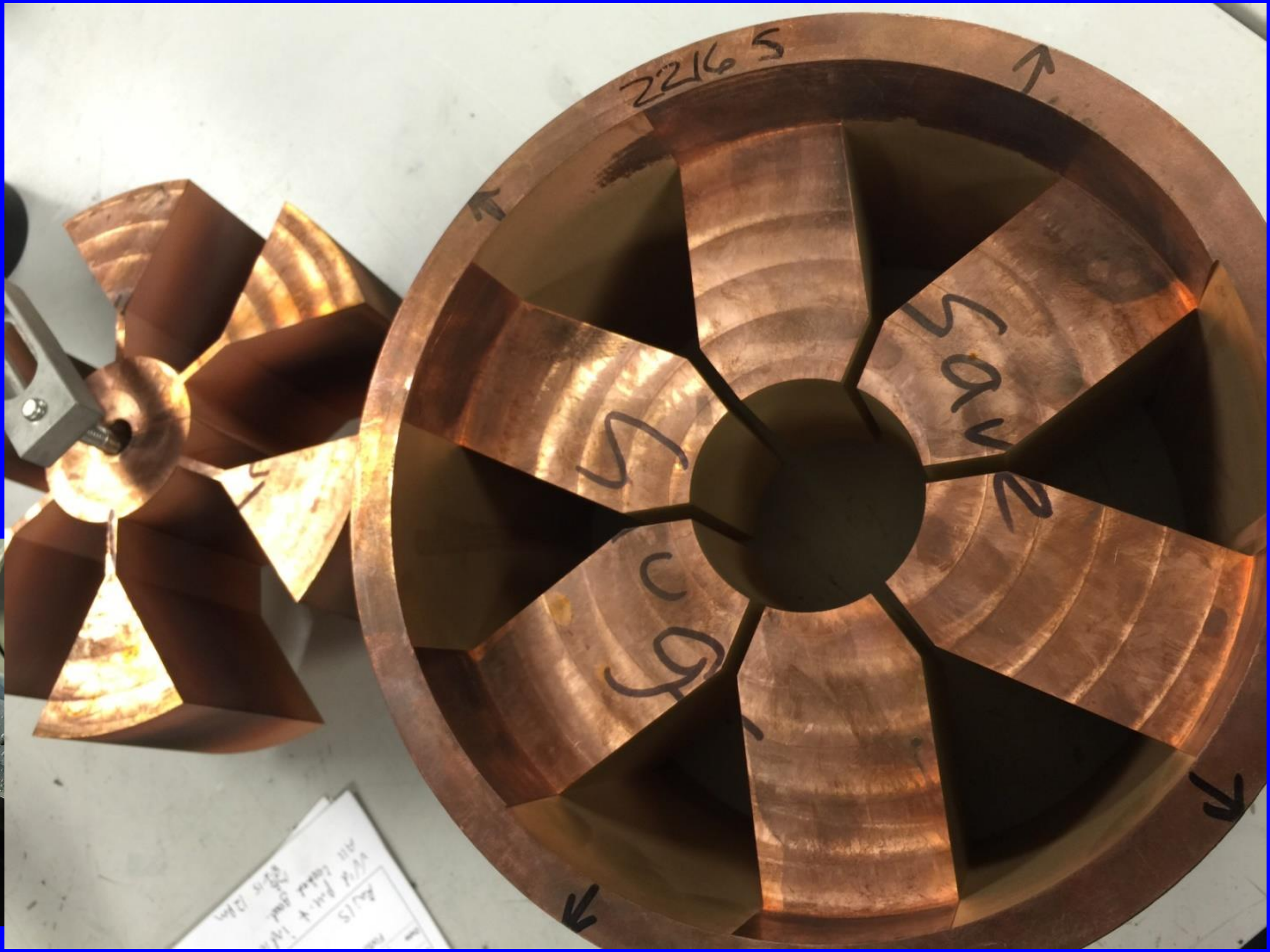
# EDM of 350 MHz Magnetron Anode





# US Industry can take nuclear waste or excess plutonium and produce energy from it

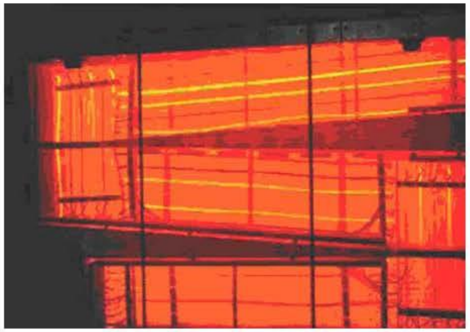
- Molten-salt Reactor Experiment (MSRE) 1965-1969
  - continuous purging of volatile radioactive elements – no zircaloy
- Accelerator-Driven Subcritical Reactors (ADSR)
  - reactor concept uses molten salt fuel (e.g. $UF_4$ ,$ThF_4$, or $PuF_3$)
  - GEM*STAR
    - Avoids nuclear weapon proliferation concern of reprocessing for 200 years
- The next step is a prototype ADSR machine to inspire industry
- Inexpensive natural gas changes things in the US
  - New Nuclear Power cannot compete with 4.5 c/kW-h from natural gas
  - ADSR process heat can make synthetic diesel out of natural gas and carbon
- GEM*STAR technology can
  - Turn excess weapons-grade plutonium into process heat,
  - with remnants useless for weapons,
  - to provide the DOD with inexpensive, green diesel fuel

- An intrinsic safety problem for conventional reactors is enclosed solid fuel.
- a natural solution is to use <u>molten-salt fuel</u>
- that is also well suited to accelerator-driven subcritical reactors.
  - A major difficulty is fatigue of $UO_2$ fuel in rods caused by accelerator trips – no such problem for molten salt fuel
- The technology of molten-salt fuel was developed in the 1960s in the Molten-Salt Reactor Experiment (MSRE) at ORNL.
  - Use of molten salt fuel was later abandoned
    - not enough Pu-239 for bombs?
    - President Nixon?

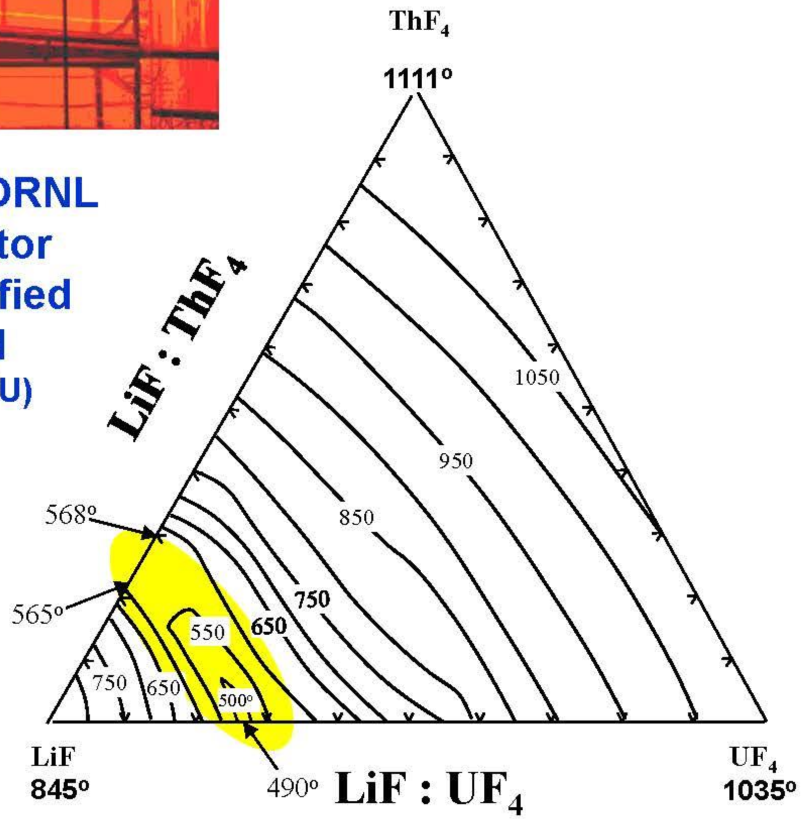
      (See MSRE on wikipedia for nice summary)

# Molten-salt Reactor Experiment

# Molten Salt Eutectic Fuel



**Proven in ORNL MSRE reactor using Modified Hastelloy-N**
**($^{235}U$, $^{239}Pu$, $^{233}U$)**




**Uranium or Thorium fluorides form eutectic mixture with $^{7}$LiF salt.**

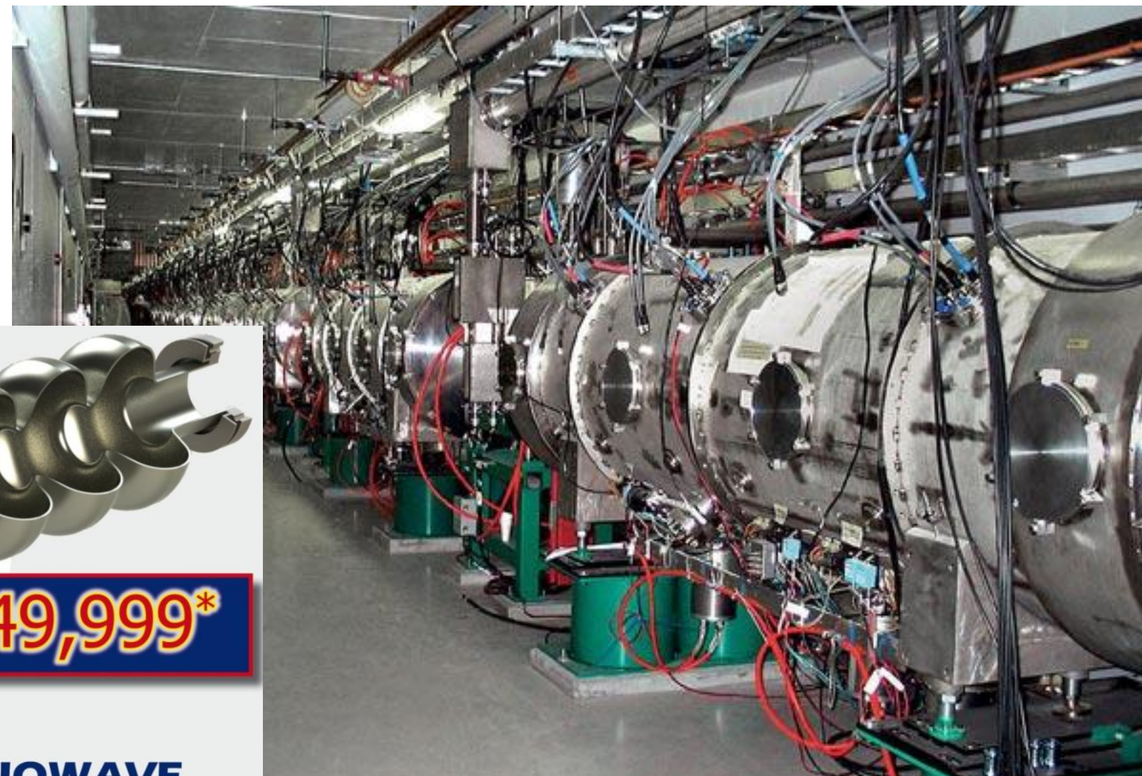
**High boiling point → low vapor pressure**



GEM*STAR

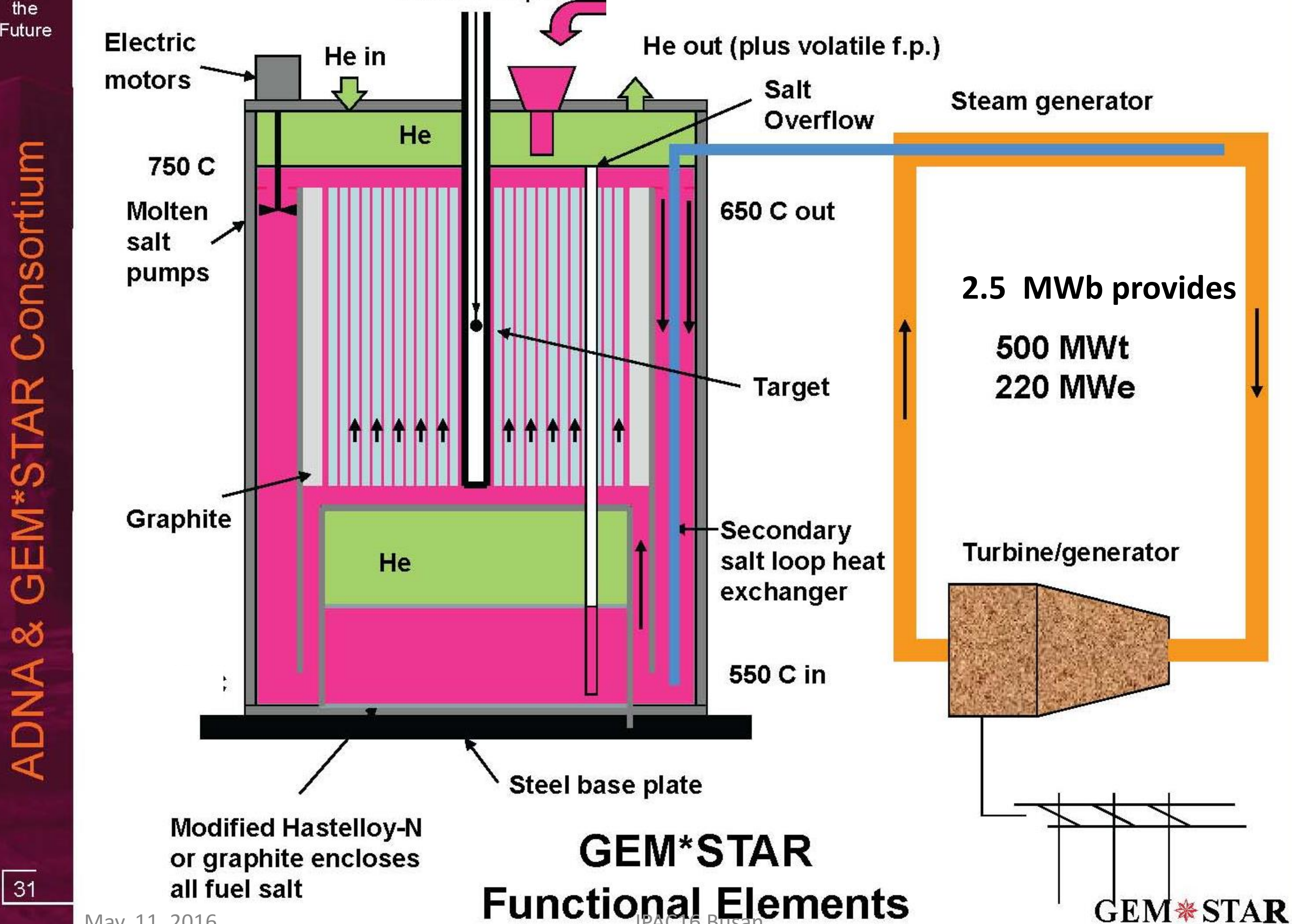
# New Accelerator Technology Enables GEM*STAR

OAK RIDGE, Tenn., Sep. 28, 2009 — The Department of Energy's 1 GeV Spallation Neutron Source (SNS), breaks the one-megawatt barrier! Operating at <10% duty factor, this corresponds to >10 MW at CW. Based on Superconducting RF Cavities, available from U.S. Industry:



**W-Pu as $PuF_3$ (30 g/h) plus carrier salt**

**2.5 MWb provides**



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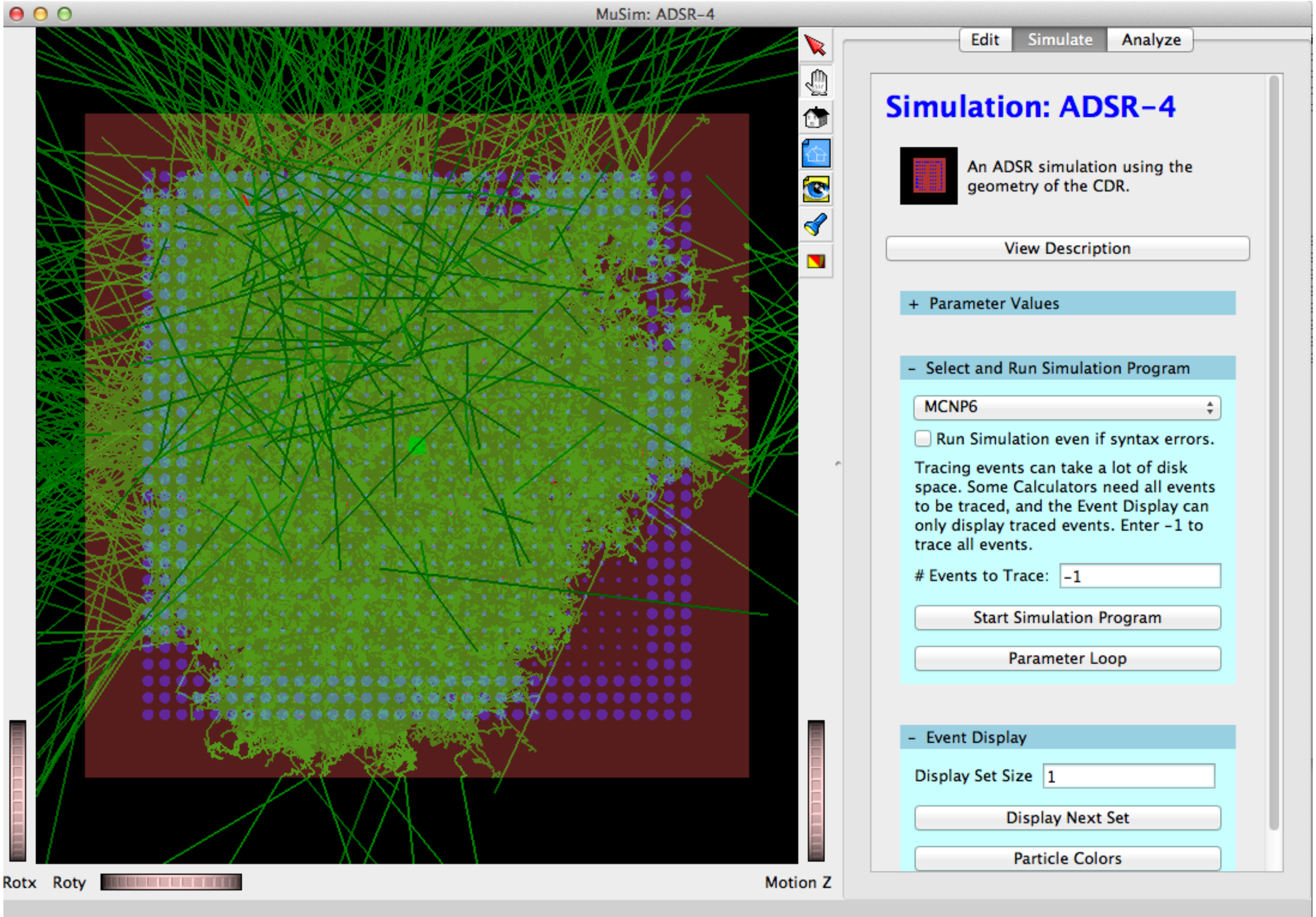
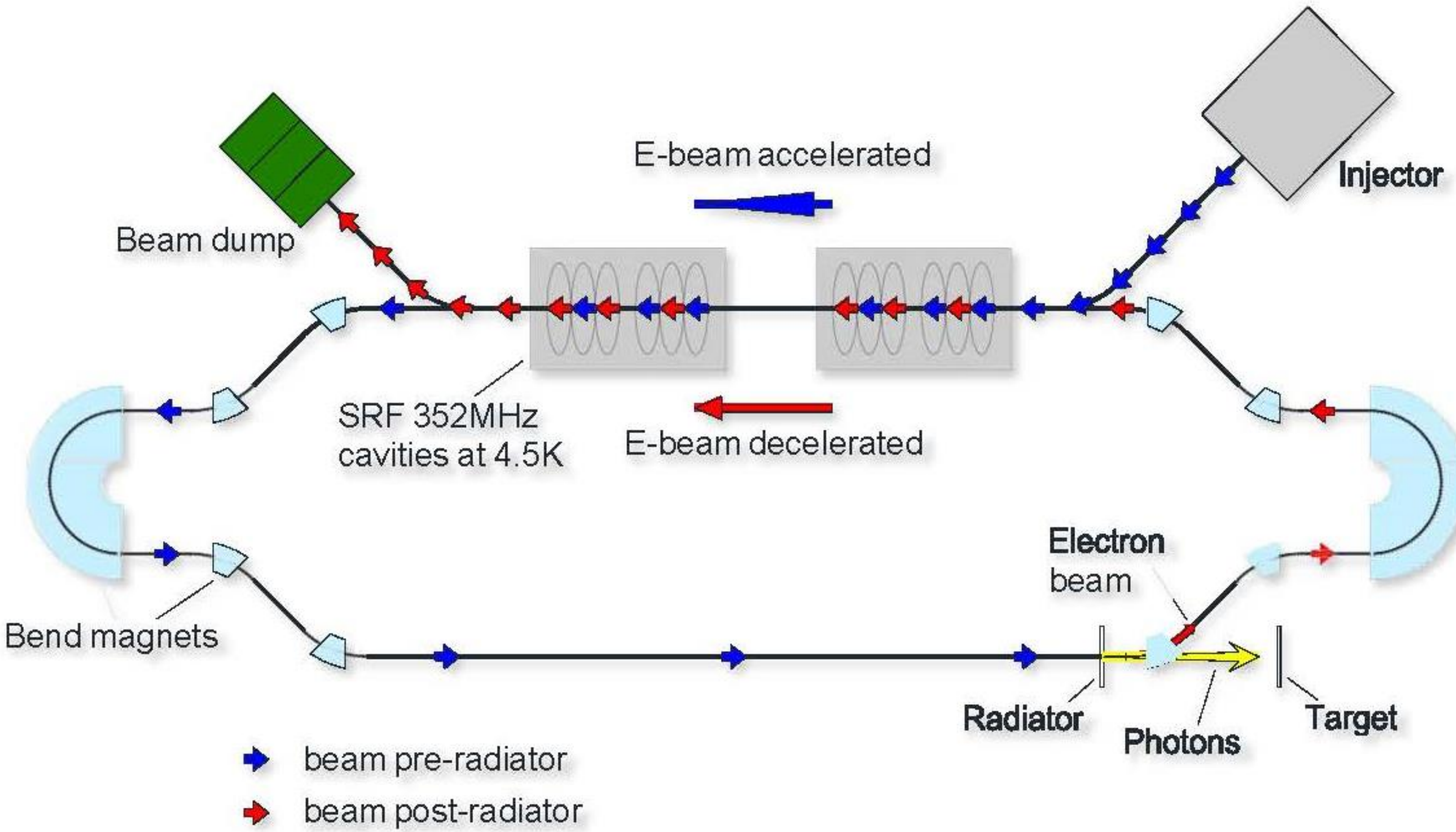
# MuSim MCNP6 single event display




Here is a single event, green=neutron, darkgreen=gamma. This single proton generated 402,138 tracks (not counting e- < 0.5MeV). I used a "transparency slider" to make the solids mostly transparent, so tracks inside them can be seen. This makes the solids darker, because the black background show through; tracks inside them affect their color.

# ERL for Radioisotope Production




Higher energy electron beams allow radioisotopes not yet studied for new applications.
The ERL can reduce energy cost per gram of isotope produced by more than factor of 3

# Industry Role for Advanced Accelerator R&D Conclusions

- The SBIR-STTR model to support smaller industries to participate in advanced accelerator R&D can be very productive
  - especially when leveraged by people and infrastructure from national labs and universities

- The lab and university partners benefit from being pushed to think out of the box
  - the SBIR-STTR funds give them a budget code to allow this!

- Very creative and competent accelerator scientists in industry can be involved in
  - accelerator problems of national and global significance –
  - for everyone's benefit