Graphene Stripper Foil

SBIR Phase II Grant DE-SC0000852
Carbon Stripper Foil for the Next Generation
Rare Isotope Beam Facility

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R.L. Fink, I. Pavlovsky
Applied Nanotech, Inc
3006 Longhorn Blvd #107
Austin, TX, 78758
dfink@appliednanotech.net
ipavlovsky@appliednanotech.net

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Outline

- Who is Applied Nanotech, Inc
- Scope of the Program
- Need for new stripper foils
- Graphene foil manufacturing
- Foil characterization
- Summary

ANI Introduction

- Located in Austin, Texas USA
- Founded 1988
- Nanotechnology R&D with emphasis in:
  1) Thermal Management
  2) Nanocomposites
  3) Nanoelectronics
  4) Nanosensors
- Three pronged business model:
  1) Commercialization by IP Licensing
  2) R&D Services
  3) Commercialization by Venture Formation

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Scope of the Program

- **Develop and test robust carbon stripper foils for next generation Facility for Rare Isotope Beams**

- **SBIR Phase II: two year program Aug 2010 thru Aug 2012**

- **Deliverables: Progress and Final Reports**

- **Provide samples of the foils with area density 0.5 to 2.0 mg/cm^2 and diameter >15 cm**

Diagram from http://www.phy.duke.edu

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Stripper Foils

- Need to increase the charge state of the ions being accelerated and reduce the total voltage used in the accelerator thus reduce cost
- A thin media such as carbon film is inserted in the beam

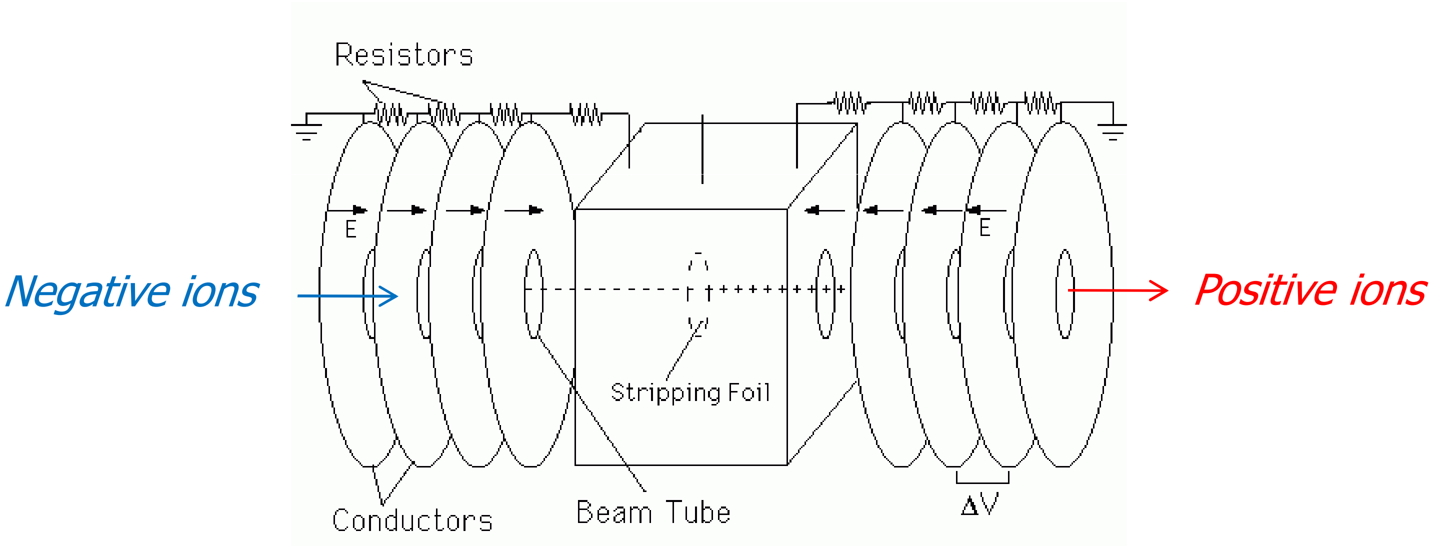

Diagram from http://www.phy.duke.edu

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Challenges

- **High power density**
  - Uranium beam power at stripper energy (17.5 MeV/u) is ~ 50 kW
  - Carbon foil equilibrium thickness is ~ 0.5 mg/cm^2 (2.2 μm thick)
  - Power deposited on the stripper foil ~ 700 W ~ 3.8 kW/mm^3
  - Beam spot should be as small as possible (take 5 mm diameter beam)
  - High temperature leads to foil <u>degradation</u>

- **Thermal and mechanical issues**
  - Foils tend to get thinner for heavy ions
  - The typical failure modes are <u>foil thinning</u> (energy changes) and <u>foil tearing</u>

- **Formation of defects due to radiation damage**
  - Displaced atoms and vacancies are formed under irradiation. They have higher mobility at high temperatures affecting the foil lifetime.
  - Lattice deformation results to the foil failure

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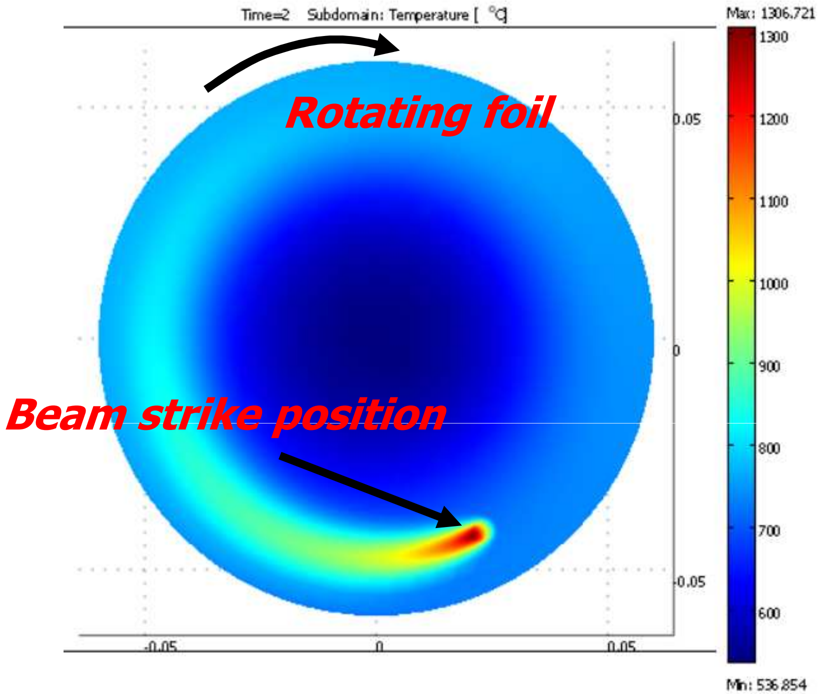
Approach

- New generation of stripper foils are needed to accommodate the ~700W beam power dissipated in the foil in 1 mm beam diameter
- One approach is to use large area carbon foils that are rotated to distribute the heat load from the beam to control foil temperature



Calculation of temperature increase of a rotating graphene disk at 1000W dissipated power

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Technical Requirements

We need to:

- **Maintain beam quality**
  - Small beam diameter - minimize beam degradation from passing through stripper
  - Small (<±5%) stripper thickness variation
- **Have reliable operations**
  - Stripper system long lived and/or fast replacement
- **High thermal conductivity**
  - Needed to spread the dissipated heat over larger area
- **Mechanically robust and thermally stable**
  - High angular frequency of foil rotation requires high tensile strength of foil
- **Large area fabrication**
  - Currently 13 cm diameter --> 15 to 25+ cm diameter goal
- **Low cost: target < $1000 for large area**
  - Current materials cost: ~$30 per 13-cm foil

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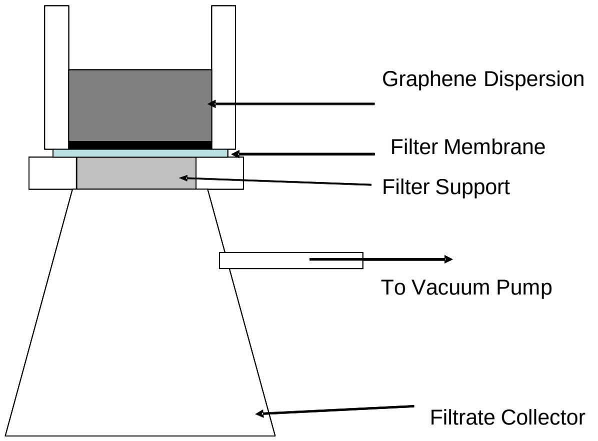
Why Graphene?

- Very high thermal conductivity
- Excellent mechanical properties
- Can be made uniform over large area
- Low cost in production

Graphene Foil Preparation



- Obtaining graphene oxide (GO) aqueous dispersion
- Reduce GO to graphene dispersion (using hydrazine+NH_3)
- Create foils by vacuum filtration of dispersion
- Lift-off foil from the filter for free-standing foil
- Amenable to scale-up fabrication.

D. Li *et al.*, Nature Nanotech, 2008, 3, 101-108

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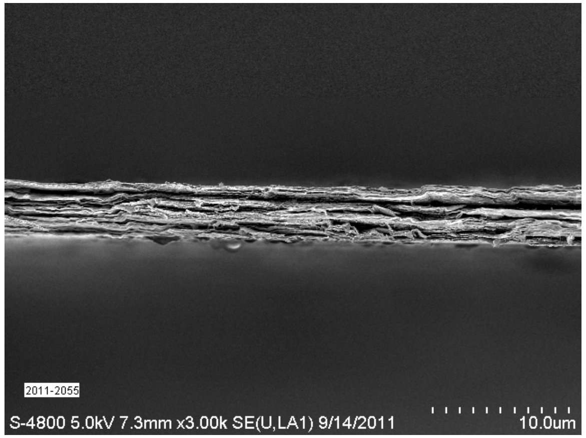
Images of Graphene foils

- Foils of areal mass density 0.5 – 2.0 mg/cm^2 and diameter of 13 cm are made successfully
- The foils are quite smooth and have a metallic luster and shine.
- The foils have a layer structure. At the edge, the foil appears like a deck of cards.
- Foils are robust, easy to handle and survive express shipping.



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Tensile Strength of Graphene Foil

Tensile strength was measured for as-produced and treated foils.
Treatment conditions: 600°C for 1 hr in 4% H_2 in N_2 gas mixture

Sample#	thk, um	width, cm	force, N	TS, MPa
10U1	**3.8**	1.9	12	**166.2**
10U2	**3.8**	2.25	13	**152.0**
10U3	**3.8**	2.23	15.5	**183.3**
Average untreated				**167.2**
Standard deviation				**15.7**
10T4	**3.8**	2.15	2.5	**30.6**
10T5	**3.8**	2.1	9.5	**119.0**
10T6	**3.8**	2.15	3	**30.6**
10T7	**3.8**	2.15	5	**61.2**
10T8	**3.8**	2.1	12.75	**36.7**
10T9	**3.8**	2.1	3	**37.6**
10T10	**3.8**	2.1	6	**159.8**
Average treated				**67.9**
Standard deviation				**51.3**

Tensile strength of **150 MPa** is sufficient to keep the integrity of a foil rotating at angular frequencies up to **60,000** rpm for a 13-cm circle foil and over **400,000** rpm for 1 cm wide ring foil

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Thermal Conductivity of Graphene Foil

A 20-micron thick foil was fabricated for a thermal conductivity test.

Measured* in-plane thermal conductivity - 1480 W/m·K

ASTM E1461 Flash Method Thermal Conductivity Results

	thickness	bulk density	temperature	specific heat	diffusivity	conductivity
	@ 25℃	ρ @ 25℃		c_p	α	λ
Sample	**(mm)**	**(g/cm^3)**	**(℃)**	**(J/g-K)**	**(mm^2/s)**	**(W/m-K)**
graphene foil	0.020	1.55	25	0.730	1308	1480
(in-plane)						

**Measured by NETZSCH Instruments North America LLC*

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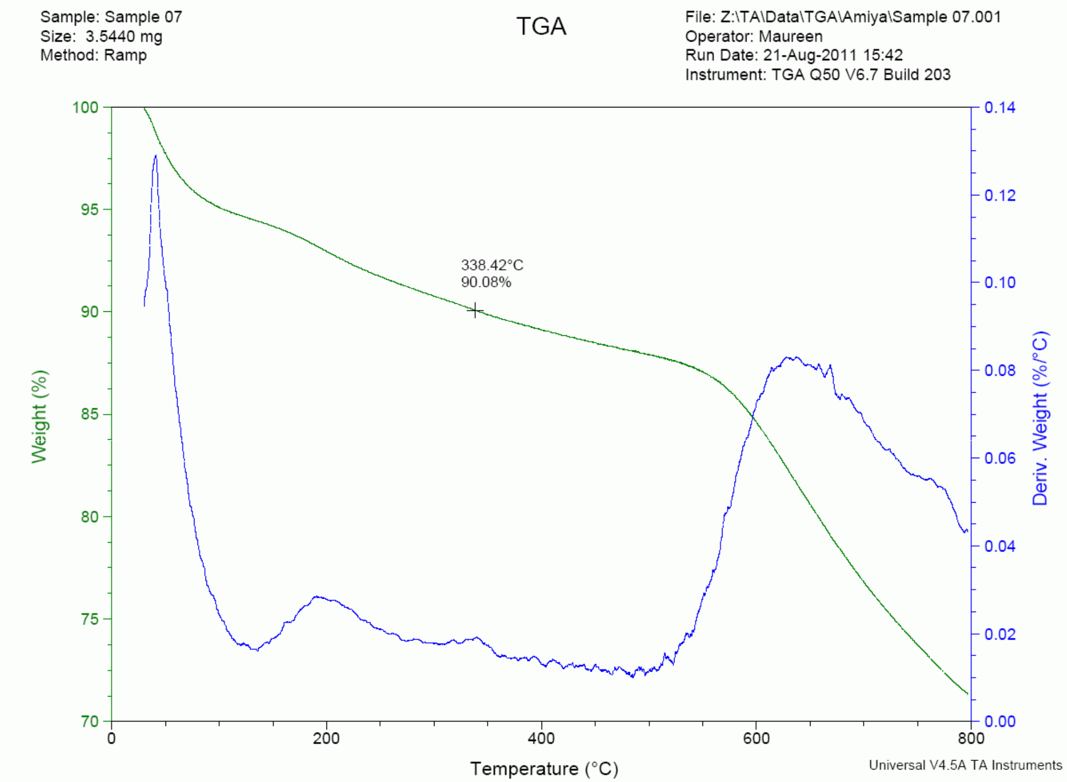
Temperature Stability of Graphene Foil



Stripper foil will operate in vacuum. After temperature conditioning, good stability is expected (tested in N_2, peaks due to water, -OH groups, and possibly oxidation in residual air; TGA Q50).

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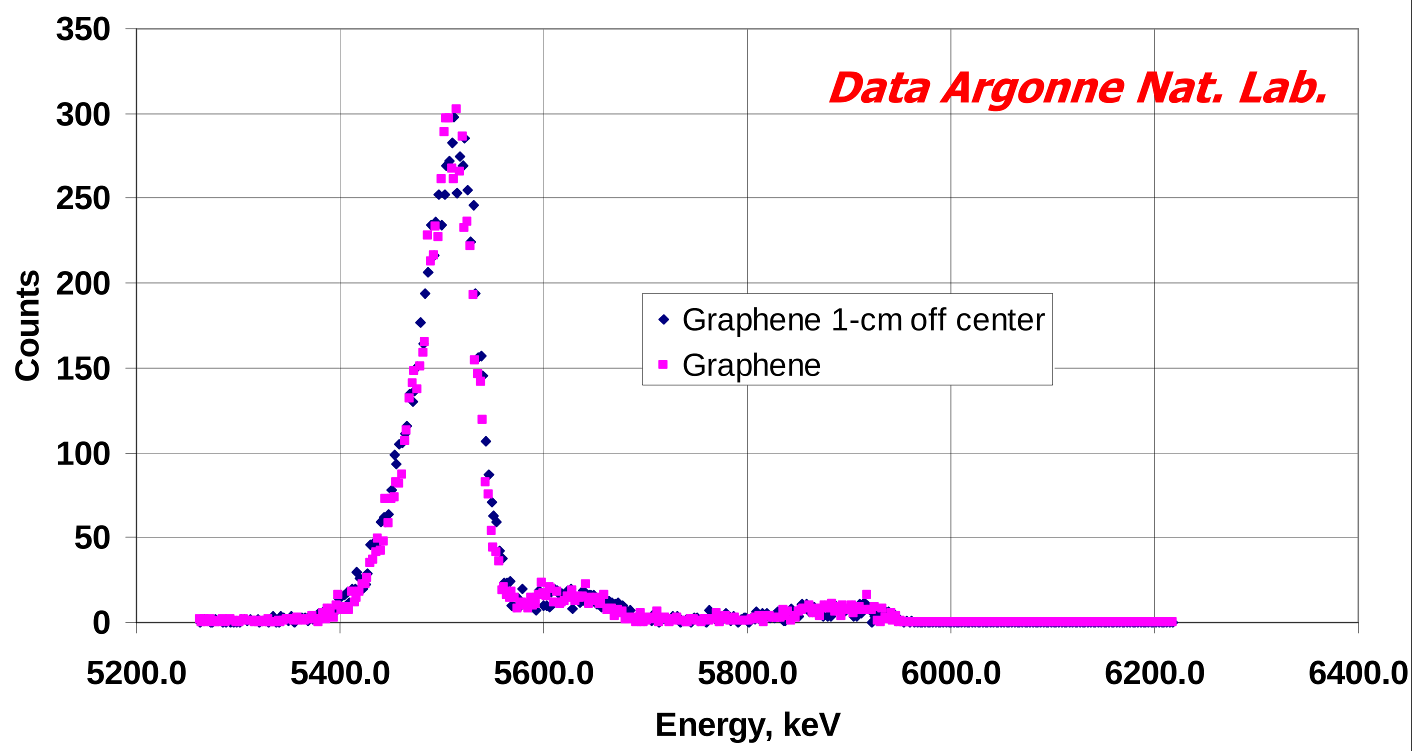
Alpha Probe Characterization



Spectrum of Cf source through graphene foil in the center of the foil and 1-cm off center (foil obtained from U. Wollongong).

Spectra lie on top of each other with calculated mass density 0.421 +/- 0.01 mg/cm^2, achieving <5% uniformity.

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Tests at Michigan State U.

- **Over 300% foil lifetime vs. predicted value was observed using graphene foil with ^{87}Kr 13 MeV/u beam**
- E-beam tests performed to mimic ion beam exposure.
- E-beams were positioned a fixed spots for many hours. No difference seen on sample between fixed spot or fast beam sweep line across the sample.
- Current of electron gun adjusted to maintain temperature below 1800K
- Slight mass loss measured – may be degassing of residual oxygen from production process
- No pinholes created by e-beam.

- **Graphene foil obtained from U. Wollongong*

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H-Ion Beam tests at Texas A&M University

- Foils of 1.0 – 2.0 mg/cm^2 tested in 1-60 MeV H- ions to protons and 10 – 60 MeV D- ions to deuterons on K150 cyclotron.
- No reduction of stripped beam current after testing at 30 MeV H- ions at 20 μA for over 3 days

tests courtesy of Dr. Henry Clark of TAMU

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Windows for Gas Targets

- Potential application of graphene foils to replace metal foils as windows for gas targets (ATLAS, Argonne National Laboratory).
- Metal windows used now create secondary radioactive beams.
- Desire low-Z windows strong enough to hold gas pressure in target chambers and also must be vacuum tight.
- Preliminary tests on 0.4 mg/cm^2 windows showed that 8 mm diameter window held up 1 atm gas pressure. Tests are continuing.

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Summary

- Graphene stripper foils 0.5 – 2.0 mg/cm^2 with up to 13 cm diameter prepared.
- Graphene foils are smooth, flat and robust.
- Thickness uniformity of > 5% achieved.
- Can scale to larger area for FRIB applications.
- High temperature e-beam tests demonstrate thermal robustness – no pinholes created at fixed beam spots.
- New application as windows for gas targets identified; preliminary tests show promise.

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ANI team:
R.L. Fink, I. Pavlovsky, Y.J. Li, S. Neuburger

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