Profile Monitor SEM's for the NuMI Beamline

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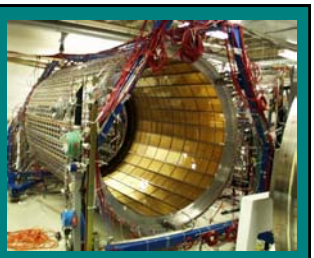
www.hep.utexas.edu/~kopp/minos/sem/

- Foil Secondary Emission Monitors
  - Data from other laboratories
  - Thermal modelling of foils/wires in the NuMI beam
  - Experience from our May 2003 prototype
- Preliminary Design
  - 'Bayonet'-style insertion mechanism
  - Review of materials in & out of the vacuum can
  - Some rough costs of critical components
- Engineering calculations
  - Forces, torques on linear motion actuator
  - Torque requirement for motor
- Results of linear motion tests
- Costs, Schedules, …

Who We Are



- **Sacha Kopp**, PI: previous major projects include
  - NuMI Neutrino Beam Monitors
  - NuMI Hadron Hose
  - Ring Imaging Cherenkov Detector for CLEO (*at Syracuse U.*)

  NB: teaching leave Spring '04 – 80% on NuMI SEM's
- **Marek Proga**, engineer
  - NuMI Neutrino Beam Monitors
  - MINOS PMT system
  - BNL 871 straw drift chamber system (basis for CKM design)

  80% on NuMI SEM's (remainder NuMI Neutrino Beam Monitors)
- **Graduate Students**
  - Dharmaraj Indurthy
  - Zarko Pavlovich

  } *Both interested in accel. phys.*

  (*60% on NuMI SEM's, 10% NuMI μMons, 30% courses*)
- **Physics Department**
  - Machine shop, 15 machinists
    - 3 CNC milling stations, rest manual
    - Typical 18K hrs/year in service to Phys Dept.
    - Provided 4000hrs in 4 mo for NuMI muon monitors
  - Cryogenics/vacuum shop:
    2 technicians, leak detectors, etc

The Making of a Beautiful Friendship…

- University groups should have a strong interest in making contributions to accelerator physics
  - Continued success of national accelerator labs essential to US HEP community
  - Accelerator physics and instrumentation of interest in their own right, equivalent to particle detectors or large-scale computing
  - Important sense of mission when funding closely tied to role in HEP program
- National labs should have a strong interest in developing university partners
  - Access to 'free labor', but also university resources (shops, nuclear reactors, engineering and material science departments) and expertise
  - Long-term partnerships to develop 'risky', unconventional ideas
  - Training of tomorrow's accelerator physicists
- Many problems are 'out-sourceable' – *eg* accelerator instrumentation
  - Requires clear, crisp statement of important spec's
  - Requires set of contacts at the lab for feedback, info.
  - Requires sustained commitment to completion, scope of project from both sides

Intro: Fermilab SEM's

- Thanks to Gianni Tassotto (RF&I?, I?) for tutoring and tour of their SEM's
- Essential features of Fermi SEM's:
  - W-Rh wires, Au plated (75 μm)
  - Ceramic circuit board with Pt-Ag solder pads for stringing wires
  - No clearing field applied
  - Frame is on all four sides of beam
  - Frame swings in-out like a door
  - SEM aging observed (signal decreased by 37% by end of KTeV run), but not studied.
- Issues to be addressed for NuMI
  - Insertion/removal during beam operations
  - Longevity of secondary emission coefficient of W-Rh/Au wires
  - Each plane (*X* and *Y*) Causes beam loss of order 6E-5 if have 1mm pitch
  - Size matters: reduce device size along beam direction

Specifications

Active Medium

- Non-invasive frame
- 1mm pitch (carrier) or 0.5mm pitch (pretarget)
- Beam loss ~ 10^{-6} (but total 7×10^{-6} ok'd in 8-15-02 NuMI primary beam meeting)
- Clear aperture 3" (40mm measurement aperture, remaining is halo meas't)
- Longevity to 10^{20} prot/cm^2

Vacuum chamber

- <10.25" flange-to-flange
- Fit in tightest area of MI (chamber body <8"Ø)
- Hold **~ 10^{-8} Torr** on 30 l/sec ion pump (*ie*: outgas 3×10^{-7} Torr-liter/sec)
- FNAL quick-disconnects **(4" OD)**
- Total mass **<200lbs**.
- Components survive **10kRad**

Foil Positioning

- Repeatability 50μm
- Foils surveyed to **0.020"** with repect to external tooling balls.
- Motion in/out of the beam accomplished within **~15sec**
- Stepper motor controllable by Al Legan's system (6-wire unipolar, <4A, 1Ω, 3mH)
- Any readback (*eg* LVDT) produces 0-10VDC or ±10VDC output
- Limits switches to stop travel

- *NB: values in **yellow** given by S.K., lacking input*

Building on Past Experience …

While our requirements are different from SEM's (multiwires) built elsewhere here at FNAL, the various ingredients of the SEM we want to explore are not different from instrumentation currently in use here and at other labs.

With time & budget constraints, we did not want to embark on an R&D effort. Thus, going with reasonably proven design choices was desirable.

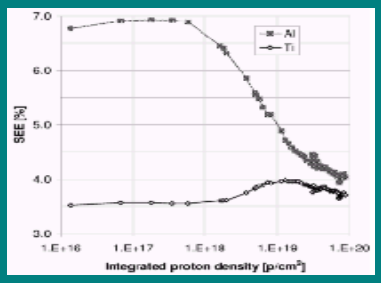
Specifically, you will find the proposed conceptual design has borrowed from:

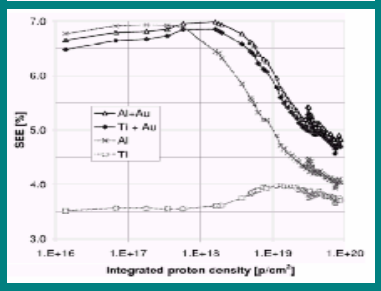
• Active element – 5 μm Ti foils	CERN (G. Ferioli)
• Motion Feedthrough (bellows)	LANL (D. Gilpatrick)
• Mechanical Travel – linear stages	*cf* MDC, Huntington catalogs
• Feedback – Schaevitz LVDT	FNAL (R. Reilly)
• Stepper Controls, Readback	FNAL (A. Legan)

With some modification, the design presented here might be of general utility.

Aging Effects in SEM's

- Secondary electron emission yield observed to drop after long exposure to beam
  - V. Agoritsas (CERN)
  - R. Witkover (BNL)
  - D. Garwin (SLAC)
  - M. Awschalom (FNAL)
- Eg: Aluminum drops to 20% of original value (from 7% to 1-2%) after 10^{20} protons/cm^2
- Note central strip on NuMI SEM would see ~0.8×10^{20} protons/year assuming 1mm pitch and σ_{beam}=1mm and 0.2mm wide strip
- Extensive studies performed in '60's-'70's
  - Oxide layers on SEM's
  - Even CO_2 surface layers important
- Elaborate process techniques to maintain clean foils
  - Handle only in Argon/N_2 glovebox (see FNAL TM-0850, for example)
  - Bake under vacuum
  - Glow discharge in 0.1Torr Argon
  - Best 'Golden SEM' lasted to 10^{20} p/cm^2 with 'no degradation'
- Effect is also tied to beam heating of SEM
  - Observed 'dimpling' of surface on damaged SEM's
- Plots at right are results from CERN (courtesy G. Ferioli)
  - Foils only handled in air (no Ar)
  - Baked at 200C, but no glow discharge





Candidate SEM Materials

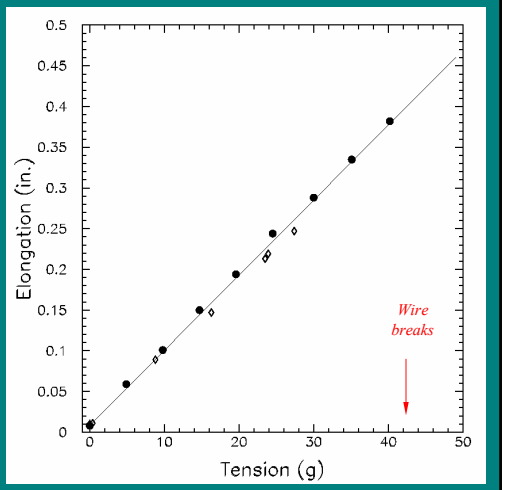
	Z	X_0 (cm)	λ_{int} (cm)	SEE (%)	Propose wire/foil	Thickness (μm)	Beam Loss (10^{-6})[d]	Comments
Be	4	35.3	40.6	?	foil	25	12	SEE unknown; foils <0.001" difficult to procure; biological hazard
C	6	18.8	38.1	2-2.5	Wire	33	2.7	Used at LANL, SLAC (wire scanner); VERY fragile mechanically
Al	13	8.9	39.3	~7	Foil	5	2.5	SEE ages badly in beam [11,13]
Ti	22	3.6	27.5	3.5	Foil	5	3.6	Excellent longevity to 10^{20} p/cm^2 dose[13]
Ni	28	1.46	~15[a]	3-5?	Foil	10	13	Ages in beam [16]
Ag	47	0.87	~9[b]	~6	Foil	5	~10	Data from [11], but requires great care because oxidation will degrade signal.
W	74	0.35	9.6	4	Wire	75	60	SEE is for Au-plated [15]. Degrades in beam. Experience of wire breakage if < 75μm?
Au	79	0.30	8.8[c]	~7	Foil	10	22	Does not oxidize, but does adsorb CO [11]; signal loss observed [13]

[a]Value for Cu (Z=29,ρ=8.9g/cc)
[b]Scaled from λ_{int}(Cu) using $\lambda^{-1}\propto A^{0.77}$
[c]Value for Pt (Z=78,ρ=21.5g/cc)

[d]Beam loss calculated from λ_{int} assuming σ_{beam}=1mm, 1mm pitch profile monitor, and 0.2mm wide strips for foil detectors.

Experience with Carbon Wire

- Carbon monofilaments (33μm Ø) used in LANL wire scanners
- We purchased roll of same material from same manufacturer.
- Bulk modulus measured by stretching several wires with suspended weights, measuring elongation with transit.
  - Agrees with manufacturer's value
- Wire breakage at ~60ksi, compared to 128ksi stated by manufacturer (after much practice, got wire to break in middle, not at ends, eg due to mounting problems).
- Wire strong longitudinally, but *fragile* if transverse force (blow!).
- Could even break filament at edge of wire comb!
- Given fragility, seemed impractical to fabricate planes of ~40-50 wires in 6mo. timescale

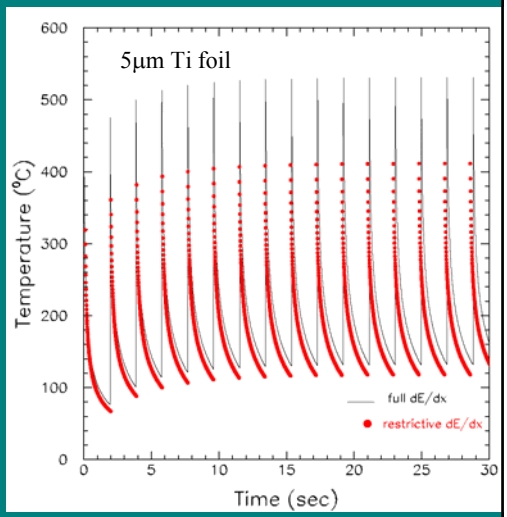


- Results of two out of 12 wires measured. Final four broke 42-45g tension.

Foil/Wire Heating

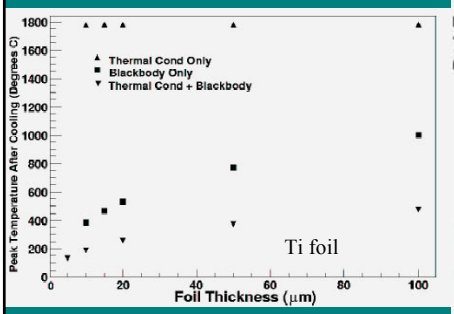
(see NuMI-B-929)

- Wire heating grows with ***volume***
  - For round wire:
    - Wider wire intercepts more beam -- goes like ~ r
    - dE/dx dumped into wire grows – goes like ~ r
  - For flat foil
    - Wide foil intercepts more beam – goes like width
    - dE/dx dumped in goes like thickness t
- Blackbody cooling grows with ***surface area***
  - Gas cooling assumed nil
  - Blackbody radiation goes like surface area ~ r (Emissivity of bare Aluminum is poor ~ 0.1)
- Conduction to the ends grows with ***cross-sectional area***
  - But note many materials have poor thermal conduction (in W/cm-°C)
  - Don't expect this to be dominant heat loss.
- Suggests that surface to volume ratio is critical
  - Wire surface/volume ~ $2/r$
  - Foil surface/volume ~ $1/t$
- Crude thermal model of foil/wire
  - σ~ 1mm beam at 4×10^{13}/pulse every 1.9 sec
  - Assumed ε, k_{cond}, C_p, dE/dx, ρ from CRC, PDG
  - Assumed round wire or 0.2mm wide strips, 10" length
  - All plots are for center-most (hottest) strip/wire
  - Also tested if *restrictive* energy loss important (loss of δ rays out back of device – more imporatant for thin foils).

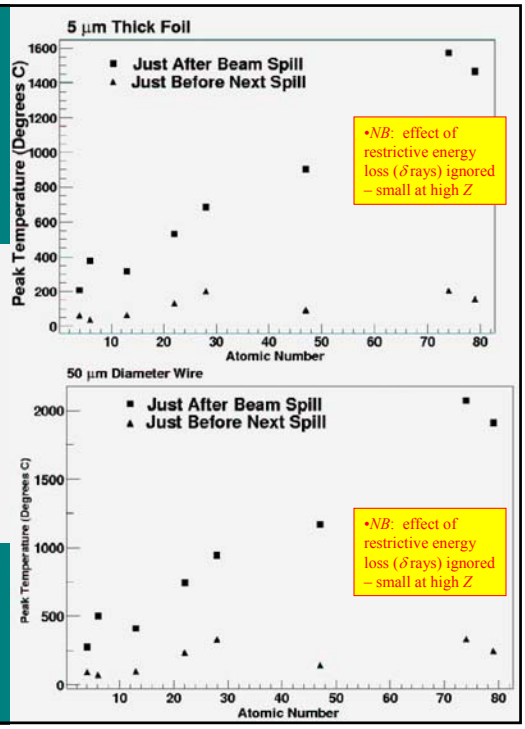


Foil *vs.* Wire?

- As a check of these assertions, tried 'turning off' either blackbody radiation or thermal conduction through foil/wire



- Looked at all materials, modelling with correct thermal and bulk properties
  - C and Al ideal,
  - Ti is not far behind.



Beam-Induced Sag for Wire SEM's

Material	Z	CTE (10^6/°C)[3]	Yield Strength [4] (MPa)	Yield Strength [4] (grams)[a]	Young's Mod. (GPa)[4, 5]	Fractional Elongation at Yield Str.($\times 10^{-3}$)	Fractional Elongation from Beam Heating ($\times 10^{-3}$)[a,b]
Beryllium	4	12	240[d]	48	287	0.84	0.28
Carbon	6	0.6-4.3	469[c]	40-45[c]	40.3[c]	11.6	< 0.083
Aluminum	13	25	10-35[d]	2-7	70.3	0.14-0.50	0.68
Titanium	22	8.5	140-250[e]	28-50	115.7	1.21-2.16	0.27
Nickel	28	13	1580[d]	316	199.5	7.9	1.1
Silver	47	19	-	-	83	-	-
Tungsten	74	4.5	550[d]	110	411	1.34	0.63
Gold	79	14.2	205[f]	41	82.7	2.48	1.46

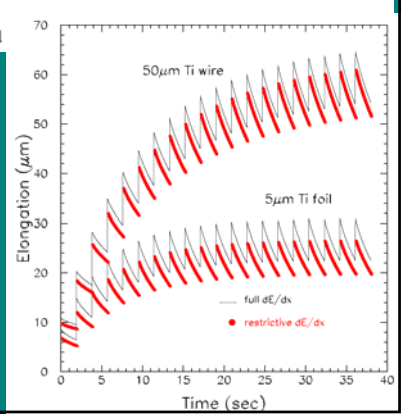
[a] For a 50μm diameter wire
[b] Taken from data in Figure 13
[c] Our measurements of 33μm diameter C monofilaments
[d] soft
[e] annealed
[f] hardened

- Gravitational sag δy improves with greater *stress* ($=T/A$)

$$\delta y = g\rho AL^2/T$$

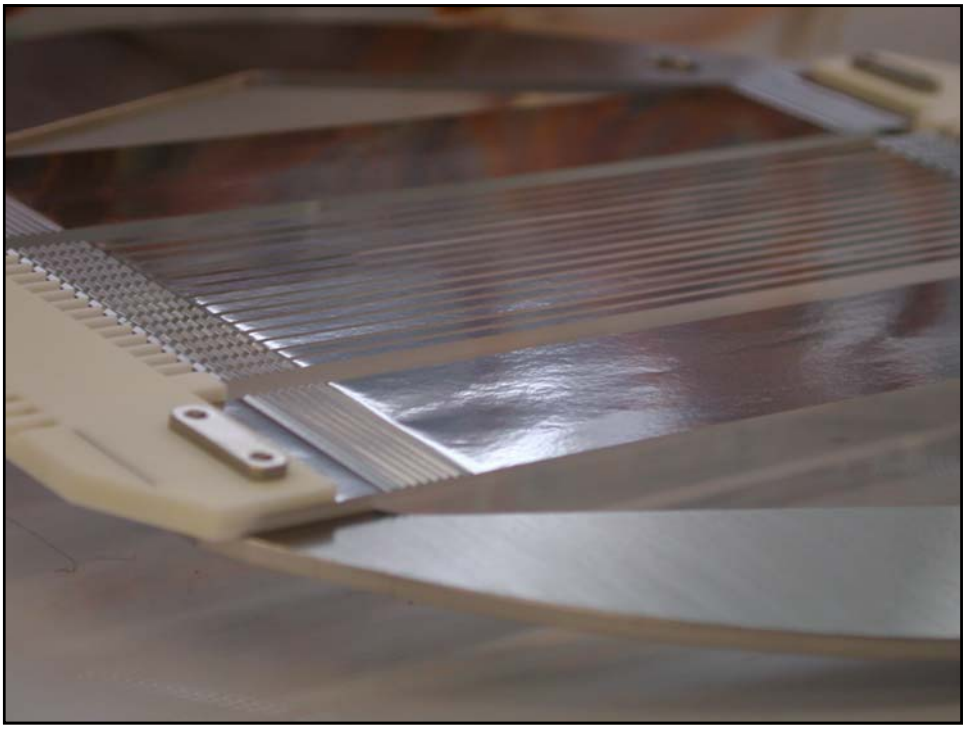
(T=tension, L=length, A=cross sect. area, ρ=density, g=9.8m/s^2)

- Yield stress is where wire breaks. Elastic limit typically lower
- For sake of discussion, assume can tension wire to yield stress.
- Compare tension elongation to beam heating elongation.
- If elongation from beam heating is xx% of elongation from stringing at yield strength, then wire loses xx% of tension in beam, so gravitational sag worsens by xx%
- Only Carbon is an attractive material for wire SEM



CERN: SEM foils

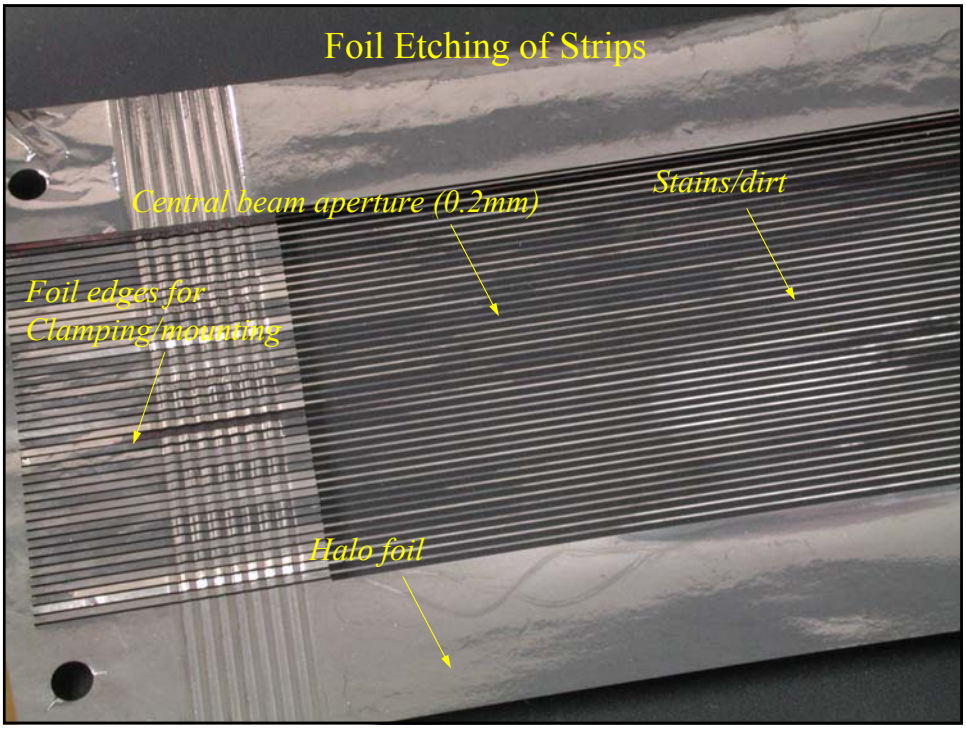
J.Camas, G.Ferioli, R.Jung



Foil Material

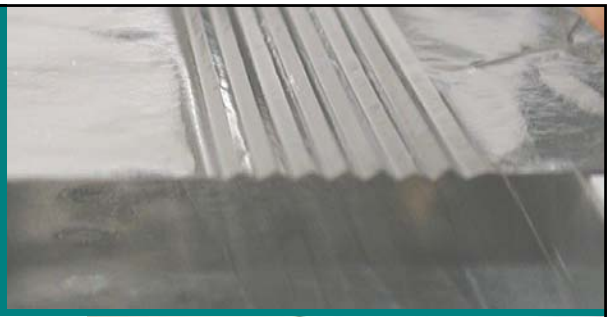
- Searched for Grade I or II Titanium (same as used at FNAL in beam vacuum windows)
- Thickness of 0.0002" (5 μm) or 0.0001" (2.5 μm) easily available. We have gone with 5 μm at present
- Typical tolerance on thickness ± 10% (*no* effect on SEE yield, only on beam loss).
- Vendors
  - Group Arnold (IL) -- 100 ft (4") for $3,500
  - Hamilton Precision Metals (PA) -- 100 ft (3.25") for $4,450
  - Goodfellow (UK) -- 30 m (100mm) for $21,000.
  - Metalmen (NY) -- 100 ft (3.75") for $5,000
- Experience with material to date:
  - Outer ¼" of material less uniform flatness (defect of the rolling procedure?)
  - Material VERY strong, but can be inelastically deformed if pull too hard (would distort strips, etc), so handling must be done non-manually.

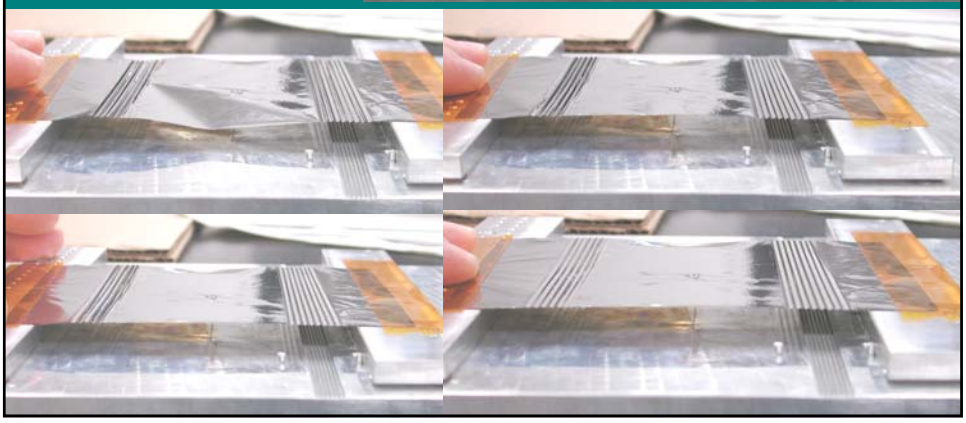
Foil Etching of Strips

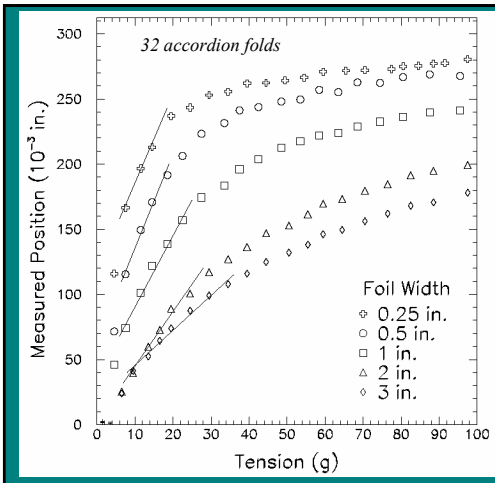


Accordion Springs

- Apply tension to each strip individually.
- Compensates for different beam heating on each strip.

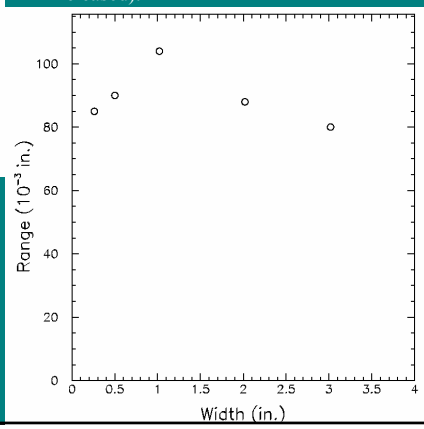






Accordion Spring Tension

- Tests performed of elasticity of accordion springs (measure elongation *vs* appl tension)
- *NB:* large systematic as foil "straightens out" other (non-accordion) wrinkles
- Observe near-elastic region and then region of inelastic deformation of accordions (don't return to original length when tension released).



- Max elastic tension scales with foil width: 1mm width ⇒ achieve 0.7g
- Max elongation at elastic tension limit does not scale (?) with foil width
  - may tension 32 folds by ~ 0.080"
  - beam heating causes ~ 0.001"

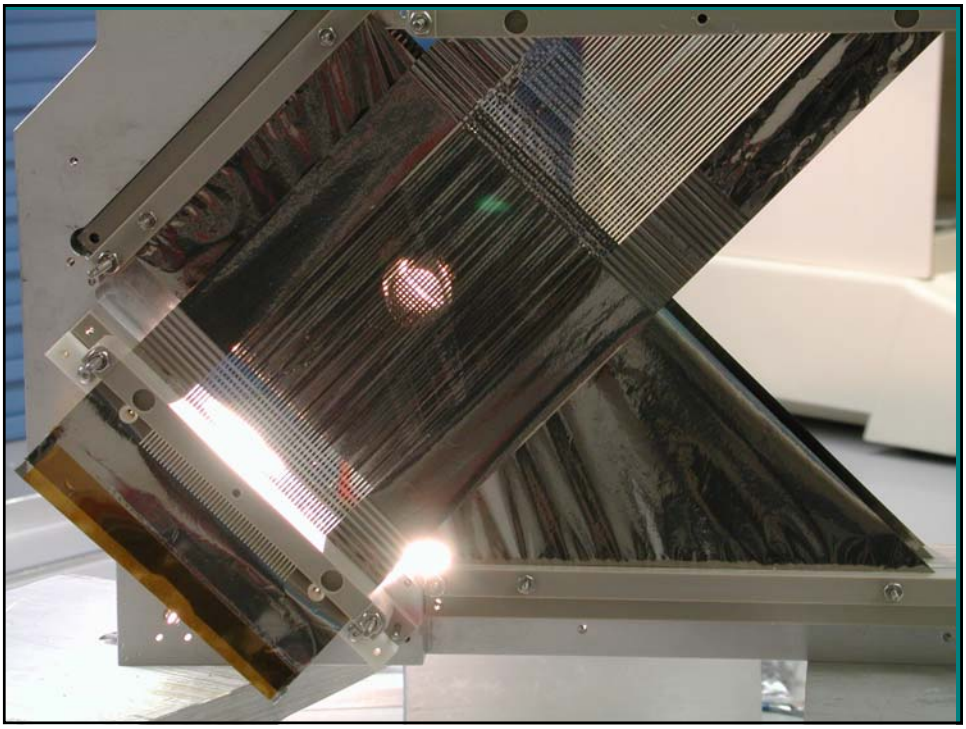
BEAM HEATING → ~1% TENSION LOSS

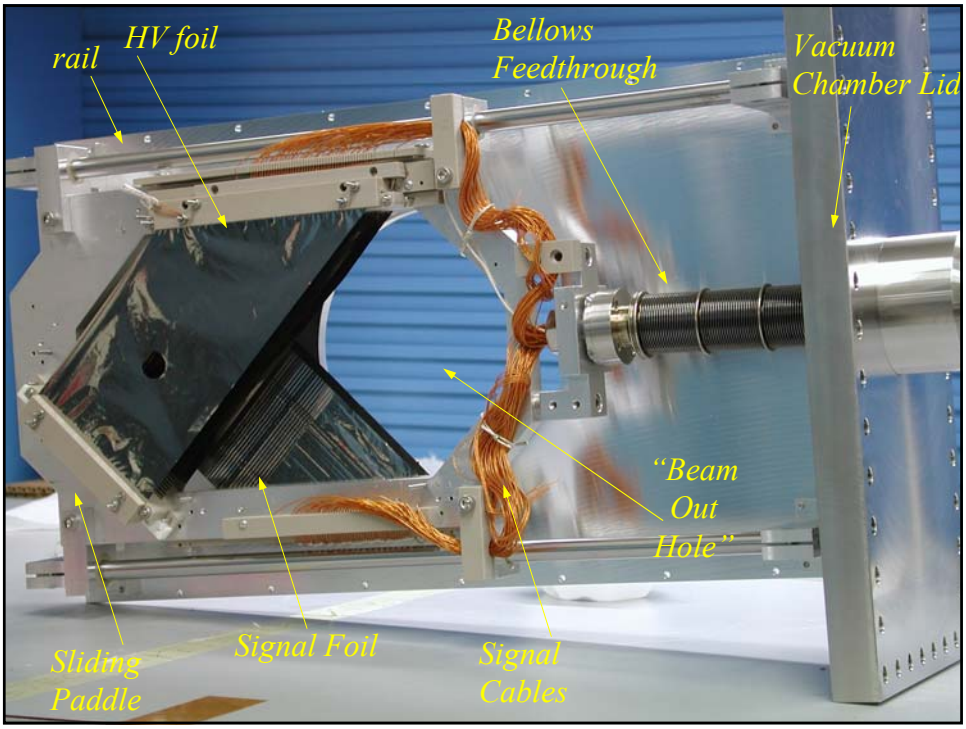
Foil Cleaning In Sulfuric Acid

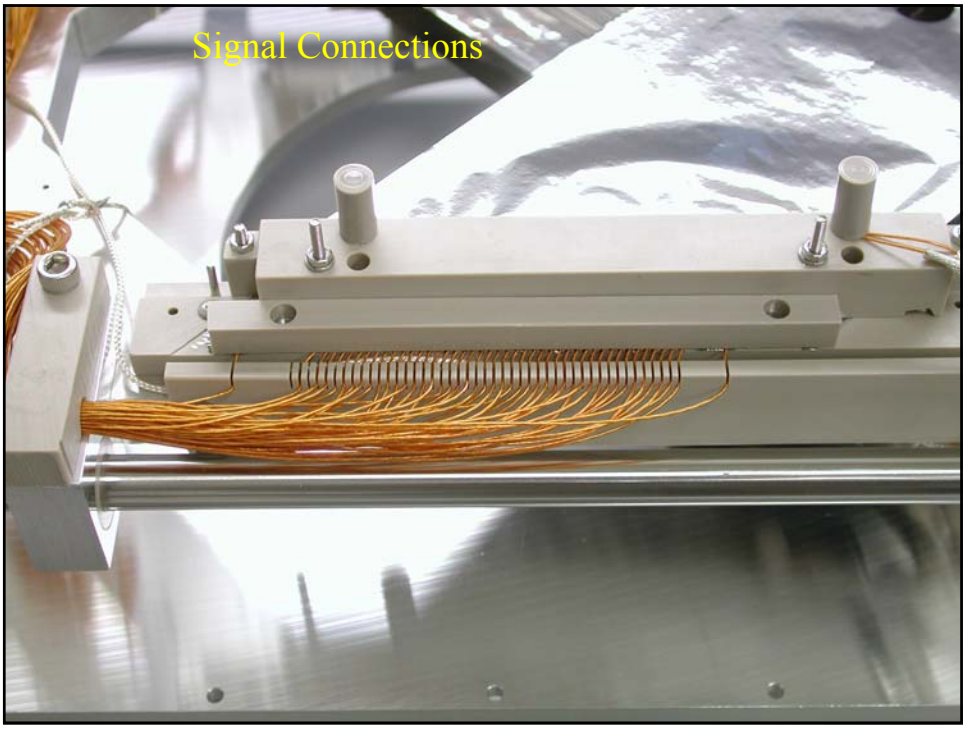
- Technique improved (no burning of Ti material)
- Found photo-resitive layer that is easier to clean off.

Foil Mounting

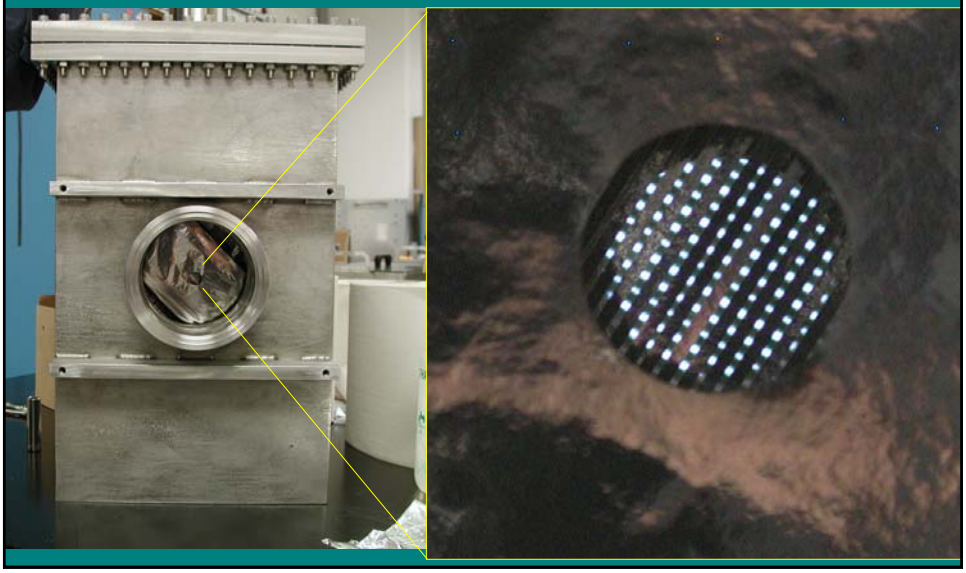
- Epoxy to PEEK comb using Epo-Tek H27D
- Epoxy is recommended by condensed matter group (10^{-12} Torr vapor pressure)
- Cures at 200ºC, bakeable to 350ºC




rail
HV foil
Bellows
Feedthrough
Vacuum
Chamber Lid
"Beam
Out
Hole"
Sliding
Paddle
Signal Foil
Signal
Cables



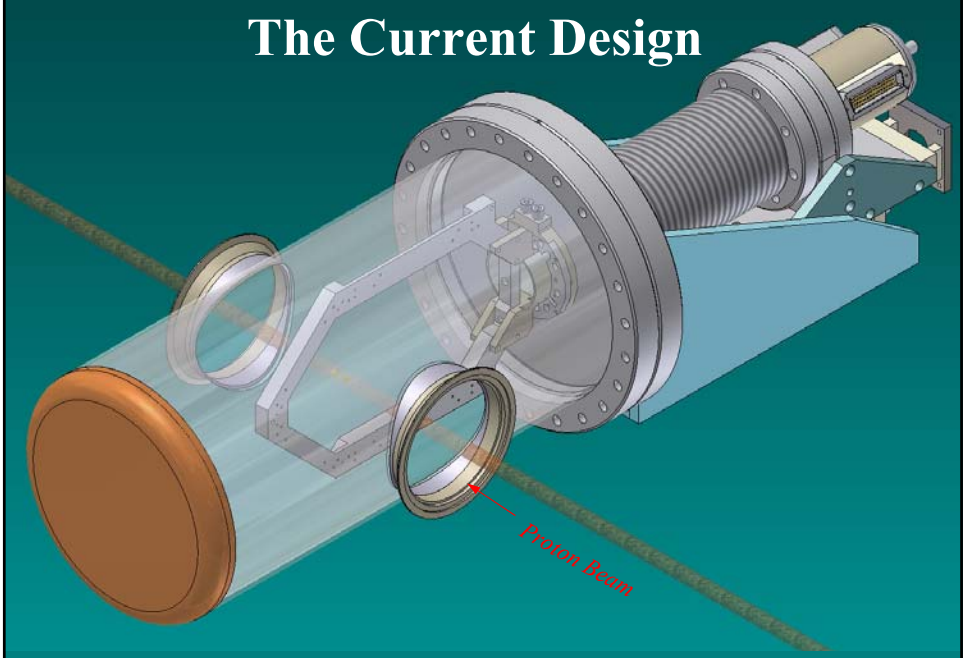
Assembled SEM Chamber



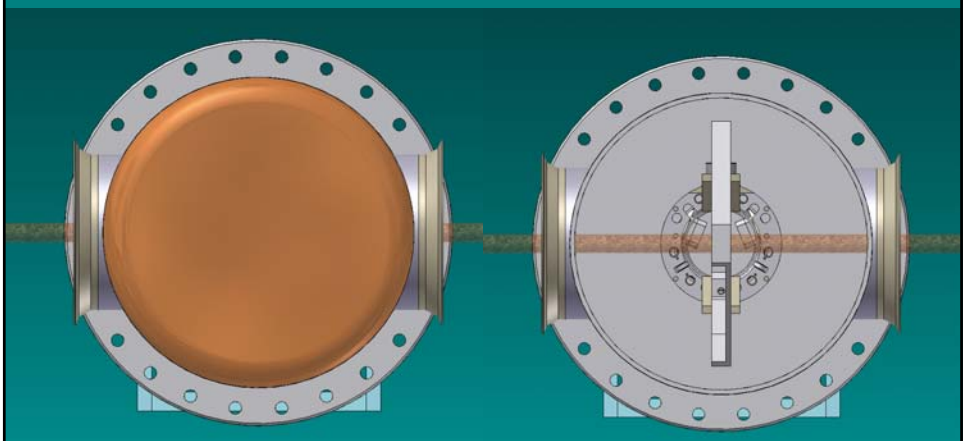
Foil Mounting Lessons From Prototype

- Cleaning is important, but challenging
  - Vendor now using different photo-resist that is aqueous-based – easier to clean
  - Our cleaning procedure is now 'mature' (after many ~~failures~~) *refinements*
- Handling of foils can stretch the material
  - If strips are distorted, they will receive less tension from accordions
  - Some distorted strips seen not to lie in the plane well, or to affect 1mm pitch
- HV foils should have accordions, too
- Accordion springs have many beautiful features
  - Lessen sensitivity to handling
  - Protects foil during bakeout and during epoxy curing at 250ºC
  - Space is available to increase number of accordions – which increases tension
- Precision in foil location comes from combs
  - These should have precise dowel pins for assembly onto paddle
  - If paddle has other precise markers, can now mechanically align foils to those markers

The Current Design

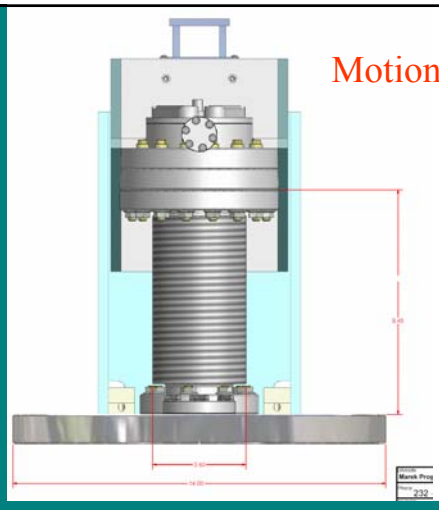


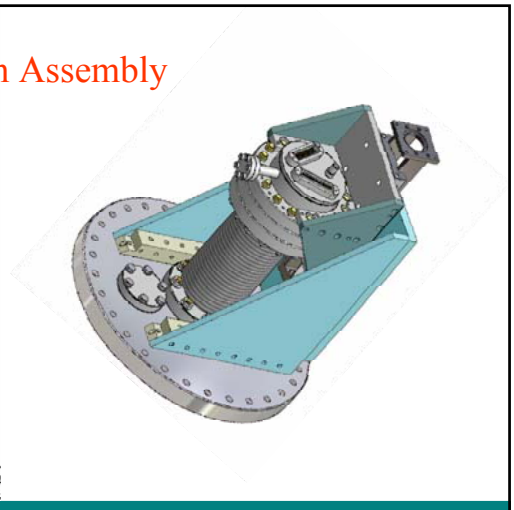
End-on View



- Flange-to-flange distance is 9.25” (less than required 10.25”)
- Cylindrical chamber fabricated from 8” OD pipe, 8” vacuum endcap
- Upper lid is now 10” OD conflat (change from wire seal in prototype)
- Cylindrical design sacrifices longitudinal space along beam for ease of manufacture.
- Total mass to lift: <70 lbs.

Motion Assembly





- Large aperture (2.5” ID, 3.5” OD) bellows to better pump out connector box region.
- Connector box here shown made of 6”OD conflats, but now using 4.5” OD
- Feedthrough’s are same Ceramaseal 50-pin model used in FNAL multiwire
- Bellows effective area ~ 7in^2, so ~100lbs force due to vacuum suction.
- Crossed-roller bearing ball screw stage provides lift to the connector box.
- Assembly driven by NEMA-23 stepper motor.
- Mounting brackets for linear based on brackets shown in NEAT, Parker-Daedal catalogs

Note Resemblances…

MDC Vacuum

Kurt J. Lesker Co.

•All these products are motorizable.

Industry-wide invariant: cost is about $1000/inch of travel for 2.5" ID bellows assembly (even when quoting for 10-15 units for our NuMI order!)

•In general the sizes of these objects larger than our design.

Difficult to obtain gaurantee from manufacturer for 50μm reproducibility unless encoder system added.

Use of any of these requires "engineering" & R&D on our part to add LVDT, switches, ensure repeatability.

Huntington Laboratories

Thermo Vacuum Generators

Bellows

- Purchased from Standard Bellows Co supplier for
  - MDC Vacuum
  - Varian
  - Thermo Vacuum Generators
- Also received quotations from
  - Flexial — Bellows Tech
  - Flex-weld — Seymour Sheridan
  - MS Bellows — LaserTech USA
- Price ~$800 in qty 15 (still dropping)

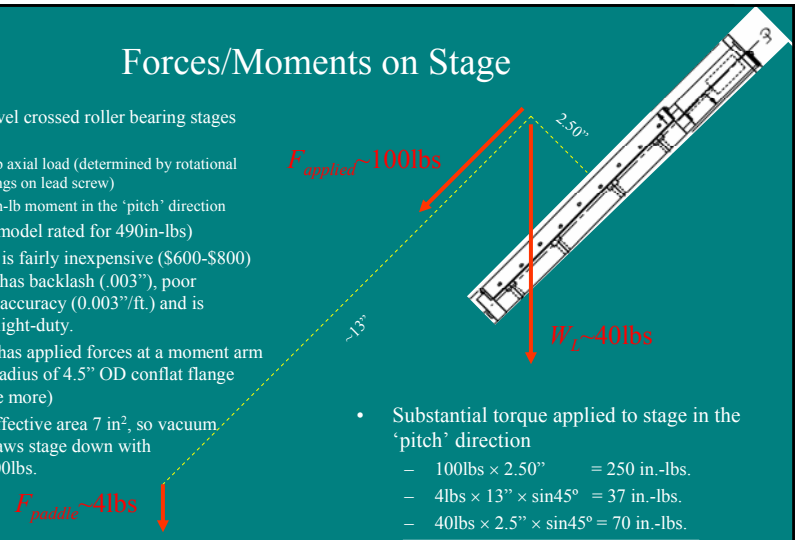
- Edge-welded, SS 316 construction
- Rated to 10K cycles at full stroke
- Lifetime doubles for every 20% of stroke not used
- We purchased 5.3" stroke bellows, will use 4.50" ⇒ lifetime ~20K cycles
- Bellows has spring force 1.2lbs/in.

- Lifetime degrades if angular offset ⇒ rotatable flange on one end
- Life time affected by lateral offsets of flanges, effect is more severe if there is an offset and bellows is driven to full compression ⇒ use upper 4.5" of the 5.3" full stroke

Forces/Moments on Stage

- PIC 6" travel crossed roller bearing stages rated for
  - 200 lb axial load (determined by rotational bearings on lead screw)
  - 370 in-lb moment in the 'pitch' direction

  (8" travel model rated for 490in-lbs)
- This stage is fairly inexpensive ($600-$800) because it has backlash (.003"), poor leadscrew accuracy (0.003"/ft.) and is relatively light-duty.
- Our stage has applied forces at a moment arm of 2.50" (radius of 4.5" OD conflat flange plus a little more)
- Bellows effective area 7 in^2, so vacuum suction draws stage down with $F_{applied}$ ~100lbs.



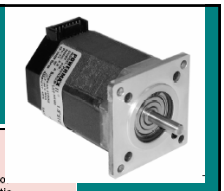
- Substantial torque applied to stage in the 'pitch' direction
  - 100lbs × 2.50" = 250 in.-lbs.
  - 4lbs × 13" × sin45º = 37 in.-lbs.
  - 40lbs × 2.5" × sin45º = 70 in.-lbs.

  Total = 360 in-lbs.
- Bellows spring constant 1.2lbs/in, so $F_{applied}$ varies 96-101 lbs at ends of stroke.
- For this review, we purchased and tested 6" PIC stage, for final design, will use 8" stage.

Motor Requirements

- Calculated required holding torque for motor assuming
  - 3/8" Ø, 8 rev./in. lead screw
  - 15 seconds to perform full stroke (negligible effect on torque requirement)
  - W_L = 40 lbs is moving mass attached to stage
  - $F_{applied}$ = 96-101 lbs is axial force on stage (vacuum suction + bellow spring force)
  - Ball screw stage has screw efficiency ε = 0.9, sliding friction μ=0.03
  - 45º angle mounting of the stage
- Calculated torque requirement is **45.8 oz.-in.** (details given in weekly reports, though different numbers than above assumed back then)
- Usual rule of thumb in industry is to double calculated requirement ⇒ 90 oz-in?
- In our application a motor brake does not appear useful
  - Lift foils 'up' into the beam
  - Power off will backdrive paddle to 'beam out' position
  - Only need to hold paddle 'in' the beam for ~1/2hr – 1hr time intervals?

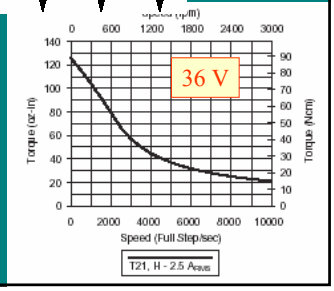
Stepper Motor: PowerMax-II (Pacific Scientific)



Rated Currents are in descending order

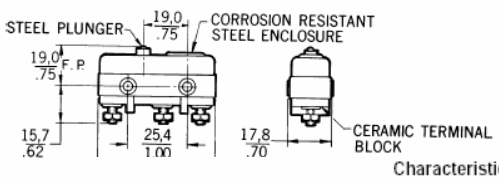
Motor Model Number	Connection: Parallel	Connection: Series	Connection: Unipolar	Holding Torque (2 phases on) oz-in (Nm) ±10%	Rated Current/ Phase (amps DC)	Phase Resistance (ohms) ±10%	Phase Inductance (mH) Typical	Detent Torque oz-in (Nm)	Thermal Resistance (°C/watt)	Rotor Inertia oz-in-S² (kgm² x 10⁻³)	Weight lbs (kg)
Torque range: 95-144 oz-in. .67-1.02 Nm											
M21NXXA-LXX-XX-00	•			142 (1.00)	5.6	0.23	0.7				
M21NXXA-LXX-XX-00		•		142 (1.00)	2.8	0.92	2.8				
M21NXXA-LXX-XX-00			•	100 (0.71)	4.0	0.46	0.7				
SIGMAX® M21 Series 1 rotor stack											
M21NXXB-LXX-XX-00	•			137 (0.97)	4.6	0.32	1.0				
M21NXXB-LXX-XX-00		•		137 (0.97)	2.3	1.28	4.0				
M21NXXB-LXX-XX-00			•	97 (0.68)	3.3	0.64	1.0	9.4 (0.066)	5.5	0.0017 (0.012)	1.5 (0.68)
M21NXXC-LXX-XX-00	•			144 (1.02)	3.5	0.53	2.0				
M21NXXC-LXX-XX-00		•		144 (1.02)	1.75	2.12	8.0				
M21NXXC-LXX-XX-00			•	102 (0.72)	2.5	1.06	2.0				
M21NXXD-LXX-XX-00	•			135 (0.95)	1.51	2.61	8.7				
M21NXXD-LXX-XX-00		•		135 (0.95)	0.76	10.4	34.8				
M21NXXD-LXX-XX-00			•	95 (0.67)	1.07	5.22	8.7				

- Our motor speed will be ~10 rev/sec, so torque should not fall much from 97 oz-in stated above.
- Electrical specs compatible with Al Legan's controller
- *NB*: we will obtain greater torque performance out of the motor at FNAL because of 48V operating voltage of the controller system here (using 36V controller at UT)



Limit Switches

- Manufactured by Honeywell
- High temperature switch manufactured with ceramic insulators
- Same switch used in Tevatron scraper system
- Switch engages within 1mm stroke (but repeatability of where within that stroke is not specified by manufacturer)

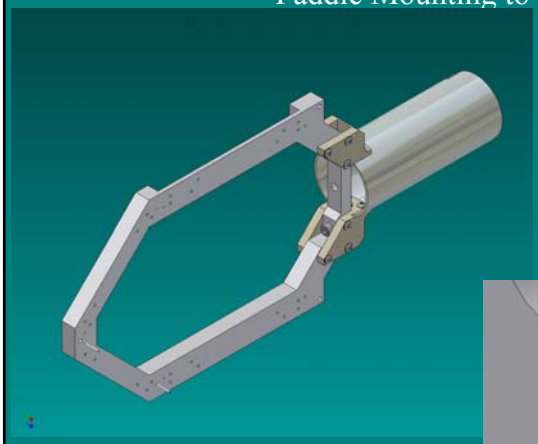


Characteristics: O.F. — Operating Force; R.F. — Release Force; P.T. — Pretravel; O.T. — Overtravel; O.P. — Operating Position.

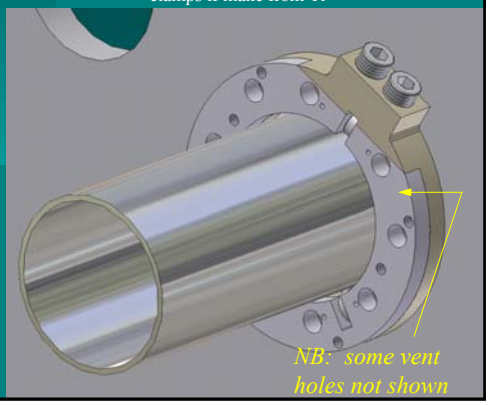
ORDER GUIDE

Catalog Listing	Description	Electrical Rating	O.F. newtons ounces	R.F. min. newtons ounces	P.T. max. mm inches	O.T. min. mm inches	O.P. mm inches
2HT1	Pin plunger side mount	3 Amps	2,78-5,56 10-20	1,67 6	1,27 .050	0,25 .010	16,8 .66 approx.

Paddle Mounting to Manipulator



- Paddle to be bolted to the 2" OD shaft
  - Cables transmitted up hollow shaft
  - Bolt slop used to help align paddle on jig
- Cantilevered by ~9" from the support at the conflats at "connector box"
  - Deflection of tube is <0.001" due to paddle weight
  - Can keep paddle weight <4lbs including clamps if make from Ti



- Worried about vibration of paddle down in tunnel
- Add roller bearing assembly inside vacuum chamber lid
  - Two stiffly mounted rollers
  - Roller at top is spring-loaded to contact shaft
- Now cantilever distance is <1" when paddle is drawn up toward lid ("in beam position")

HR Series

Readback Mechanism:

General Purpose LVDT

The high reliability HR Series of LVDTs is suitable for most general applications. The HR Series features a large core-to-bore clearance, high output voltage over a broad range of excitation frequencies, and a magnetic stainless steel case for electromagnetic and electrostatic shielding.

Features

- ❑ *Optimum performance for a majority of applications*
- ❑ *Large 1/16 inch radial core-to-bore clearance*
- ❑ *Calibration certificate supplied with all models*
- ❑ *Compatible with all Schaevitz® signal conditioners*
- ❑ *High temperature (220°C) and high pressure (vented case) available – consult factory*

Applications

- ❑ *General*

Options

- ❑ *5.0 kHz excitation frequency testing**
- ❑ *Metric thread core*
- ❑ *Guided core*
- ❑ *Small diameter/low mass core*
- ❑ *Mild radiation resistance (withstands 10^{12} NVT total integrated flux; 10^{7} rads Gamma)*

** Performance and electrical specifications for alternative frequencies will differ from the standard specifications listed below which are based on a 2.5 kHz excitation frequency. Consult factory for further information.*

Specifications

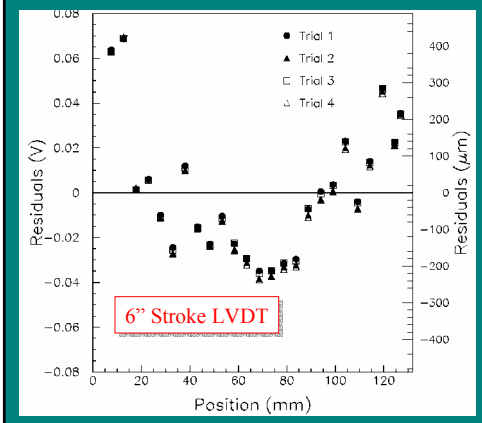
Input Voltage	3 V rms (nominal)
Frequency Range	400 Hz to 5 kHz
Operating Temperature Range	-65°F to 300°F (-55°C to 150°C)
Null Voltage	<0.5% full scale output
Shock Survival	1,000 *g* for 11 msec
Vibration Tolerance	20 *g* up to 2 kHz
Coil Form Material	High density, glass-filled polymer
Housing Material	AISI 400 series stainless steel
Lead Wires	28 AWG, stranded copper, Teflon-insulated, 12 inches (300 mm) long (nominal)

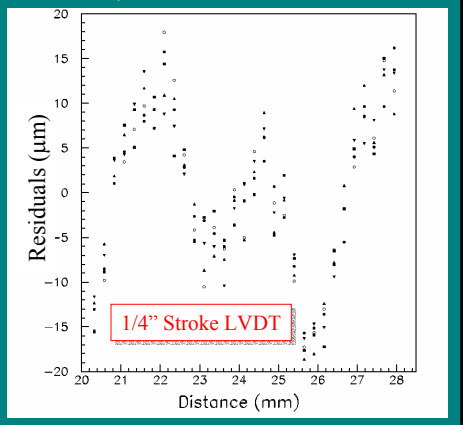
Or kapton

phenolic

Measurements of LVDT Accuracy

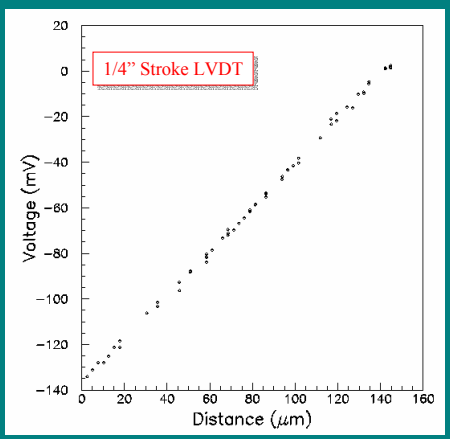
(*ie*: linearity over full stroke)

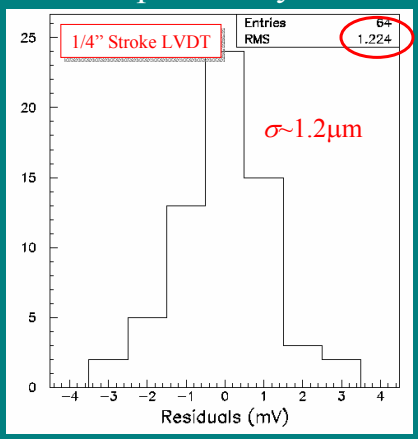




- Mounted LVDT on motion stage and confirmed position with dial indicators.
- Devices rated to have ~0.25% linearity – consistent with our measurements
- The statement has been made to us that LVDT's are not better in accuracy than ~0.5mm. For long-stroke LVDT which are *assumed* to be purely linear, this can readily be seen.
- If want better accuracy, must calibrate V_{out} vs position – simple but tedious

Measurements of LVDT Repeatability



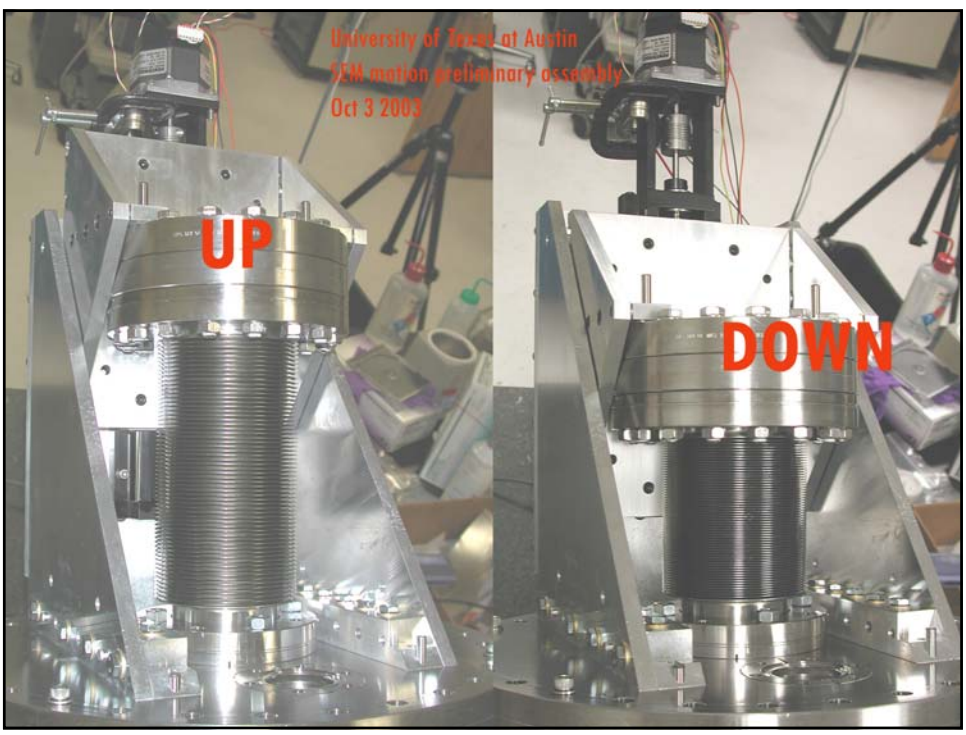


- Our feeling is that it is not important to know SEM position throughout travel
- May therefore used small stroke LVDT to confirm 'stop' position (in beam)
- In this case, the spec for the LVDT is how well it repeats to a given position.
- The LVDT is better than any dial indicator in our possession at the time of the test.
- In separate test, sent the motion stage to a hard stop, trusting the stop position. In this case achieved resolution of σ~0.5mV=0.5μm.

Repeatability Test

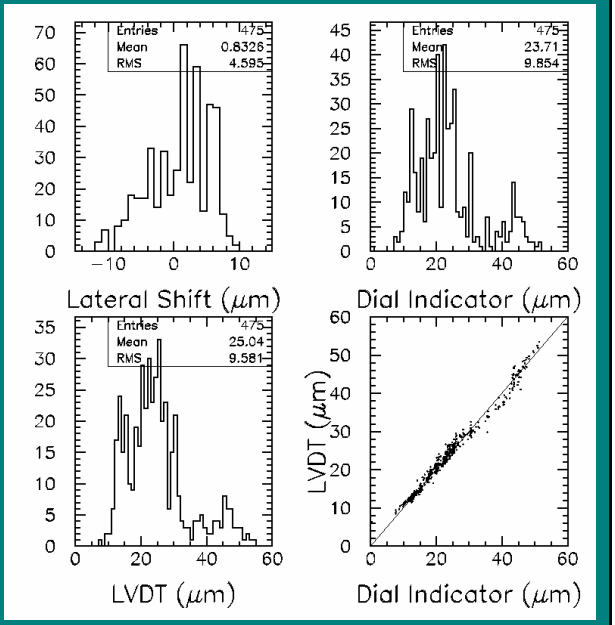
- Cycle motion up and down until motor cuts off at the limit switch
- Paddle weight simulated at end of shaft
- Vacuum suction simulated by Pb brick over a pulley

- LVDT measures position along axial motion (cross-check with dial indicator)
- Additional dial indicator monitors lateral position of shaft at fully-inserted or fully-retracted position.

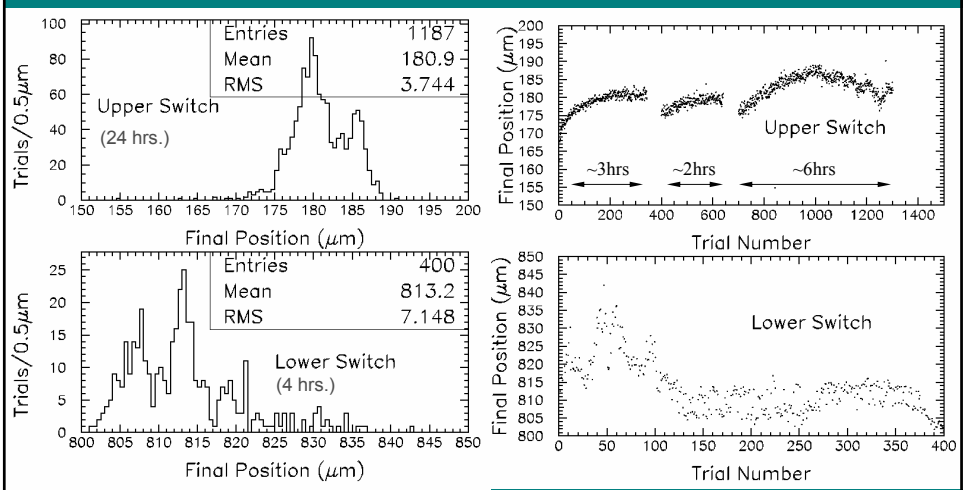


First Test Results

- First test was to drive stage to 'lower' switch
- Confirmed that LVDT measures axial motion quite well (better than the dial indicator used to confirm it!)
- Test result is fine – sort of. Obtain good reproducibility over short periods (hours) but there appeared drift in the system over the course of day(s).
- Lateral variation was OK, but a little large. *Highly* correlated with axial motion.
- Conjecture for observed variation: motor requires certain time to stop after switch engages, continues to move downward due to gravity, vacuum suction.



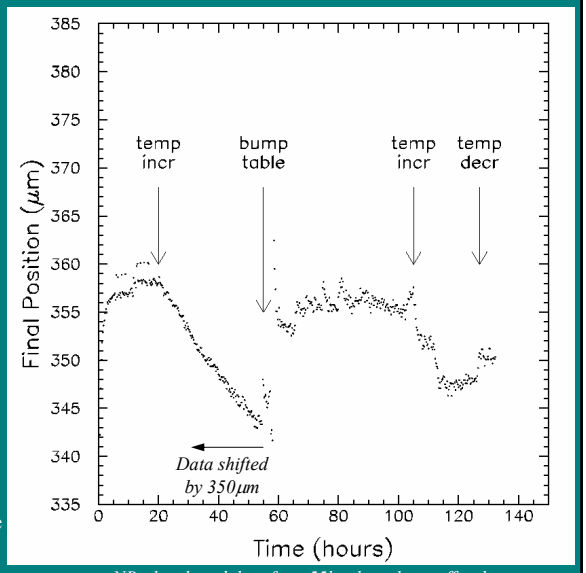
Results of Repeatability Tests (*cont'd*)



- Now compare results if drive to upper switch
- Switch engages with few μm accuracy.
- There appears to be drift in the system (thermal effects!!)
- *NB*: still no applied load in these tests to simulate vacuum suction – only mass of flanges, shaft
- We conjectured that it's better to drive the system to the upper switch, where gravity + vacuum helps slow system down after switch engages

Discussion of Errors

- Motion test setup positioned next to vacuum checkout table now under bakeout.
- Temperature in lab varies by ~1ºC if room is closed for the evening or if bakeout is underway on the vacuum stand.
- Our motion manipulator is mostly stainless steel (CTE~12×10^{-6}/ºC), while the support stand is aluminum (CTE~25×10^{-6}/ºC)
- Differential expansion of test stand materials ⇒ shifts in our data of ~8µm/ºC
- This behaviour confirmed in recent test (motion cycle every 15minutes) in which vacuum test stand was both ramped hotter and cooler.
- NuMI SEM will be all stainless and Ti (ΔCTE~4×10^{-6}/ºC), so effect there may be smaller, but clearly at the ±10µm level things will move?

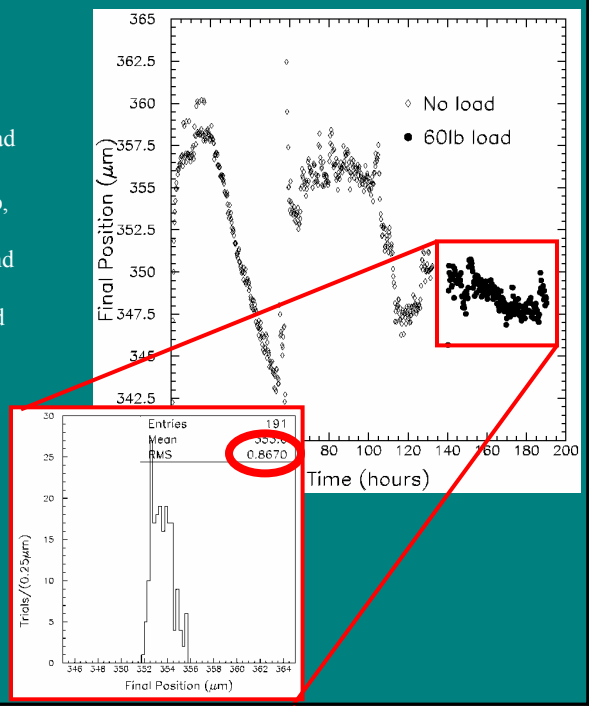


NB: the plotted data for <55hrs have been offset by 350µm to allow them to fit on the same plot. The motion test table was bumped by S.K.

Final Motion Test

- Simulated load on manipulator from vacuum suction – 60lb lead brick
- Actual vacuum suction is 100lb, but in the final design it will be applied at 2.5" moment arm, and in this test it is applied at 3.3" moment arm. So reduce applied load by 2.5/3.3~0.67.
- Data continue to support the hypothesis that error is due to motor continuing to move after switch engages (load actually helps us in this direction).

- Axial variation now ~0.9µm RMS
- Lateral variation now ~3µm RMS



Production

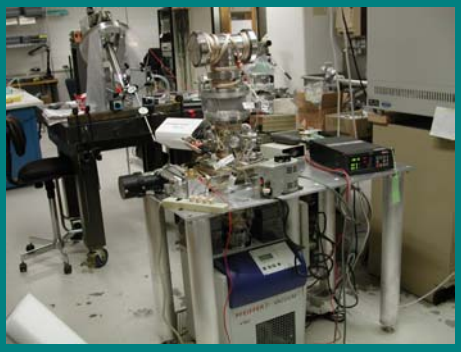
I. Foil paddle production
   - Require 24 signal foils for 12 SEM devices
   - Budget 50% spares assuming low yield, installation difficulties ⇒ 36 total
   - Have ordered first 10, these due Nov. 15
   - Require ceramic clamps → these already ordered, due Nov. 30
   - Require paddle frame made from Ti – received Ti plate, design now complete

II. Motion Manipulator
   - Design near-complete (require mounting for LVDT's, switches, drip cover for external components, slight revision for 8" travel stage)
   - Require 12 PIC catalog stages → lead time of order is 6wks
   - Require 12 welded bellows assl'ys → lead time of order is 6wks
   - Require 24 signal feedthroughs and 12 SHV feedthroughs → lead time of order is 8wks

III. Vacuum Can, Testing
   - Design near-complete (require final specs for flanges, mounting from FNAL)
   - Design much simpler to fabricate – fewer shop hours, HEP hours for assl'y
   - Require construction of a custom 'oven' for careful bakeout
   - Have recently purchased 3 dry pumping stations for simultaneous check-out of 3 devices

IV. Survey, alignment, referencing
   - Must add view ports to vacuum can
   - Must design jig for mounting paddle on motion manipulator

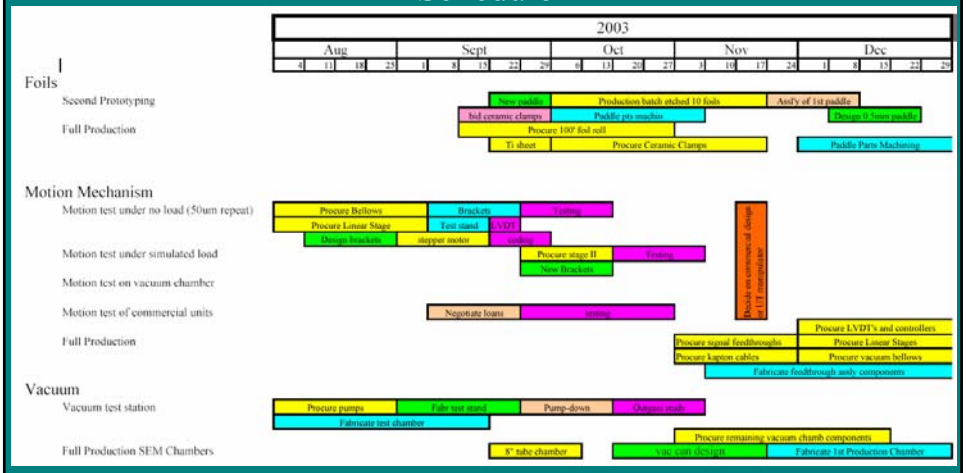
Vacuum Testing



- Built one system for baking & checkout of our SEM's.
- Recently, local Austin chip fab plant closed ⇒ we acquired *2 additional* dry pump stations
  - Dry rough pump (diaphragm or tri-scroll)
  - 250l/sec turbo (Pfeiffer or Leybold mag lev)
  - Varian 60l/sec ion pump
  - 6-way cross for connecting the ion pump, turbo, our SEM, gauges
- Additionally, have Pfeiffer QualyDryTest portable leak detector
- Have one Pfeiffer 80 amu residual gas analyzer

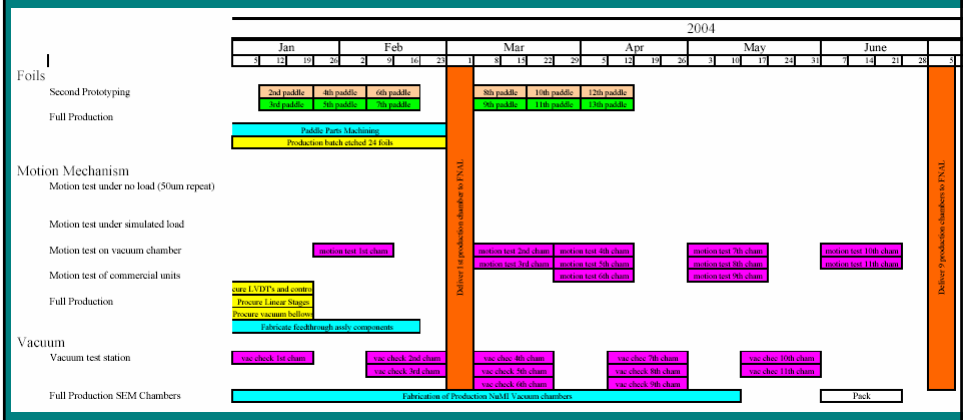
- Even if every chamber requires 1 mo. to check out, we can now do all 12 in 4 mo.

Schedule



- Schedule developed early Sept '03, when thought required demonstrations were: foil mounting, vacuum outgassing, motion tests
- We are since then ahead of schedule on some tasks, deliberately slowed on others (lower priority), and date of this review moved up.
- Our focus changed to increase production capacity
- We need to re-evaluate priorities together with FNAL, develop set of milestones ⇒ ***and we will meet them***

Schedule (*cont'd*)



- Schedule now fleshed out to include production of 10 chambers
- Note that motion testing is fairly automated at this point

Cost Estimate

NuMI Profile Monitor SEM's

Number of SEM's assumed: 12 Cost/SEM: 17726

June 14, 2003	Cost (unburdened)	FNAL G&A	Cost (burdened)	Amount Already Spent
SEM foils	40437	607	41044	10588
Vacuum Can	102418	1536	103954	620
Personnel	69856	1048	70904	0
Shipping	8428	126	8554	0
Total	221139	3317	224456	11208

- Based on pricing components for prototypes
- Quantity discounts applied when known (bellows, foils, stages…)
- Cost for 24 SEM devices is closer to $12K (still on steep curve)
- Note that costs include infrastructure (jigs, testing), so is not simply parts costs
- UT overhead rates:
  - M&CS: 0%
  - SWF (tech's, professionals): 22.5%
  - SWF (undergraduates): 50%

FNAL overhead rates

M&CS: 16%

SWF: 47%

What are the Risks?

- This review must address whether there is risk to the NuMI project if we continue to the foil SEM as the default profile monitor.
- Going into this effort, there were several technical 'risks'
  - Active medium survives in beam? *CERN says OK (too bad we didn't test)*
  - Vacuum chamber OK to 10^{-8} Torr? *Modifications should allow it.*
  - Motion manipulation reproducible to 50μm? *How about 860nm?*
- We believe these are solved
- Production risks?
  - Cost of device might balloon? *No. Well documented based on prototype effort, vendor quotations and contracts. UT-Austin is* ***highly*** *cost-effective*
  - Schedule slip? *We have taken several steps to accelerate schedule. We must develop milestones to allow tracking. We think it will be under control.*
- Long term risks?
  - Device uses "non-standard" mechanics, vacuum. *It certainly employs new things to FNAL, but not new elsewhere in HEP or in commerce!*
  - Will FNAL be left with maintenance of outsider's device? *We would pledge to maintain, repair, etc for period into future. This allows time to integrate drawings, vendor orders into FNAL system.*

Getting SPECIFICATIONS from Fermilab…

- While this review must certainly critique the technical merit of the UT-Austin SEM design, this is not the most urgent feedback we need to proceed.

WE NEED SPECS

- We have lost and continue to lose time because we're awaiting
  - Environmental conditions (*eg*: rad levels, allowable space, pumping speed available in the beamline, outgas rates of existing devices, vacuum connections to adjacent beamline elements)
  - operating conditions (#cycles/day, acceptable insertion time into beam, acceptable beam loss, device lifetime, required resolution, required survey accuracy)
  - controls (stepper controls, ACnet software)
- Establishing answers to these questions requires *work* from FNAL, admittedly challenging when manpower is in shortage. Such work from FNAL is required for any vendor contract with any outside company.

Summary

- Foil SEM design borrows from demonstrated techniques employed elsewhere
- Design has solved salient requests made for NuMI beamline
  - Beam loss 7×10^{-6} (*cf* 1.2×10^{-4} current multiwire, or 1.3×10^{-5} in 'thin' multiwire)
  - Longevity in 120 GeV beam up to ~10^{20} protons/cm^2 (*cf* 2×10^{18}/cm^2 for W, Au)
  - Accurate (1μm) insertion of foils without interruption of beam
  - Smaller device size in beamline direction (9.25", *cf* 16" current multiwire)
  - Integrates well into FNAL readout, controls
- Several steps over past 3 mo to allow improved schedule
  - Vacuum can made of 'off the shelf' components
  - Long-lead items already ordered.
  - Increased UT-HEP infrastructure in vacuum testing, pumping
- UT-Austin HEP group is committed to the job
  - Strong experience in instrumentation
  - Close, improving ties to many parts of FNAL accelerator complex
  - Mechanical, vacuum resources in Physics Department
  - Strong interest in this device's completion, implementation, operation

SEM foils

	unit	number units	$/unit	ut indirect	total budgeted amount	Actual amount spent	Notes
Ti foil	1 roll	1.0	3800.00	0	3800	3800	a
Spare Ti foil (2.5um)	1 roll	1.0	3900.00	0	3900		
Cutting of U/V foils	1 plane	30.0	200.00	0	6000	2000	b
Cutting of HV foils	1 plane	36.0	100.00	0	3600		g
Short ceramic clamps	1 edge	24.0	100.00	0	2400	1988	c
Long ceramic clamps	1 edge	24.0	141.42	0	3394	2800	c
Middle ceramic clamps	1 edge	24.0	100.00	0	2400		c
kapton signal cable	1 foot	2304.0	1.67	0	3840		d
PEEK inside connect	1 connector	24.0	100.00	0	2400		e
signal crimp contacts	1 pin	1152.0	1.60	0	1843		f
Acid bath components	1 bath	1.0	500.00	0	500		
Acid	1 gallon	12.0	50.00	0	600		
acetone	1 gallon	72.0	20.00	0	1440		
Fabrication of paddles	1 shop hour	240.0	12.00	0	2880		
jig to cut foil	1 shop hour	40.0	12.00	0	480		
jig to crimp accordions	1 shop hour	40.0	12.00	0	480		
jig for weldin/soldering	1 shop hour	40.0	12.00	0	480		
Total					40437	10588	

Vacuum Can	unit	no. units	$/unit	ut indirect	total cost	Actual Spent	Notes
Bellows	1 bellows	12.0	700.00	0	8400		a
linear stage	1 stage	12.0	1500.00	0	18000		b
stepper motor	1 motor	12.0	100.00	0	1200		c
motor brake	1 brake	12.0	0.00	0	0		c
limit switches	1 switch	24.0	200.00	0	4800		
lvdt	1 lvdt	12.0	200.00	0	2400		
lvdt controller	1 controller	12.0	400.00	0	4800		
SHV feedthru	1 feedthru	24.0	34.00	0	816		d
HV crimp contact	1 pin	24.0	3.40	0	82		f
multipin feedthru	1 feedthru	24.0	350.00	0	8400		e
exterior 48-pin	1 connector	24.0	20.00	0	480		g
copper gaskets	1 gasket	60.0	10.00	0	600	20	i
4" KF flanges	1 flange	24.0	100.00	0	2400		j
bolts	1 bolt	1200.0	0.10	0	120		
tooling ball	1 ball	120.0	18.00	0	2160		
machine shop	1 shop hour	3000.0	12.00	0	36000		
2.75" conflats	1 flange	48.0	20.00	0	960		
10" conflats	1 flange	24.0	200.00	0	4800	600	
stainless steel	1 can	12.0	500.00	0	6000		k
Total					102418	620	