Innovative Technological Solutions for Future Accelerators

Not really a good title, better would be:

Weird Technology for Accelerators

Eric Doyle, Dorel Bernstein, David Brown, Eugene Cisneros, Carlos Damien, Paul Emma, Leif Eriksson, Josef Frisch, Linda Hendrickson, Thomas Himel, Douglas McCormick, Janice Nelson, Richard Partridge, Marc Ross, Knut Skarpaas VIII, Toni Smith
(And a hoard of others)
Next Linear Collider Project – SLAC

H. Hayano, T. Naito, N. Terunuma
(And a hoard of others)
ATF Project, KEK

Technologies Discussed

- Technologies that are not part of “core” accelerator technology.
  - **Not** Structures, Magnets, BPMs, Vacuum
- Unusual materials or systems
  - Liquid metals, low noise mechanical systems, optics
- NOT necessarily “Advanced” or even “innovative”.

Systems Discussed

- Timing distribution and stabilization:
  - Picosecond stability over >10 Kilometers
- Collimation:
  - Of beams which can destroy any solid material
- Beam Diagnostics
  - Mapping beam phase space
- Vibration Stabilization Technologies
  - Low noise seismometers

Timing and RF Phase Distribution

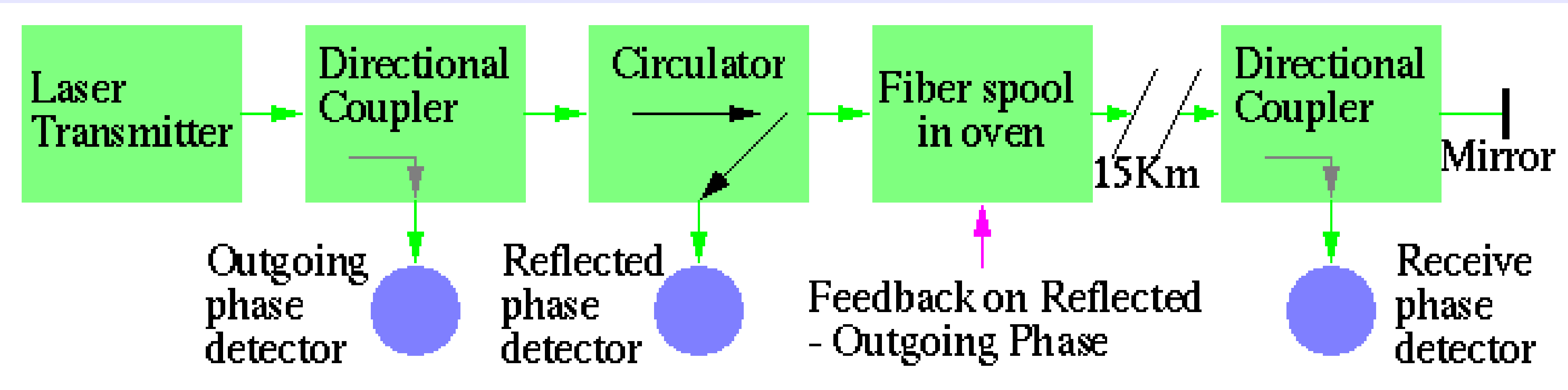
- RF Phase stability:
  - Typically require ~ 1° over length of machine
  - For NLC: 0.25 picoseconds for 30 Kilometers
  - Use beam measurements for long term feedback
  - Need about 5 picosecond long term stability from distribution system
- Trigger Timing Stability / Accuracy
  - Typically ~50 picoseconds stability / jitter.
  - Use count down timers from phase distribution system: Easily meets timing requirements

Timing Distribution Technologies

- Both copper cable and fiber optics have similar phase coefficients with temperature ~$2x10^{-5}$/°C
  - Note: fiber coefficient due to change in index with temperature
  - Would require 0.005 °C temperature stability: **tough!**
- Need to use feedback
- Fiber preferred over Copper due to lower loss and lower cost.
  - Radiation sensitivity must be considered
  - Use fiber for long haul, coax in tunnel.

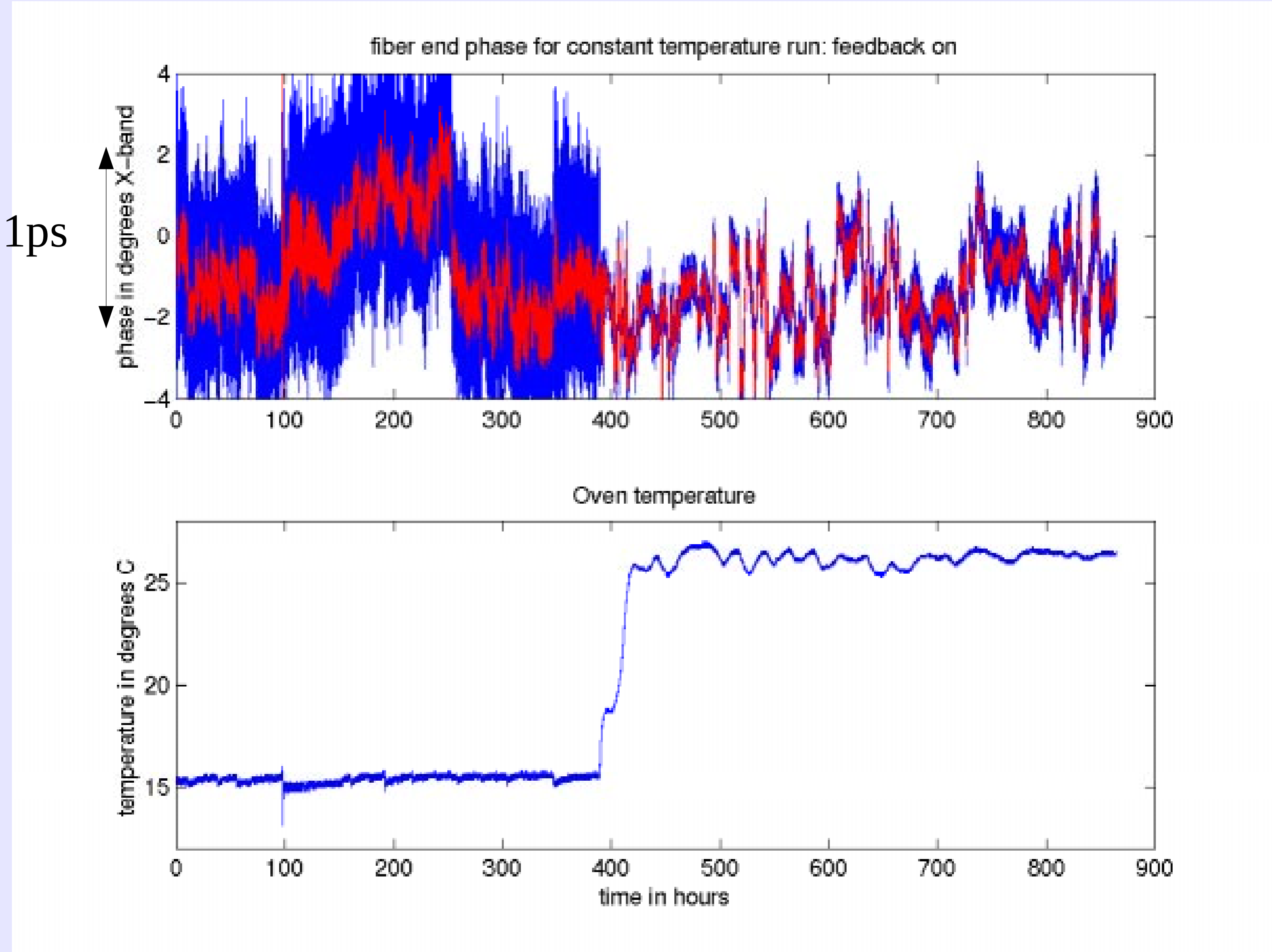
NLC Timing System

- Point to point fiber system (~50 drops)
- Laser modulated by RF carrier
- Measure transmission fiber length using light reflected from far end of fiber
- Adjust length using fiber spool in oven in series with main fiber

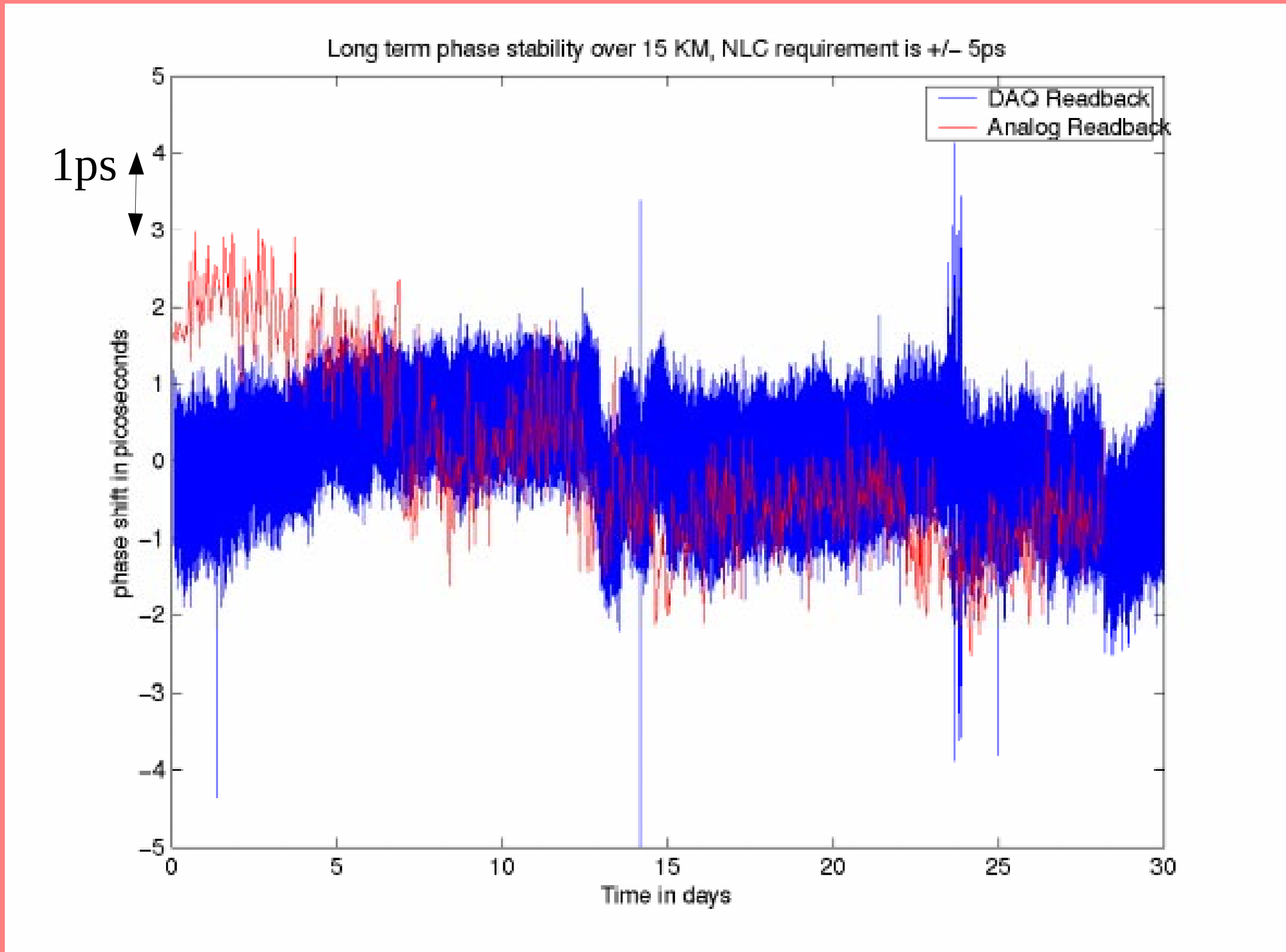


RF Distribution Test System

1 Month, 10 °C Temperature Step



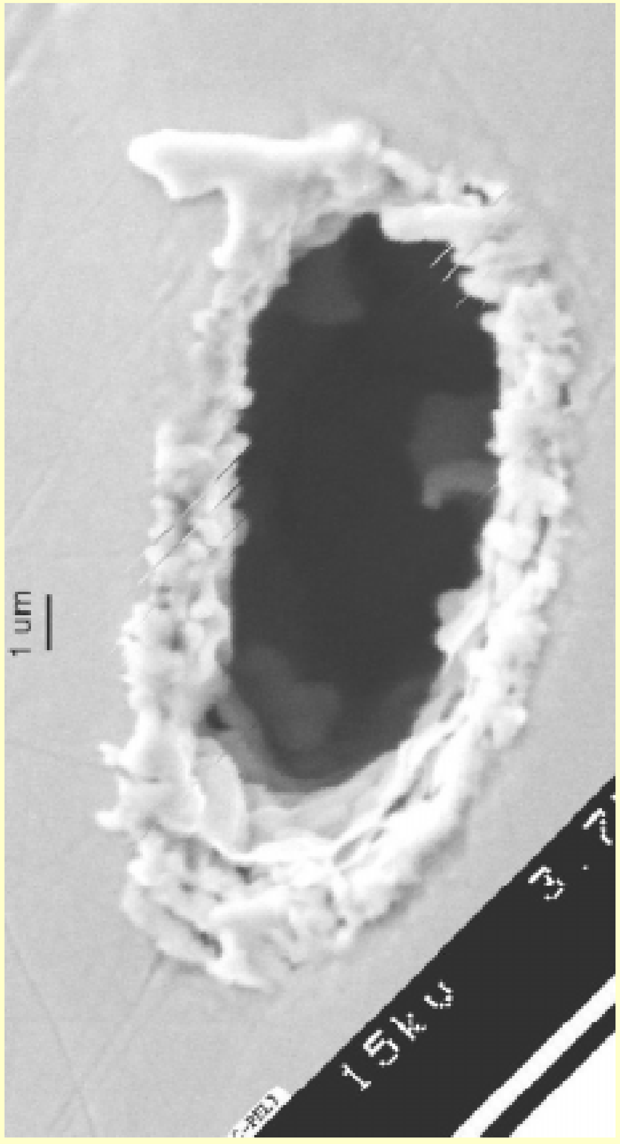
Performance test for 1 month



Timing System Status

- Test system meets NLC requirements for phase stability and phase noise
- Fault tolerant system architecture developed
  - Completely single point failure immune
- Prototype system (10-U rack mount) under construction
- On hold due to other higher priorities

Linear Collider Collimation



- Full beam will destroy any solid object at nominal LINAC beta functions (10um spot size).
  - ~10 MW average power
  - $\sim 10^{10} e^-$/pulse, $10^{12} e^-$/train (NLC),
  - Even a single bunch will cause damage
- Large beta functions -> increase spot size
  - Tight alignment tolerances
  - Wakefield problems

Collimation

- Use “Spoiler / Absorber” scheme
- Thin (~1 radiation length) spoiler
  - Increases transverse momentum spread
- Thick absorber downstream
  - Absorbs high beam power, but low density
- Critical damage problems are on spoiler.

Spoiler Materials

- Damage typically caused by thermal fracture
- Carbon (glassy or graphite) has best damage threshold (in calculation). ~<$10^{16} e^-/cm^2$
  - Poor conductivity -> resistive wake problems
  - Diamond? (suspect radiation damage issues)
- Beryllium ~$2.5 \times 10^{15} e^-/cm^2$
  - Some concerns about toxicity

    (may be less serious than radiation hazard)
- Titanium similar to Beryllium
- None will survive full beam

Indestructible Spoilers ?

- Use high power lasers for collimation:
  - Laser power requirements (wildly) impractical with current technology.
- Liquid metal jets:
  - No known way to obtain micron level surface stability
- Nonlinear magnetic collimation
  - Very useful idea, but can't do entire job
  - Too much like "accelerator physics" to discuss here
  - Will be used for NLC (in addition)

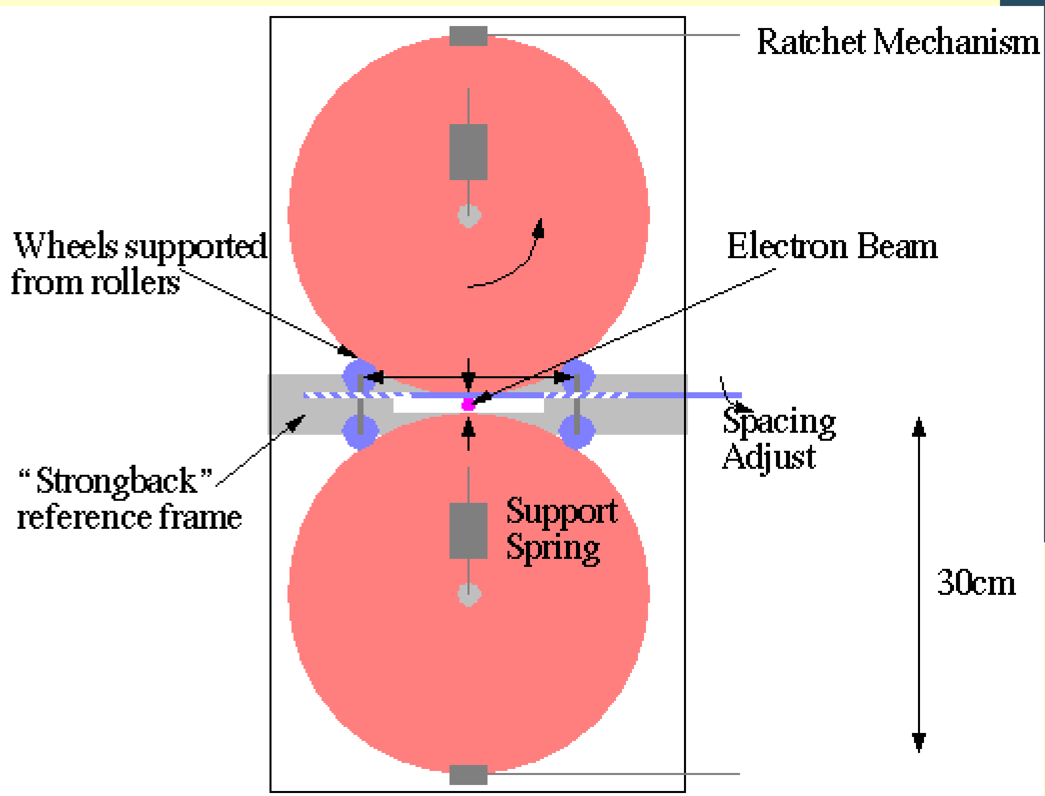
No clear solution (Yet)

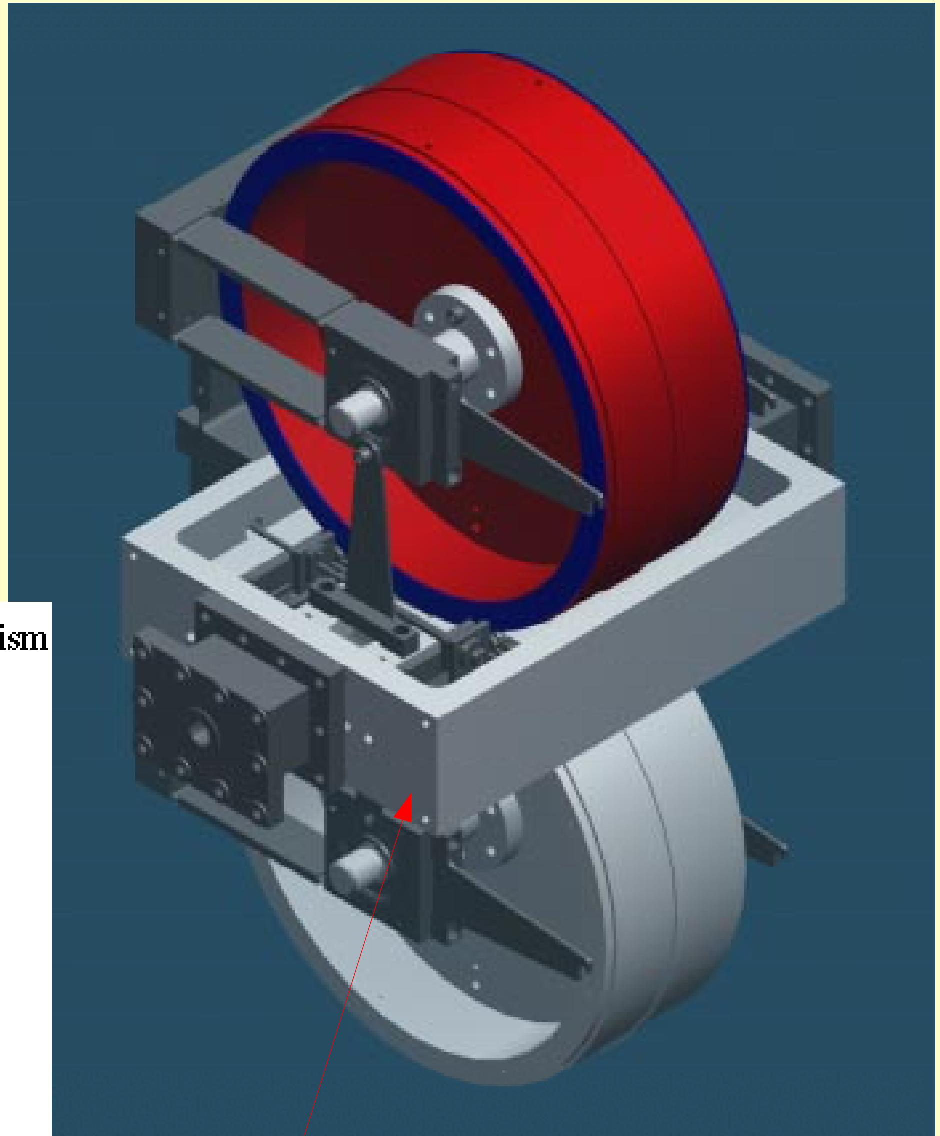
Spoiler Schemes

- Must assume that occasionally the Machine Protection System will fail
- Can design "Consumable" spoiler to remain usable after some number of damage events.
  - Not too difficult: NLC baseline design
- Alternately design "Repairable" spoiler which can be continuously repaired after damage.
  - In- vacuum spoiler factory.
  - Difficult: Requires exotic technology

Consumable Spoiler

After damage is detected, wheels are rotated to new location

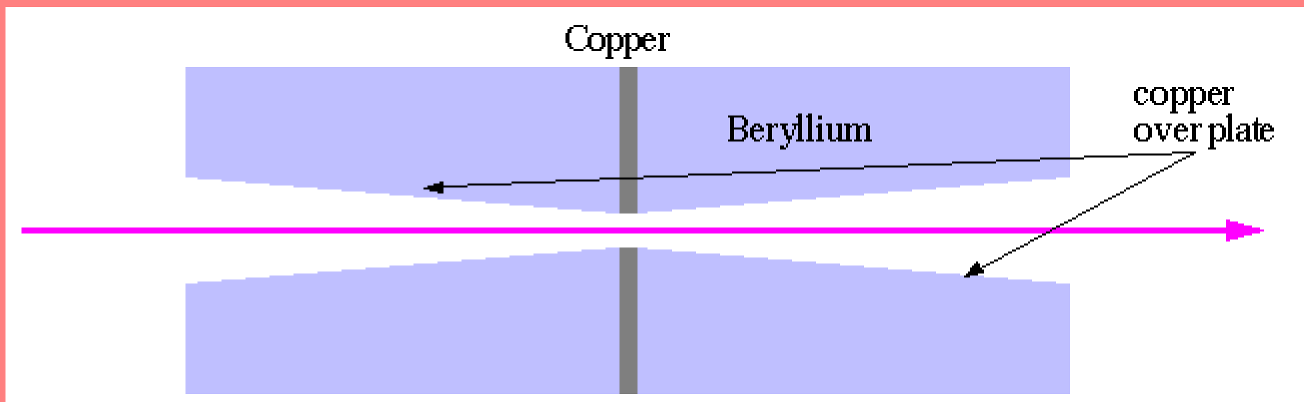




Wheels referenced to central frame (with BPMS) for stability

Composite Spoiler Jaws

- Would like collimation (spoiling) depth to change abruptly as a function of R.
- For wakefields would like surface to change gradually as a function of R.
- Use Composite Copper Beryllium spoiler.
- Be is "invisible" to the beam.

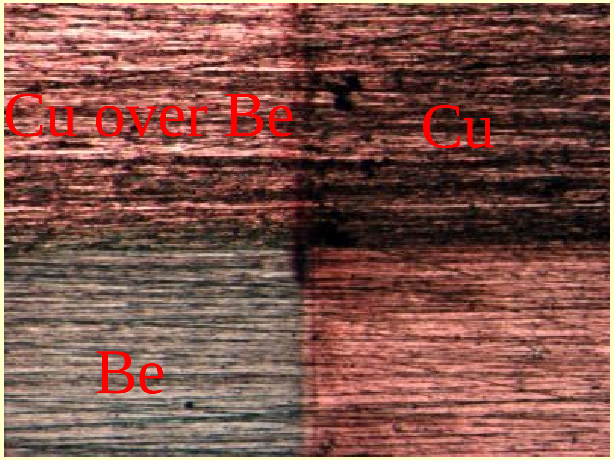


Prototype Unit

Real mechanicals, but rotors are Aluminum, not Be/Cu

Gap 0-700 microns
stability: 0.5 um / C

Rotation: causes 7um gap variation due to out of round support wheels: easy to fix

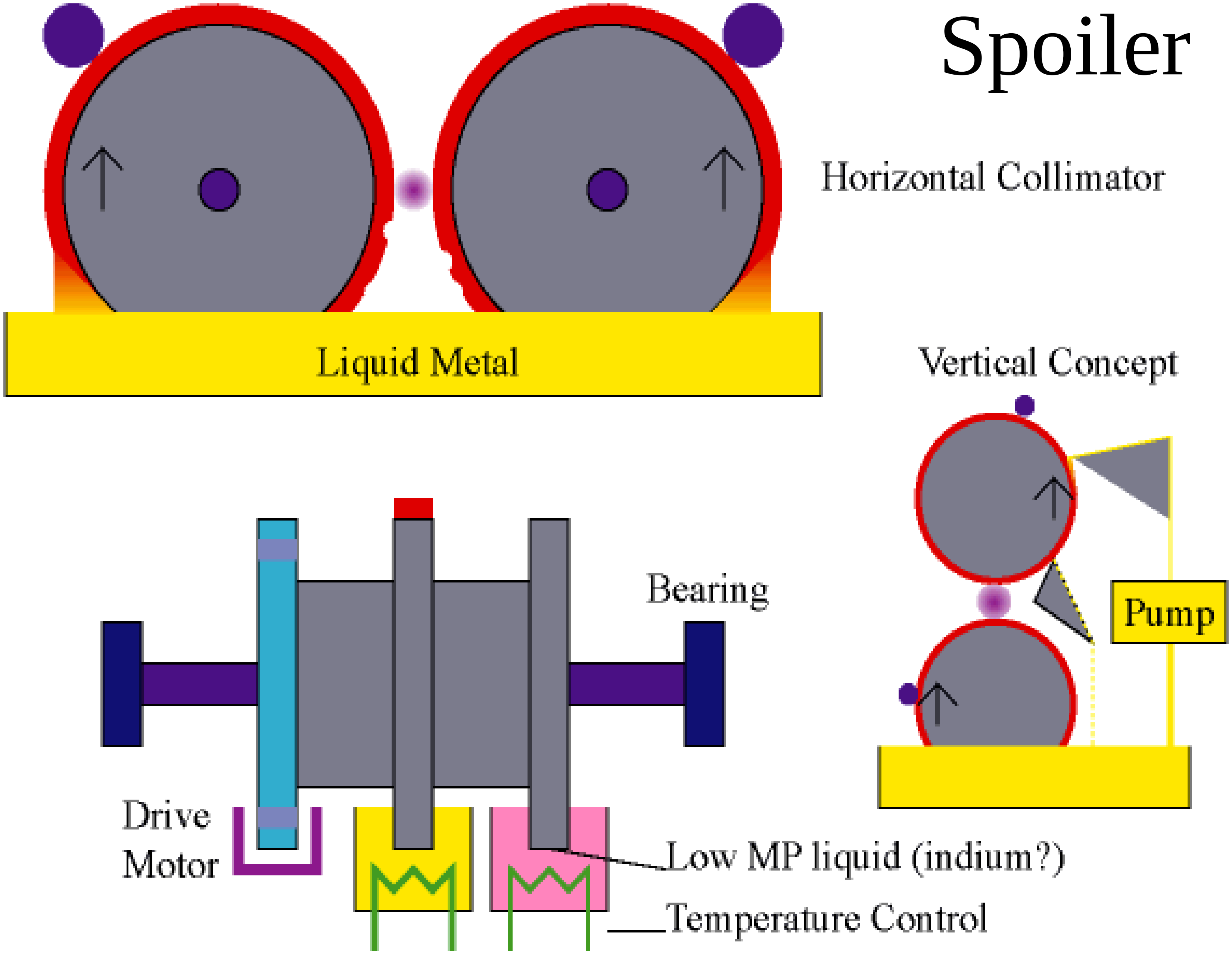


Prototype Be/Cu bond

Repairable Spoilers

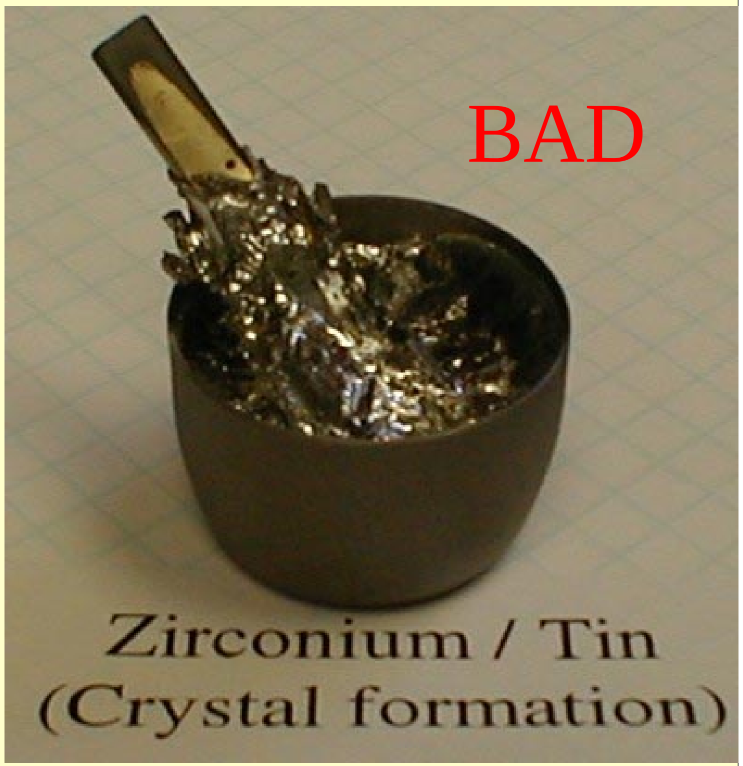
- Since we can't make an indestructible collimator, we design one we can continuously repair in vacuum.
- Several crazy ideas considered, finally selected:
- Use a solid wheel rotating in a pool of liquid metal. Liquid metal freezes onto the wheel and serves as the spoiler surface. After damage the surface is reformed on each rotation.

Solidifying Metal Spoiler



Materials Compatibility

- Liquid metal needs to adhere to the substrate, but not dissolve it.
  - Note: solder on copper doesn't work – solder dissolves copper.
- After lots of "Alchemy" found:
  - Substrate: Niobium
  - Smoothing Roller: Molybdenum
  - Liquid metal: Tin
    - vapor pressure at melting $< 10^{-11}$ Torr

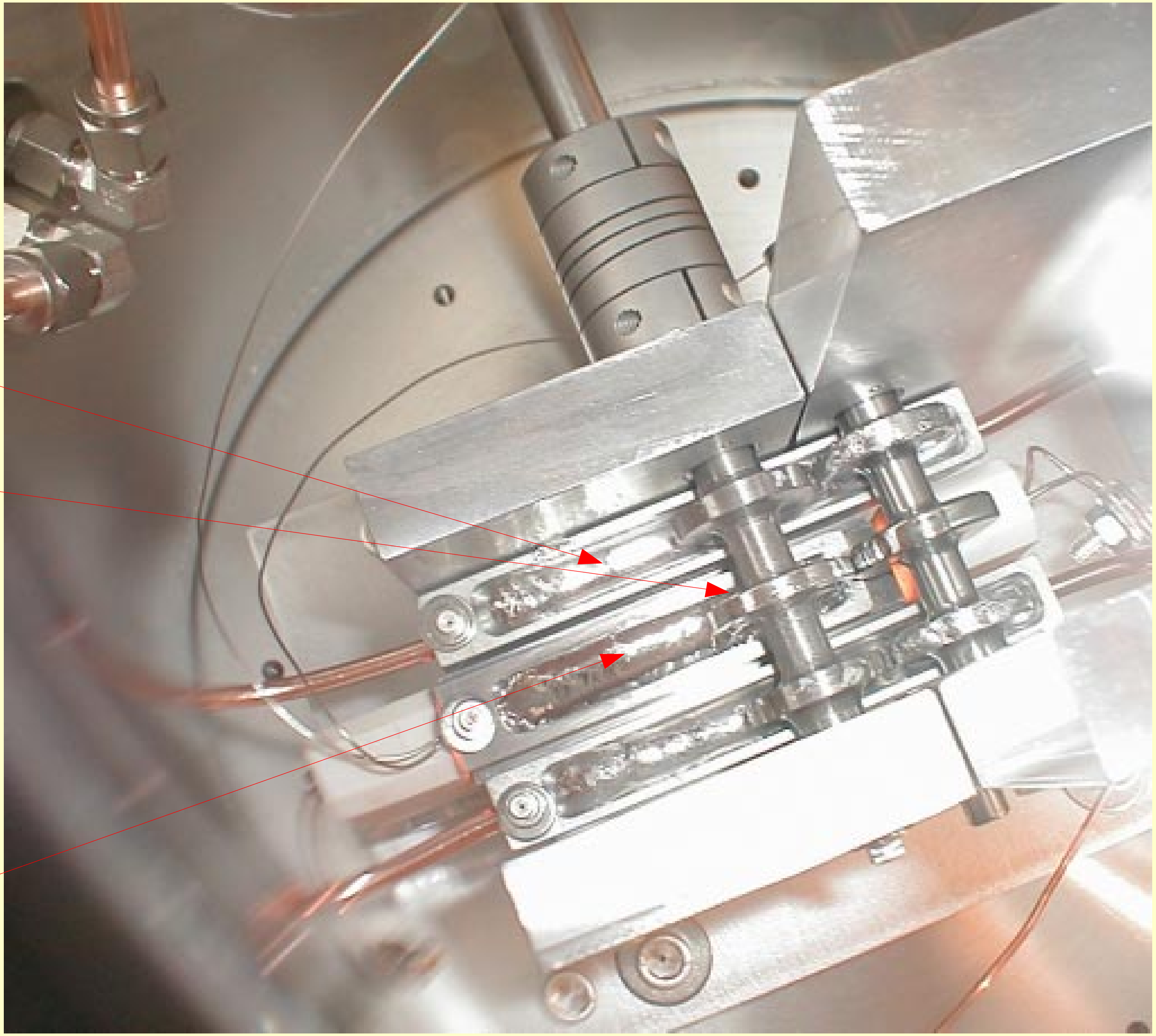


Proof of Principal Test

InGaSn eutectic (cooling)

Niobium wheel

Liquid Tin

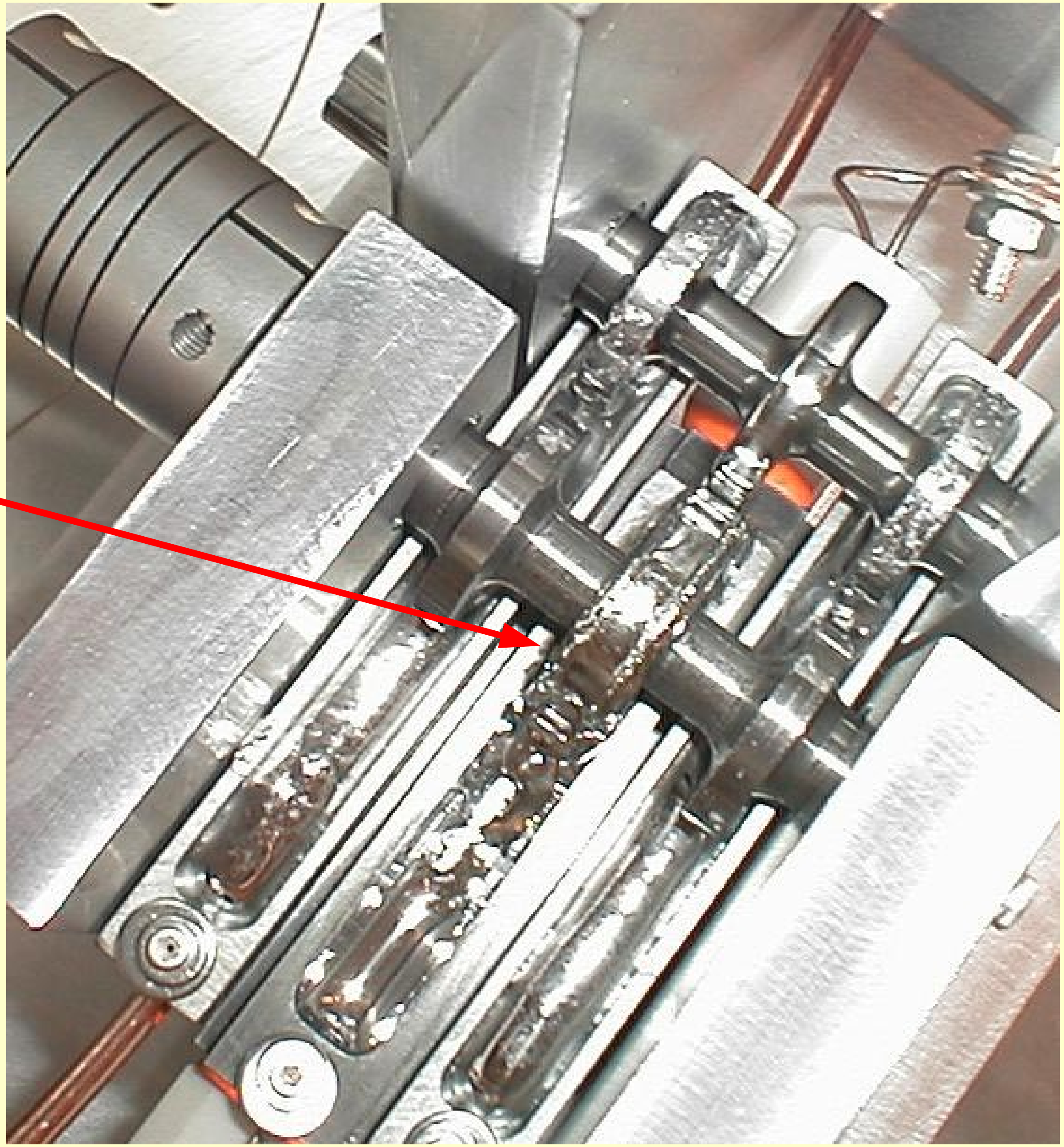


Solidifying Metal Spoiler Prototype Performance

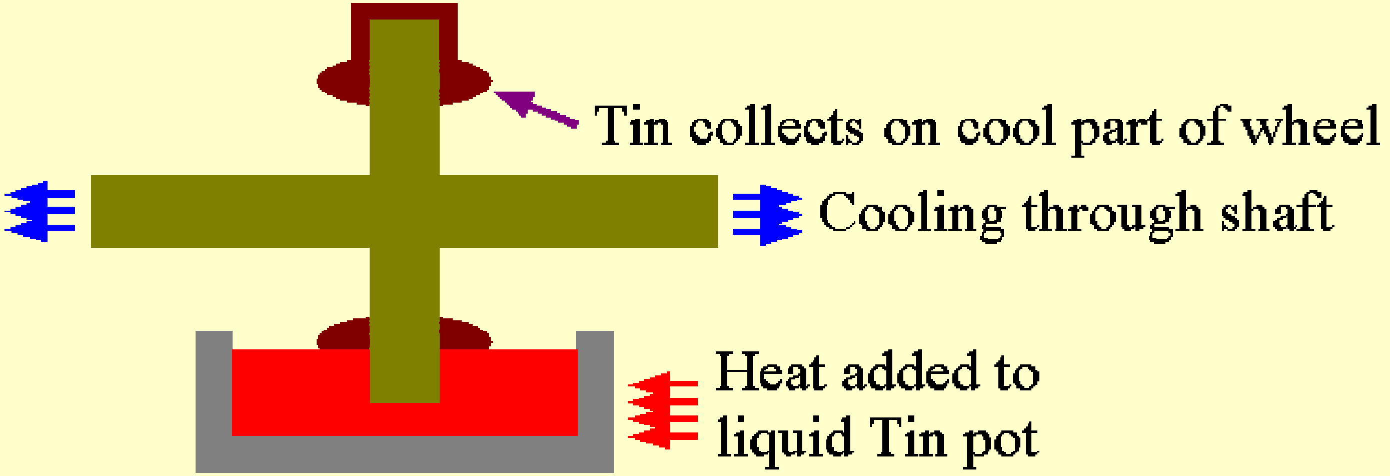
- Vacuum good (10^{-8} Torr), limited by pump.
- Problems with bearings in UHV and at high temperature.
  - Switching to SiN bearings will probably fix this.
    - Work well in initial test
- Works with a thin (~100 micron?) coat formed by surface tension.
- Thicker coat (>3 mm) works briefly, but eventually Tin solidifies in the wrong places.

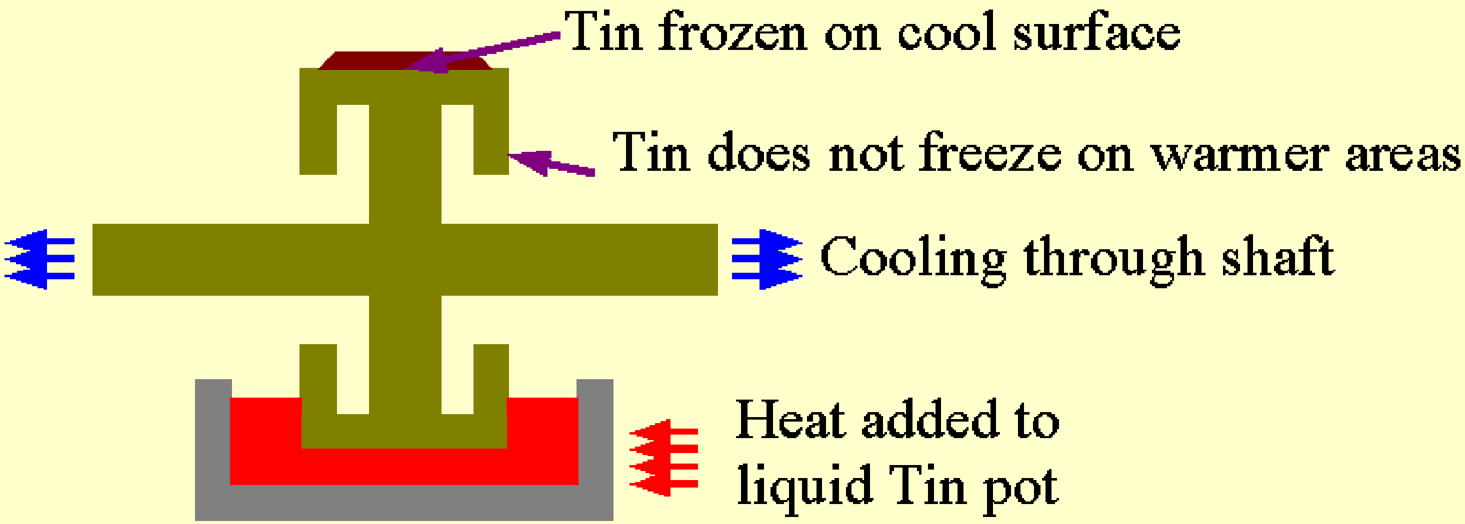
Thick Coating: Problems

Tin builds up on sides of roller



Possible Fix for "Thick Coat"





Collimation System Status

- NLC baseline has passive survival for energy collimation and consumable spoilers for position collimation
- Prototype consumable spoiler meets most requirements, remaining problems appear easy to fix
  - Damage detection system required
- Solidifying metal repairable spoiler is under development
  - Project on hold due to other priorities

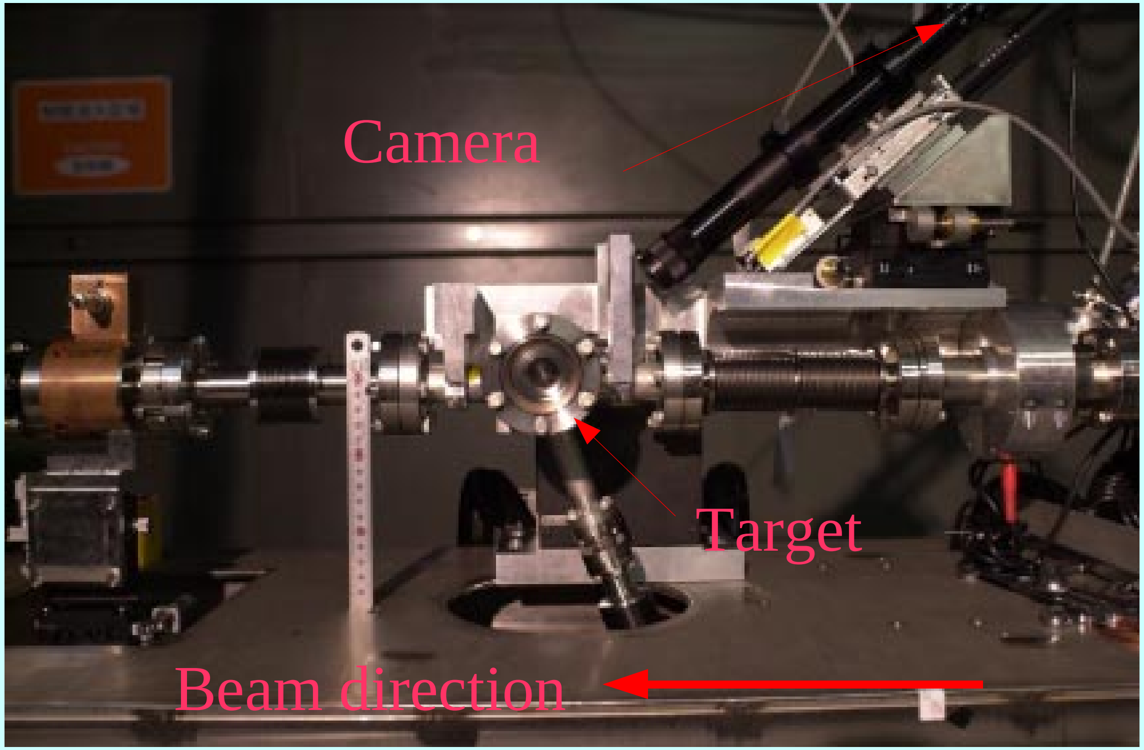
Beam Diagnostics

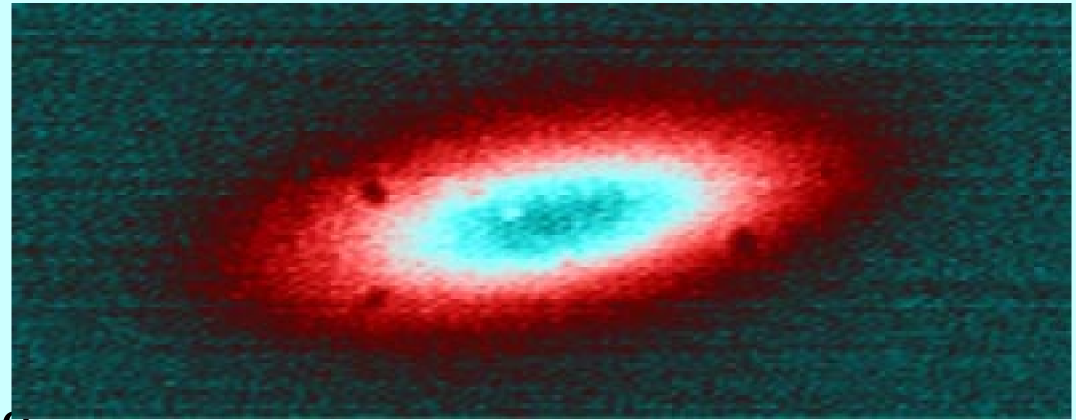
- Transition Radiation Beam Profile Measurement
  - Tested at KEK ATF, (est.) 2um sigma resolution
  - Damage issues
  - High resolution options
- Beam Slicer / Dicer
  - Deflection cavity bunch length monitor
    - OLD idea – used at SLAC in mid 1960s
  - Can take slice of any pair of phase space parameters

Transition Radiation Imager

- Transition radiation produced when a charged particle enters or leaves a conducting surface.
- Like a phosphor screen, but better resolution
  - No grain size or thickness limits
- Resolution NOT limited to $1/\gamma$
  - TR has long angular tails – OK diffraction limit.
  - Roughly resolution is 2x worse than for uniform source.
- Measured 5 micron spots at ATF
  - Believe instrument resolution is 2 microns

Transition radiation monitor at ATF at KEK





Spot Image (~15 micron sigma)
Note tilt on spot

Damage Issues

- Limited to ~$10^{15}e^{-}/cm^{2}$.
- Carbon – best damage threshold
  - Glassy carbon can have good surface finish
  - Low conductivity gives smaller optical signal
- Beryllium – best damage threshold for a metal
  - Industrial experience with polishing surface.
  - Low Z, little beam scattering / radiation
  - Some concerns about toxicity
- Titanium
  - Good damage threshold

Improved Resolution?

- TR image of a spot has a null on axis.
  - Depth of null determined by beam size
- BUT: All null measurement type tricks suffer in the presence of beam tails.
  - Essentially measures RMS of entire beam.
- Not clear what is ultimate resolution
  - Very unlikely to reach nanometer sizes
  - For small spots beam damage is also a limit
- Diffraction radiation: Similar to TR, but does not require beam interception

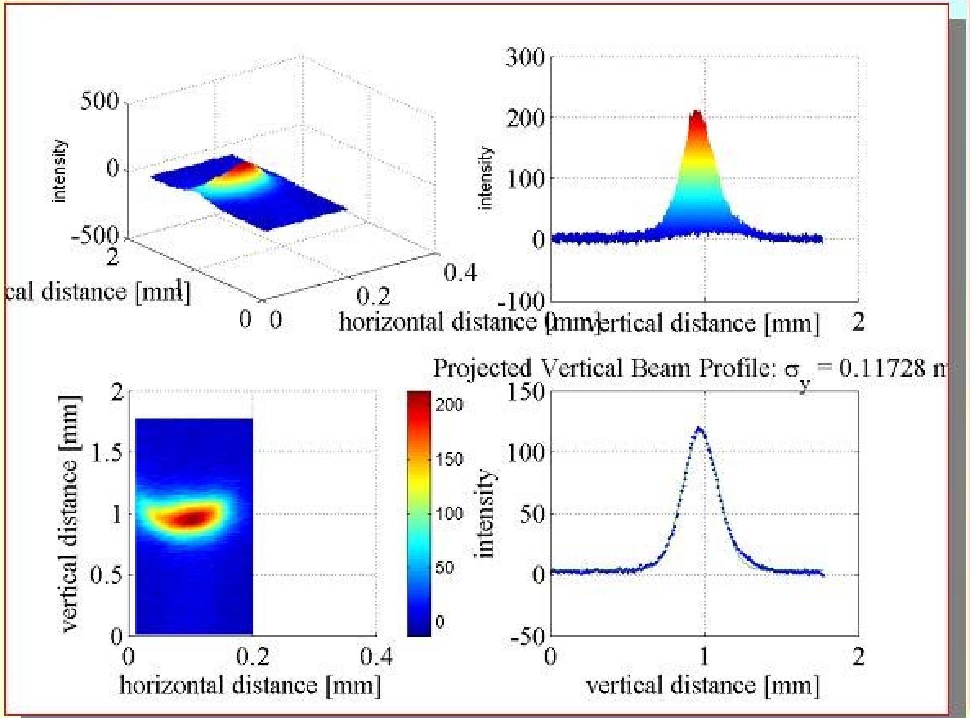
Deflection Cavity Temporal Measurement.

- Can use a RF deflection cavity to “streak” the beam onto a screen to obtain temporal profile
- Can this work at high energy? **YES!**
  - Normalized Y Emittance 10^{-8}M-R, Gamma =~10^{6}
  - Beta ~100M. -> Transverse momentum 10KeV.
  - Deflector at 10 GHz, 10 MeV get 20 fs resolution.
- Can even sweep in X (emittance ~10^{-6}M-R) with 100MeV transverse cavity

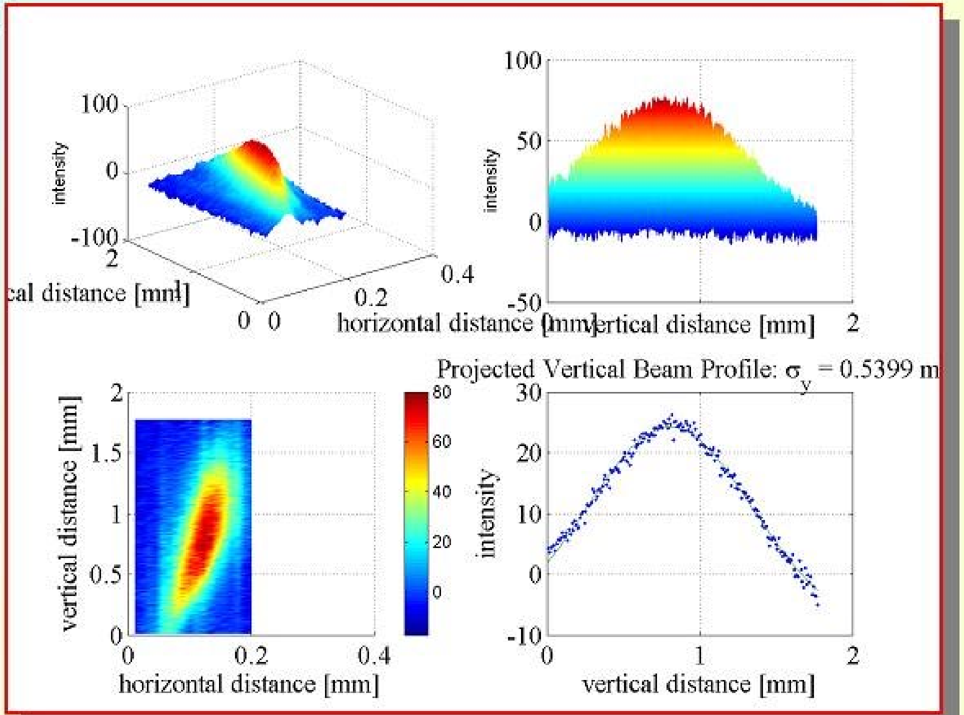
Profile Monitor Images

Damped, scavenger bunch at end of the linac

Transverse Cavity OFF



Transverse Cavity ON

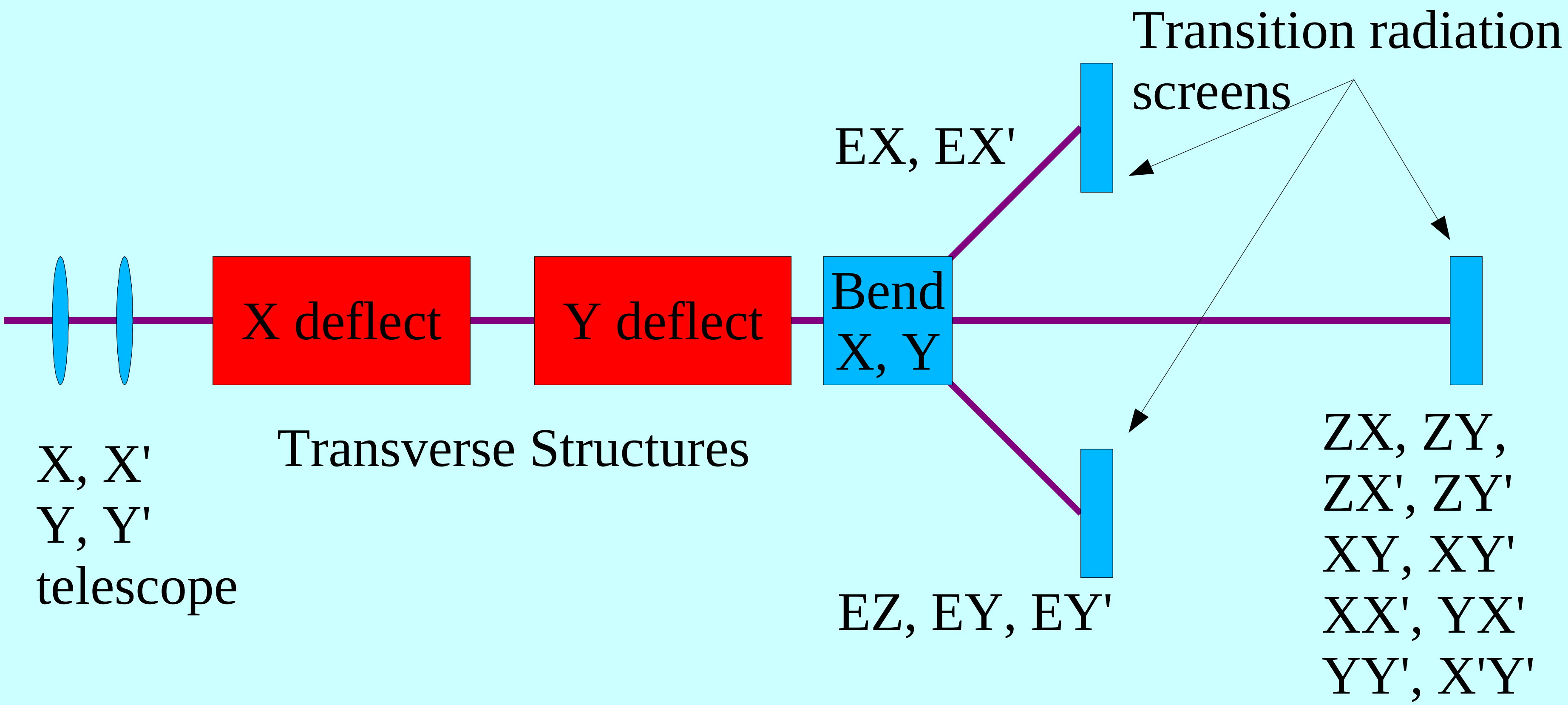


P. Emma et. al.

Beam Slicer / Dicer

- Use 2 deflection cavities, X, Y. Sweep one phase slowly, other quickly.
  - Raster scan out all pulses in train (~10x10 grid)
  - Single shot measurement on all pulses.
- Damage: If we allow $10^{15} e^-/cm^2$ and $10^{10} e^-$ / bunch, want ~30 micron spots.
- Use upstream quads, and bends to correlate any pair of 6-D phase space parameters

Correlate any pair of axes



Note: Need to locate off axis to allow pulse stealing and for MPS

Slicer / Dicer Issues / Status

- So far only a basic concept. Need beam modeling, etc to check practicality
- Machine Protection: If it can streak the beam, it can drive it into the wall.
- May not really need all phase space combinations: can use simpler system
- Deflection cavity systems in use or being installed at SLAC, DESY, BNL.

Vibration Stabilization for NLC

Finally:Something actually related to this meeting.

- Nanometer beam sizes at the IP.
- Need beam / beam deflection feedback at low frequencies. (<1Hz)
- May use fast beam / beam feedback within a train
  - Tails, Banana etc. Don't want to rely on this (NLC).
- Would like mechanical feedback above ~1Hz.
- Sensors appear to be the critical technology

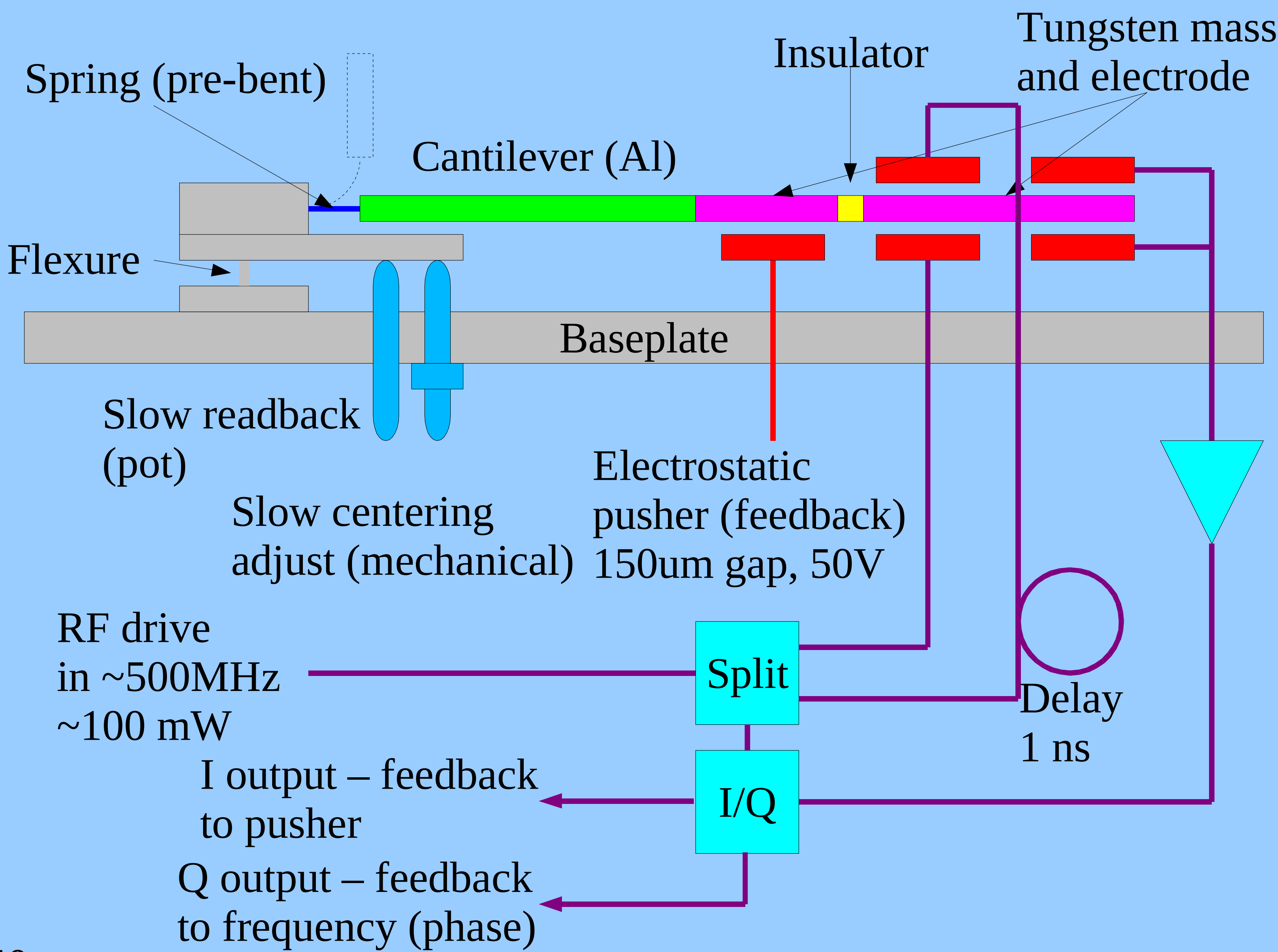
Vibration Stabilization: Sensors

- Interferometers: Measure relative to ground
  - Nanometer resolution in commercial devices
  - Operate to very low frequency
  - Use at IP requires detector penetration
- Inertial Sensors: Relative to “fixed stars”
  - Nanometer resolution at >0.1Hz in commercial devices (STS-2)
  - Commercial sensors are magnetic and physically large: Can't use them in the detector.
  - Develop custom capacitive readout sensor

Inertial Sensor Requirements / Design

- Nonmagnetic and compact.
  - Operate in detector solenoid field.
- <1nm integrated noise above 0.1Hz.
  - Corresponds to ~$2 \times 10^{-9} M/S^2/Hz^{1/2}$.
- Want high frequency limit > ~60Hz

- Use capacitive readout
- Use cantilever with "pre-bent" spring.

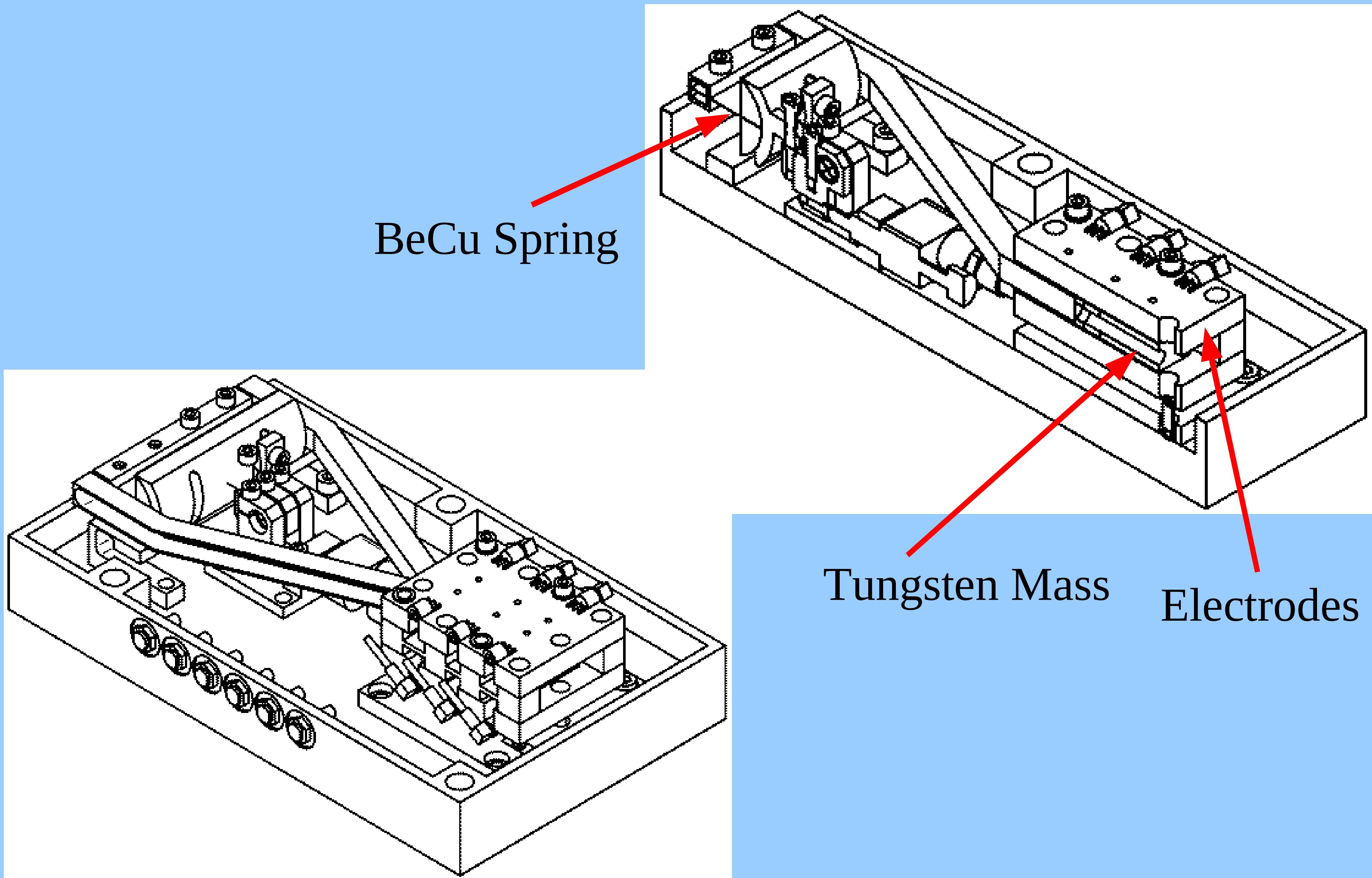

Spring (pre-bent)
Cantilever (Al)
Insulator
Tungsten mass
and electrode
Flexure
Baseplate
Slow readback
(pot)
Slow centering
adjust (mechanical)
Electrostatic
pusher (feedback)
150um gap, 50V
RF drive
in ~500MHz
~100 mW
Split
Delay
1 ns
I/Q
I output – feedback
to pusher
Q output – feedback
to frequency (phase)

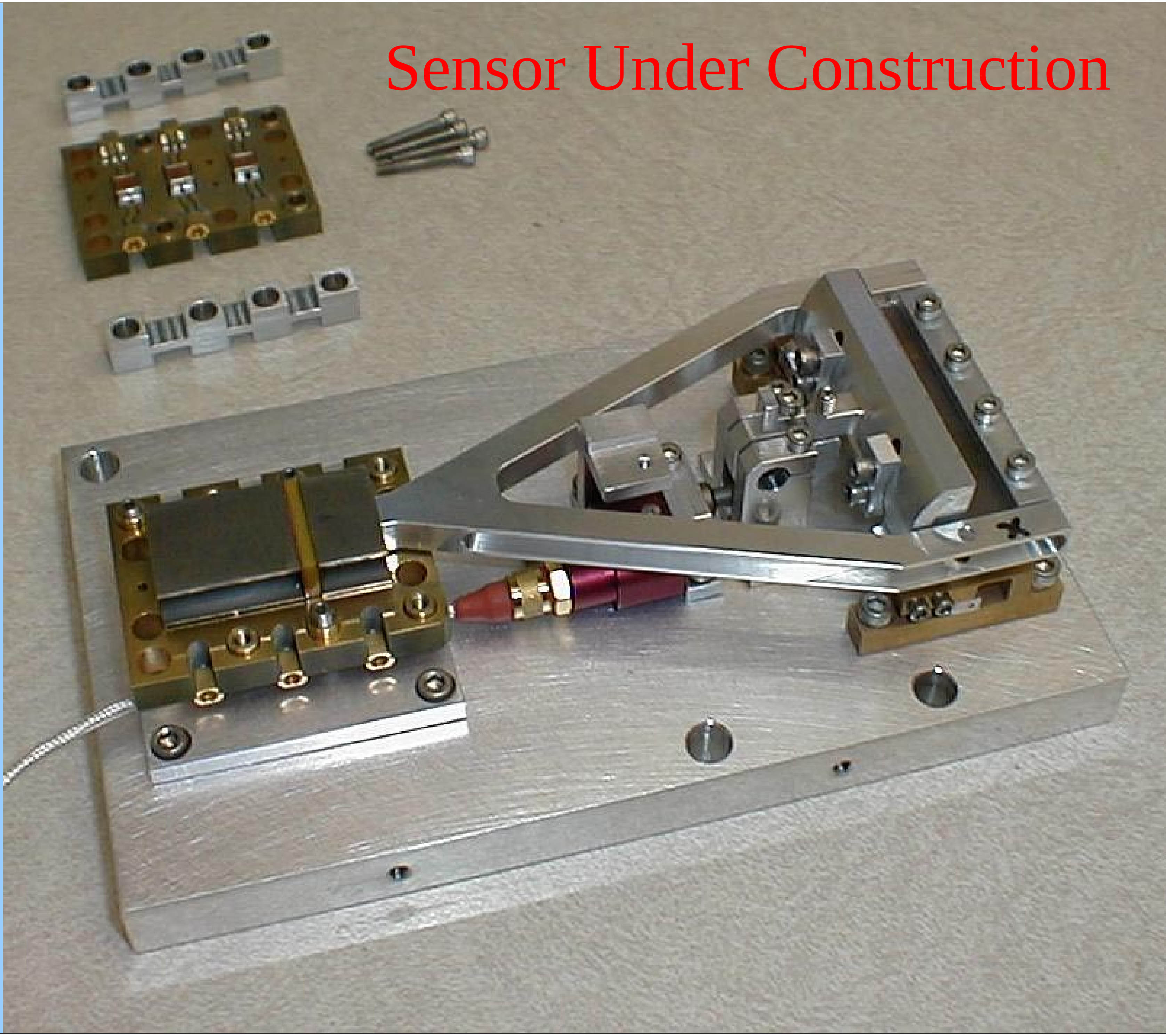
Estimated sensor performance

Resonant Frequency (ANSYS)	1.5 Hz
Next resonant mode (ANSYS)	96 Hz
Resonant Q (estimate from experiment)	>100
Thermal Noise (theoretical calculation)	$1.5\text{x}10^{-10}\text{M/S}^2/\text{Hz}^{1/2}$
Electrode gap	300 microns
RF drive power	~100mW
Thermal limit electrical resolution (cantilever)	$10^{-13}\text{M/Hz}^{1/2}$
Estimated electronics noise figure (includes losses):	20dB
Electrical noise converted to acceleration	$10^{-10}\text{M/S}^2/\text{Hz}^{1/2}$

Requirement: $2\text{x}10^{-9}\text{M/S}^2/\text{Hz}^{1/2}$, or ~10X calculated noise.

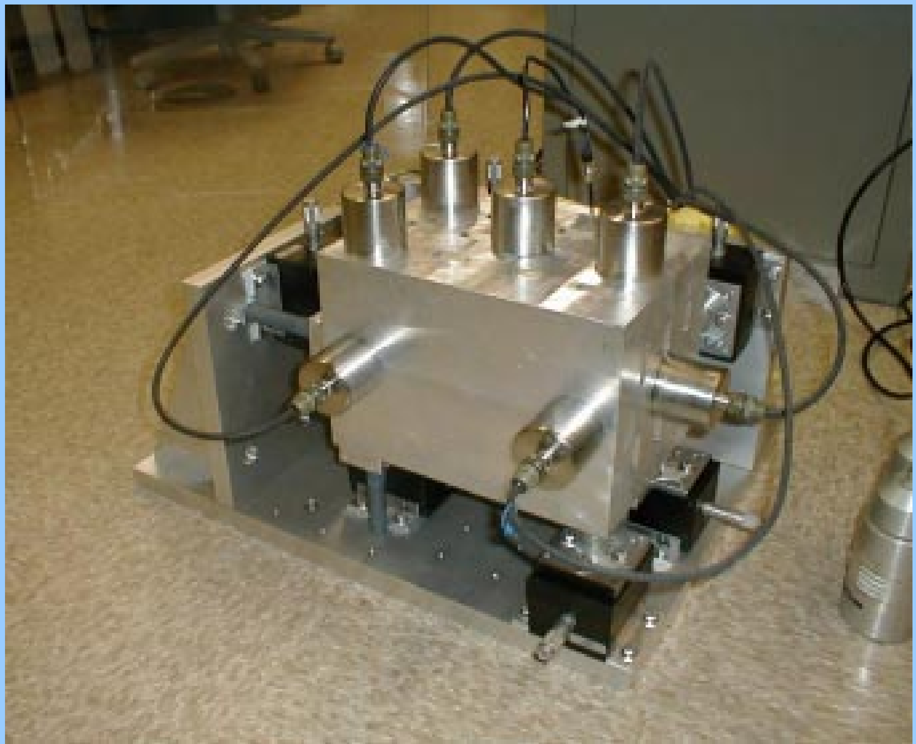
Sensor Mechanical Drawing

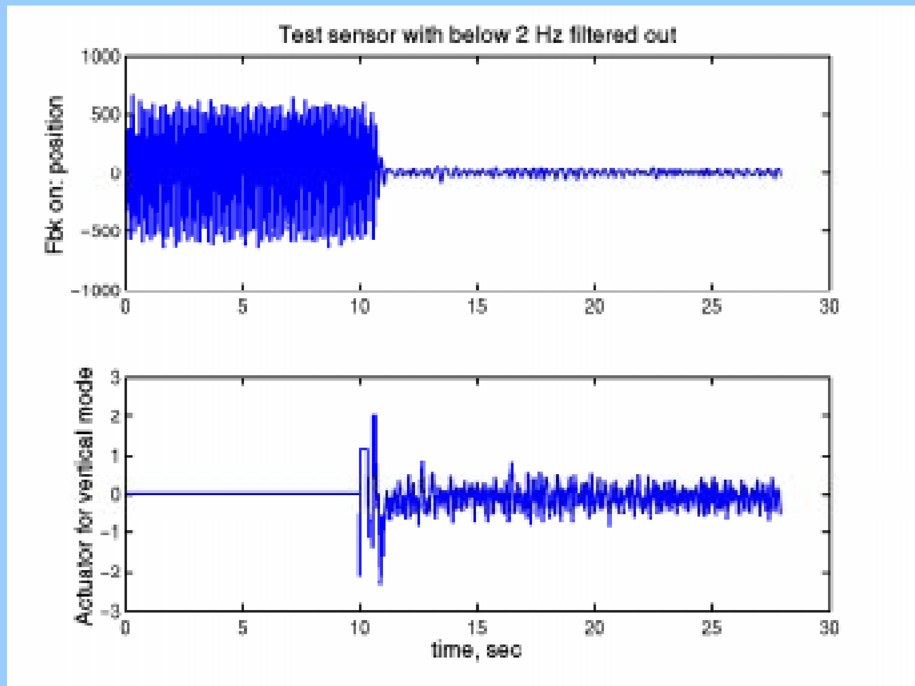



Sensor Under Construction

Vibration Sensor Status

- Sensor mechanical components and electronics under construction
- Vibration Stabilization System operating with commercial (low sensitivity sensors)





Other Unusual Technologies

- Swept frequency interferometers for alignment and feedback
- Ultra-high power lasers for positron production
- Semiconductor physics for polarized photo-cathodes
- Ultrasonic structure breakdown location
- X-ray microscopes for synchrotron radiation
- Fast pulsed power (Kickers and modulators)
- Active high power microwave devices