Innovative Technological Solutions for Future Accelerators

Not really a good title, better would be:

Weird Technology for Accelerators

(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 $\sim 2 \times 10^{-5}/^\circ C$
  
  – 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

fiber end phase for constant temperature run: feedback on

1ps

Oven temperature

temperature in degrees C

0 100 200 300 400 500 600 700 800 900

time in hours

0 15 20 25

frequency (in degrees X-band)
Performance test for 1 month

Long term phase stability over 15 KM, NLC requirement is +/- 5ps
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
  - ~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). $\sim < 10^{16} \text{e}^-/\text{cm}^2$
  - Poor conductivity -> resistive wake problems
  - Diamond? (suspect radiation damage issues)
- Beryllium $\sim 2.5 \times 10^{15} \text{e}^-/\text{cm}^2$
  - 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

- Horizontal Collimator
- Vertical Concept
- Liquid Metal
- Drive Motor
- Bearing
- Low MP liquid (indium?)
- Temperature Control
- Pump
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 \((10^{-8}\ \text{Torr})\), 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"

- Tin collects on cool part of wheel
- Cooling through shaft
- Heat added to liquid Tin pot
- Tin frozen on cool surface
- Tin does not freeze on warmer areas
- Cooling through shaft
- Heat added to liquid Tin pot
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 $\sim 10^{15} \text{e}^-/\text{cm}^2$.

• 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 $\approx 10^6$
  - Beta $\approx 100$M. -> Transverse momentum 10KeV.
  - Deflector at 10 GHz, 10 MeV get 20 fs resolution.

• Can even sweep in X (emittance $\approx 10^{-6}$ 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

X deflect → Y deflect → Bend X, Y → Transition radiation screens

EX, EX' → EZ, EY, EY' → ZX, ZY, ZX', ZY', XY, XY', XX', YY', X'Y'

X, X', X'Y, Y, Y' telescope

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.
- $<1 \text{nm integrated noise above 0.1Hz.}$
  - Corresponds to $\sim 2 \times 10^{-9} \text{M}/\text{S}^2/\text{Hz}^{1/2}$.
- Want high frequency limit $> \sim 60\text{Hz}$

- Use capacitive readout
- Use cantilever with "pre-bent" spring.
Spring (pre-bent) | Flexure | Baseplate
---|---|---
Cantilever (Al) | Insulator | Tungsten mass and electrode
Slow centering adjust (mechanical) | Electrostatic pusher (feedback) 150um gap, 50V | Split
Slow readback (pot) | I/Q | Delay 1 ns
RF drive in ~500MHz ~100 mW | |
I output – feedback to pusher | Q output – feedback to frequency (phase)
### Estimated sensor performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant Frequency (ANSYS)</td>
<td>1.5 Hz</td>
</tr>
<tr>
<td>Next resonant mode (ANSYS)</td>
<td>96 Hz</td>
</tr>
<tr>
<td>Resonant Q (estimate from experiment)</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Thermal Noise (theoretical calculation)</td>
<td>$1.5 \times 10^{-10} \text{M/S}^2/\text{Hz}^{1/2}$</td>
</tr>
<tr>
<td>Electrode gap</td>
<td>300 microns</td>
</tr>
<tr>
<td>RF drive power</td>
<td>~100mW</td>
</tr>
<tr>
<td>Thermal limit electrical resolution (cantilever)</td>
<td>$10^{-13} \text{M/Hz}^{1/2}$</td>
</tr>
<tr>
<td>Estimated electronics noise figure (includes losses):</td>
<td>20dB</td>
</tr>
<tr>
<td>Electrical noise converted to acceleration</td>
<td>$10^{-10} \text{M/S}^2/\text{Hz}^{1/2}$</td>
</tr>
<tr>
<td>Requirement:</td>
<td>$2 \times 10^{-9} \text{M/S}^2/\text{Hz}^{1/2}$, or ~10X calculated noise.</td>
</tr>
</tbody>
</table>
Sensor Mechanical Drawing

- BeCu Spring
- Tungsten Mass
- Electrodes
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