A fast rotating wire scanner for use in high intensity accelerators

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A wire scanner is a diagnostic used to measure **transverse beam profiles**.

A typical measurement scheme:

1) Intercept the beam with a wire
2) Scattered x-rays (or sometimes other particles) are generated when the beam hits the wire.
3) Measure the signal, usually with a scintillator + a photomultiplier combination.
4) The signal directly corresponds to the beam’s profile.

Wire acceleration methods vary, but Fork designs are the most common.

There are also more exotic designs, like laser wire scanners.
We want to study beam physics at **high current** in the Cornell ERL photoinjector.

**The problem:**
We can take low current measurements, but things become challenging at high current.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low current</th>
<th>Nominal/High current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>5 – 15 MeV</td>
<td>5 – 15 MeV</td>
</tr>
<tr>
<td>Beam size</td>
<td>~ 2 mm</td>
<td>~ 2 mm</td>
</tr>
<tr>
<td>Norm. Emittance</td>
<td>&lt; 0.3 µm (measured)</td>
<td>&lt; 0.3 µm (simulated)</td>
</tr>
<tr>
<td>Bunch length</td>
<td>&lt; 3 ps</td>
<td>&lt; 3 ps</td>
</tr>
<tr>
<td>Current</td>
<td>&lt; 100 nA</td>
<td>100 mA</td>
</tr>
<tr>
<td>Beam Power</td>
<td>&lt; 1 kW</td>
<td>1 MW</td>
</tr>
</tbody>
</table>
Common Beam Diagnostics

• BPMs
• Viewscreens
• Slits (for emittance)
• Pepperpot (for emittance)
• Synchrotron radiation monitors
• X-Ray beam size monitor
• Laser wire scanners
• Conventional Wire scanners
Photoinjector below 100 nA

• BPMs
• Viewscreens
• Slits (for emittance)
• Pepperpot (for emittance)
• Synchrotron radiation monitors
  (low energy linac)
• X-Ray beam size monitor
  (low energy linac)
• Laser wire scanners
  (viable but difficult)
• Conventional Wire scanners
Photoinjector above 1 mA

• BPMs
• Viewscreens (melts)
• Slits (for emittance) (melts)
• Pepperpot (for emittance) (melts)
• Synchrotron radiation monitors (low energy linac)
• X-Ray beam size monitor (low energy linac)
• Laser wire scanners (viable but difficult)
• Conventional Wire scanners (melts)
Photoinjector above 1 mA

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- Conventional Wire scanners

Let’s come up with a new design.

(melts)
(melts)
(melts)
(low energy linac)
(low energy linac)
(viable but difficult)
Photoinjector above 1 mA

- BPMs
- Viewscreens (melts)
- Slits (for emittance) (melts)
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- Synchrotron radiation monitors (low energy linac)
- X-Ray beam size monitor (low energy linac)
- Laser wire scanners (viable but difficult)
- Conventional Wire scanners

Let’s come up with a new design.
Wire scanner design goals

Main Goal:
Avoid melted wires

Requirements:

1) Wire speeds > 20 m/s (45 mph)
2) ~10’s μm resolution
3) Cheap
4) Compact
5) Quick to build and implement

Most wire scanners move at mm/s or cm/s.
A fast wire speed minimizes heating

Deposited energy

\[
T(v) = \frac{dE}{dx} \frac{I}{2ec_p\sigma} \frac{1}{v^\alpha}
\]

Maximum temperature reached during a single scan (simulated)
A fast wire speed minimizes heating

\[ T(v) = \frac{dE}{dx} \frac{I}{2ec_p\sigma_{\perp}v} \frac{1}{\alpha} \]

Deposited energy

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Deposited energy  Beam current  Heat capacity

Maximum temperature reached during a single scan (simulated)
A fast wire speed minimizes heating

\[ T(v) = \frac{dE}{dx} \frac{I}{2ec_p\sigma_\perp} \frac{1}{\nu} \alpha \]

Deposited energy \hspace{1cm} Beam current

Heat capacity

Beam size (perpendicular to scanning direction)

Maximum temperature reached during a single scan (simulated)
A fast wire speed minimizes heating

\[ T(v) = \frac{dE}{dx} I \frac{1}{2ec_p \sigma_{\perp}} \frac{1}{v} \alpha \]

- Deposited energy
- Beam current
- Heat capacity
- Beam size (perpendicular to scanning direction)

Maximum temperature reached during a single scan (simulated)
A fast wire speed minimizes heating

\[ T(v) = \frac{dE}{dx} \frac{I}{2e c_p \sigma_\perp} \frac{1}{v} \]

- Deposited energy
- Beam current
- Heat capacity
- Beam size (perpendicular to scanning direction)

Maximum temperature reached during a single scan (simulated)

Cooling factor = 0.3

About 70% heat is lost from ejected secondary particles

K. Wittenburg from DESY, “Conventional wire scanners for Tesla”
A fast wire speed minimizes heating

\[ T(v) = \frac{dE}{dx} \frac{I}{2e c p \sigma \perp} \frac{1}{\alpha v} \]

Deposited energy
Beam current
Heat capacity
Beam size (perpendicular to scanning direction)

Maximum temperature reached during a single scan (simulated)

Cooling factor = 0.3
About 70% heat is lost from ejected secondary particles
K. Wittenburg from DESY, “Conventional wire scanners for Tesla”
Choosing a wire material

It’s a tradeoff between heat capacity and durability.

Carbon is the first choice because it withstands heat so well.

Tungsten is a good secondary choice, and is more durable.

* $C_p$ for Carbon scales with temperature; this is for 1000 °C
A cartoon of the 2 gear design

Scale: 35cm / 14”
A cartoon of the 2 gear design

Detection

Vacuum flange

Scale: 35cm / 14”
A cartoon of the 2 gear design

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Detection

Vacuum flange

Electron Beam

Scale: 35cm / 14”
A cartoon of the 2 gear design

Detection

Scale: 35cm / 14”
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Detection

Vacuum flange

Electron Beam

Carbon Wire
~ 34 μm thick
~ 2-3 cm long

Scale: 35cm / 14”
**A cartoon of the 2 gear design**

- **Vacuum flange**
- **Electron Beam**
- **Carbon Wire**
  - ~34 µm thick
  - ~2-3 cm long

**Detection**

Scale: 35cm / 14”
A cartoon of the 2 gear design

Electron beam

Vacuum flange

Blade

Carbon wire

To hold the wire

Scale: 35cm / 14"

~ 34 μm thick
~ 2-3 cm long

Detection
A cartoon of the 2 gear design

Detection

- Vacuum flange
- Electron Beam
- Carbon Wire
  - ~ 34 μm thick
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Blade
  - To hold the wire

Scale: 35cm / 14”
A cartoon of the 2 gear design

- Vacuum flange
- Electron Beam
- Blade: To hold the wire
- Carbon Wire: ~34 μm thick, ~2-3 cm long

Scale: 35cm / 14”
A cartoon of the 2 gear design

- **Vacuum flange**
- **Electron Beam**
- **Blade** To hold the wire
- **Carbon Wire** ~ 34 μm thick ~ 2-3 cm long

Scale: 35cm / 14”
A cartoon of the 2 gear design

- **Electron Beam**
- **Vacuum flange**
- **Small gear (behind blade)**
- **Blade** To hold the wire
- **Carbon Wire** ~ 34 μm thick ~ 2-3 cm long

Scale: 35 cm / 14”
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Small gear (behind blade)

Vacuum flange

Electron Beam

Blade To hold the wire

Carbon Wire

~ 34 μm thick
~ 2-3 cm long

Scale: 35cm / 14”
A cartoon of the 2 gear design

- Large gear
- Small gear (behind blade)
- Blade
  - To hold the wire
- Vacuum flange
- Electron Beam
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Large gear

Small gear (behind blade)

Blade
To hold the wire

Vacuum flange

Electron Beam

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X-rays

Scale: 35cm / 14”

Detection
A cartoon of the 2 gear design

Detection

Scale: 35cm / 14”

Large gear

Small gear (behind blade)

Blade
To hold the wire

Vacuum flange

Electron Beam

Carbon Wire
~ 34 μm thick
~ 2-3 cm long

X-rays
A cartoon of the 2 gear design

- Large gear
- Small gear (behind blade)
- Blade To hold the wire
- Vacuum flange
- Electron Beam
- Carbon Wire
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Detection

X-rays

Scale: 35cm / 14”
A cartoon of the 2 gear design

- Large gear
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- Blade
  To hold the wire
- Vacuum flange
- Electron Beam
- X-rays
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  ~ 2-3 cm long

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- **Electron Beam**
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Detection

- **Scintillator**
- **X-rays**

Scale: 35cm / 14”
Electro Beam Vacuum flange
Carbon Wire
~ 34 μm thick
~ 2-3 cm long

Blade
To hold the wire

Large gear
Small gear (behind blade)

Detection
X-rays
Scintillator

A cartoon of the 2 gear design

Scale: 35cm / 14”
A cartoon of the 2 gear design

Scale: 35cm / 14”

Detection
Photomultiplier Sensor

Electron Beam

Vacuum flange

Small gear (behind blade)

Large gear

Blade
To hold the wire

Carbon Wire
~ 34 μm thick
~ 2-3 cm long

Scintillator
A cartoon of the 2 gear design

- Large gear
- Small gear (behind blade)
- Blade: To hold the wire
- Carbon Wire: ~ 34 μm thick, ~ 2-3 cm long
- Vacuum flange
- Electron Beam

Detection

- Photomultiplier Sensor
- Scintillator
- X-rays

Scale: 35cm / 14”
A cartoon of the 2 gear design

- Large gear
- Small gear (behind blade)
- Blade: To hold the wire
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- Carbon Wire: ~ 34 μm thick, ~ 2-3 cm long
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Scale: 35cm / 14”
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- Small gear (behind blade)
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  - To hold the wire
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- Vacuum flange
- Electron Beam
- Scintillator
- X-rays
- Photomultiplier Sensor

Detection

Scale: 35cm / 14”
Two obvious questions:
1) Why use 2 gears?
2) Will the wire bend/vibrate?

Scale: 35cm / 14”

Electron Beam
Vacuum flange
Carbon Wire
~ 34 μm thick
~ 2-3 cm long

Detection
Photomultiplier Sensor
X-rays
Scintillator

Blade
To hold the wire

Large gear
Small gear
(behind blade)
Outside view
Stepper motor

Outside view

1

2

3

4

5

200 mm
Stepper motor

Outside view
Stepper motor

Ferrofluidic Rotary feedthrough

Outside view
Stepper motor

Ferrofluidic Rotary feedthrough
Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges
Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges

Outside view

200 mm
Outside view

- Stepper motor
- Ferrofluidic Rotary feedthrough
- Vacuum flanges

Dimensions:
- 35 cm (14"
- 200 mm
Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges

Outside view

35cm 14”

200 mm
Outside view

Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges

Viewports

35cm 14”
Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges

Viewports

Outside view
Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges

Viewports

Camera mount

Outside view
Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges

Viewports

Camera mount

Beam pipe

Outside view

35cm 14”
Outside view

Stepper motor

Ferrofluidic Rotary feedthrough

Vacuum flanges

Viewports

Camera mount

Beam pipe

35cm 14”
3D model of the design
3D model of the design

Vacuum Flange
3D model of the design

Vacuum Flange
3D model of the design

Vacuum Flange

Beam
3D model of the design

Vacuum Flange

Beam
3D model of the design

Vacuum Flange

Beam

Blade + carbon wire attached
3D model of the design

- Vacuum Flange
- Beam
- Blade + carbon wire attached
Large stationary gear

3D model of the design

Vacuum Flange

Beam

Blade + carbon wire attached
3D model of the design

Large stationary gear

Vacuum Flange

Beam

Blade + carbon wire attached
3D model of the design

Large stationary gear

Small rotating gear

Vacuum Flange

Beam

Blade + carbon wire attached
3D model of the design

Large stationary gear

Small rotating gear

Vacuum Flange

Beam

Blade + carbon wire attached
3D model of the design

- Large stationary gear
- Small rotating gear
- Rotating Gear box
- Vacuum Flange
- Beam
- Blade + carbon wire attached
3D model of the design

Large stationary gear

Small rotating gear

Rotating Gear box

Vacuum Flange

Beam

Blade + carbon wire attached
3D model of the design

Large stationary gear

Small rotating gear

Rotating Gear box

Vacuum Flange

Beam

Blade + carbon wire attached

Able to be mass produced!

Only custom parts: 1) Blade 2) Rotating Gear Box
Why use 2 gears?

Without a two gear design, for any wire scanner to reach 20 m/s (45 mph), you would need either:

1) More acceleration  
   - Risk breaking wire
2) Larger path length  
   - Size issues

A two gear design results in a significant speed boost:

$$v_s = v_g \left( \frac{R}{R_2} + 1 \right)$$

R = distance from center of blade to center of beam pipe
R2 = radius of small gear
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\[ v_s = v_g \left( \frac{R}{R_2} + 1 \right) \]

\[ v_s \sim 6 \ v_g \]

Our design is about 6x faster than a single gear design

\[ R = \text{distance from center of blade to center of beam pipe} \]
\[ R_2 = \text{radius of small gear} \]
Taking pictures at 20 m/s

We captured several images of the moving carbon wire on a single camera frame, by using a modulating laser (8 KHz rep rate, 7 $\mu$s pulse duration).
Taking pictures at 20 m/s

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Stationary wire

Moving wire

The wire’s velocity profile
Moving wire

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The wire’s velocity profile
Taking pictures at 20 m/s

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The wire’s velocity profile
Taking pictures at 20 m/s

We captured several images of the moving carbon wire on a single camera frame, by using a modulating laser (8 KHz rep rate, 7 μs pulse duration).

To avoid excess vibrations (which lead to measurement errors), we program the motor with a smooth velocity profile.
Taking pictures at 20 m/s

We captured several images of the moving carbon wire on a single camera frame, by using a modulating laser (8 KHz rep rate, 7 $\mu$s pulse duration).

To avoid excess vibrations (which lead to measurement errors), we program the motor with a smooth velocity profile.
Vibration analysis using 2 wires

- Beam width depends on speed of each wire
- Peak separation depends only on separation of wires (not speed)

\[ v_0 = 5 \text{ m/s} \]

\[ \Delta x = A \sin(\omega t) \]
\[ \Delta v = A \omega \cos(\omega t) \]
Estimation of error due to wire vibrations

**Viewscreen** = 0.72 mm

**Wire scanner** = 0.86 ± 0.22 mm (25% error)

**A** \(\omega\) = 0.25 × 5 m/s = 1.25 m/s

Implies **A** = 2.6 mm

**f** = 75 Hz (found using a modulating laser)

Implies **A** = 2.8 mm

**Wire separation** = 11 ± 4 mm (36% error)

**Separation error** = 4 mm = \(\sqrt{2}\) **A**

If the amplitude doesn’t increase, at **v** = 20 m/s, we expect only 6% error.
Estimation of error due to wire vibrations

**Beam width** = 0.86968 ± 0.2266 mm

*Viewscreen = 0.72 mm*

*Wire scanner = 0.86 ± 0.22 mm (25% error)*

*A \cdot \omega = 0.25 \times 5 \text{ m/s} = 1.25 \text{ m/s}*

***Implies A = 2.6 mm***

*f = 75 \text{ Hz} \text{ (found using a modulating laser)}*

*Wire separation = 11 ± 4 mm (36% error)*

*Separation error = 4 mm = \sqrt{2} \ A*

***Implies A = 2.8 mm***

*If the amplitude doesn’t increase, at \textbf{v = 20 m/s}, we expect only 6% error.*
At 20 m/s it works great!
Comparisons with viewscreens at low beam current (~100 nA)

High repetition rate
Low bunch charge

v₀ = 20 m/s

Low repetition rate
High bunch charge
It works!

Vertical beam profile measurements taken at Cornell’s ERL Photoinjector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Used for experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam type</td>
<td>Electron</td>
</tr>
<tr>
<td>Energy</td>
<td>4 MeV</td>
</tr>
<tr>
<td>Power</td>
<td>0.5 MW</td>
</tr>
<tr>
<td>Current</td>
<td>&lt; 35 mA</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>&lt; 27 pC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>1.3 GHz / 50 MHz</td>
</tr>
<tr>
<td>Emittance</td>
<td>0.3 μm</td>
</tr>
<tr>
<td>Trans. Beam Size</td>
<td>~ 3 mm</td>
</tr>
</tbody>
</table>

Note: Each (normalized) curve is presented on the same plot only for easy comparison.
Take home messages

• Great option for high current/intensity beams
  – It works!
  – Compact (~40 cm)
  – Cheap (< $5000)
  – Quick to build (only 2 custom parts)
Thank you for listening!

Check out the publication for more info:
T. Moore “A Fast Wire Scanner for Intense Electron Beams”
Phys. Rev. ST Accel. Beams 17, 022801
http://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.17.022801

Thanks to Tobey Moore, our vacuum technician, for inventing this great design. And reminding us to keep it simple!

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Bruce Dunham
Yulin Li
Jim Savino
Karl Smolenski

Contact: Steve Full at sf345@cornell.edu
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