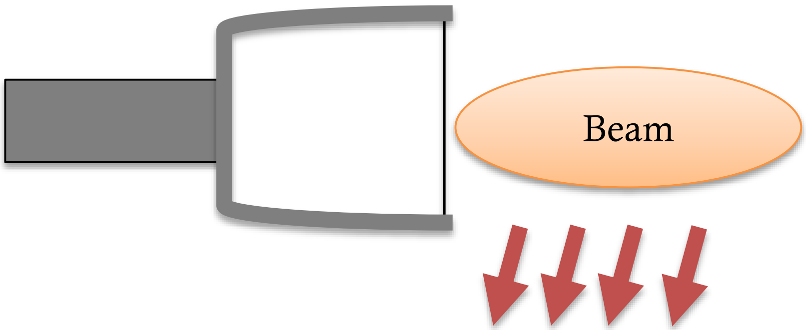
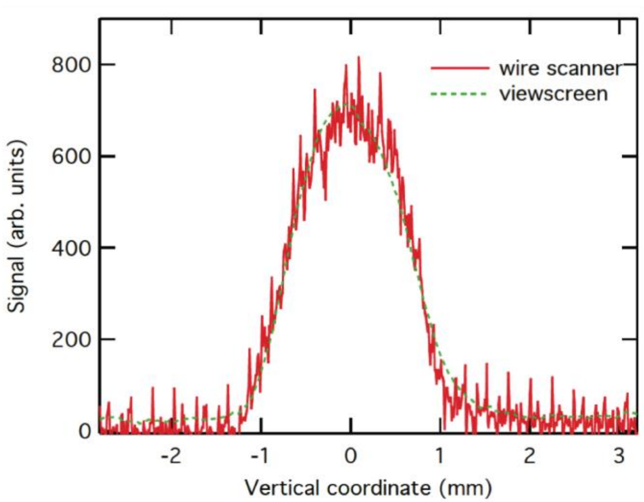
A fast rotating wire scanner for use in high intensity accelerators

Steven Full
CLASSE, Cornell University
ERL Workshop 2015
June 11th, 2015

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





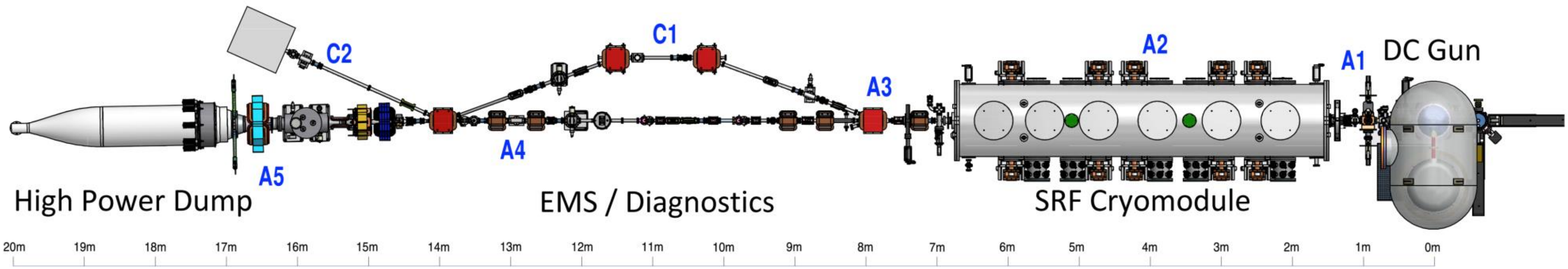
A typical measurement scheme:

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.

Motivation for a new design



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.

Parameter	Low current	Nominal/High current
Beam energy	5 – 15 MeV	5 – 15 MeV
Beam size	~ 2 mm	~ 2 mm
Norm. Emittance	< 0.3 μm (measured)	< 0.3 μm (simulated)
Bunch length	< 3 ps	< 3 ps
Current	< 100 nA	100 mA
Beam Power	< 1 kW	1 MW

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

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  Let's come up with a new design.

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Let's come up with a new design.

Wire scanner design goals

Main Goal:

Avoid melted wires

Requirements:

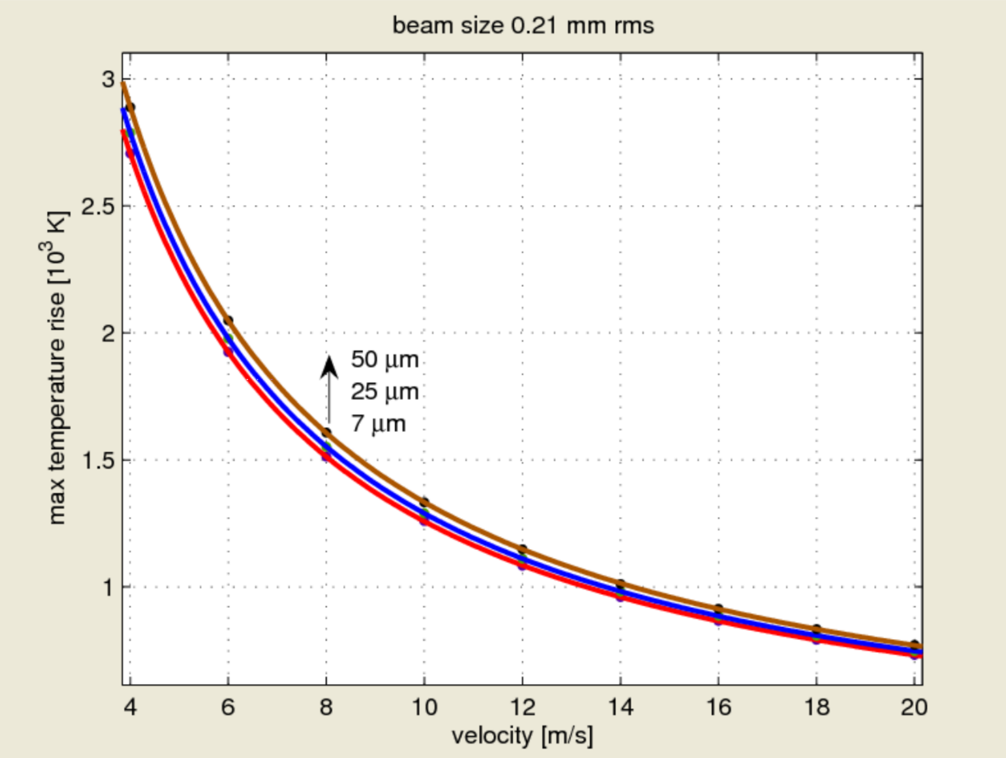
1) Wire speeds > 20 m/s (45 mph)
2) ~10's μm resolution
3) Cheap
4) Compact
5) Quick to build and implement

Most wire scanners move at mm/s or cm/s.

A fast wire speed minimizes heating

Deposited energy

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



Maximum temperature reached during a single scan (simulated)

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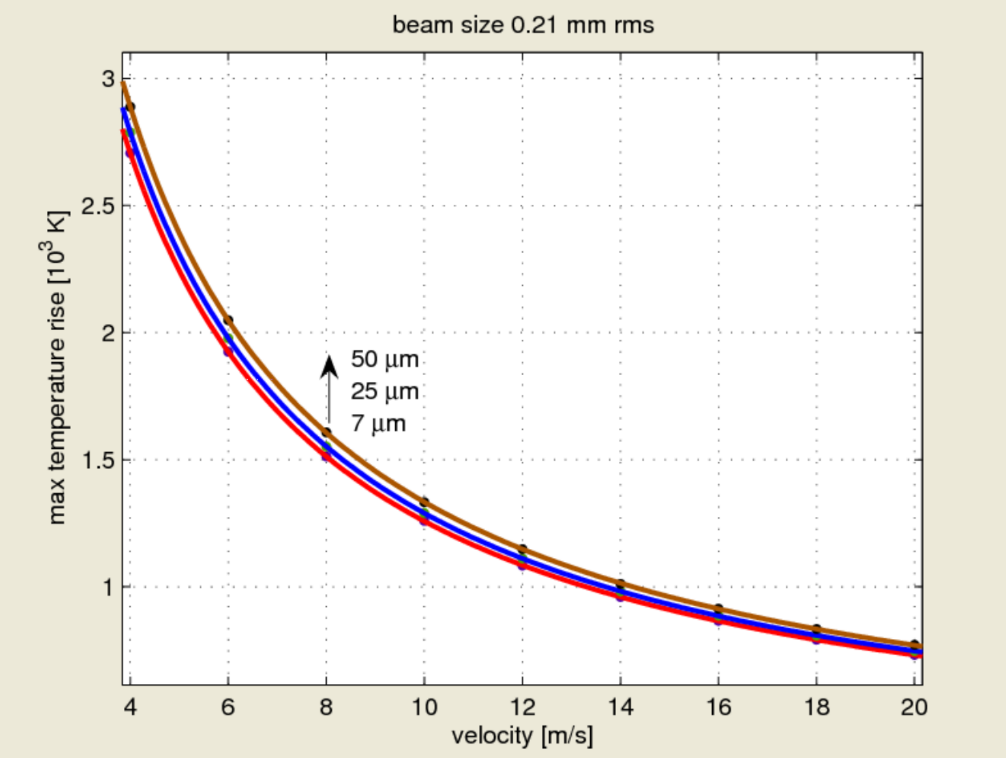

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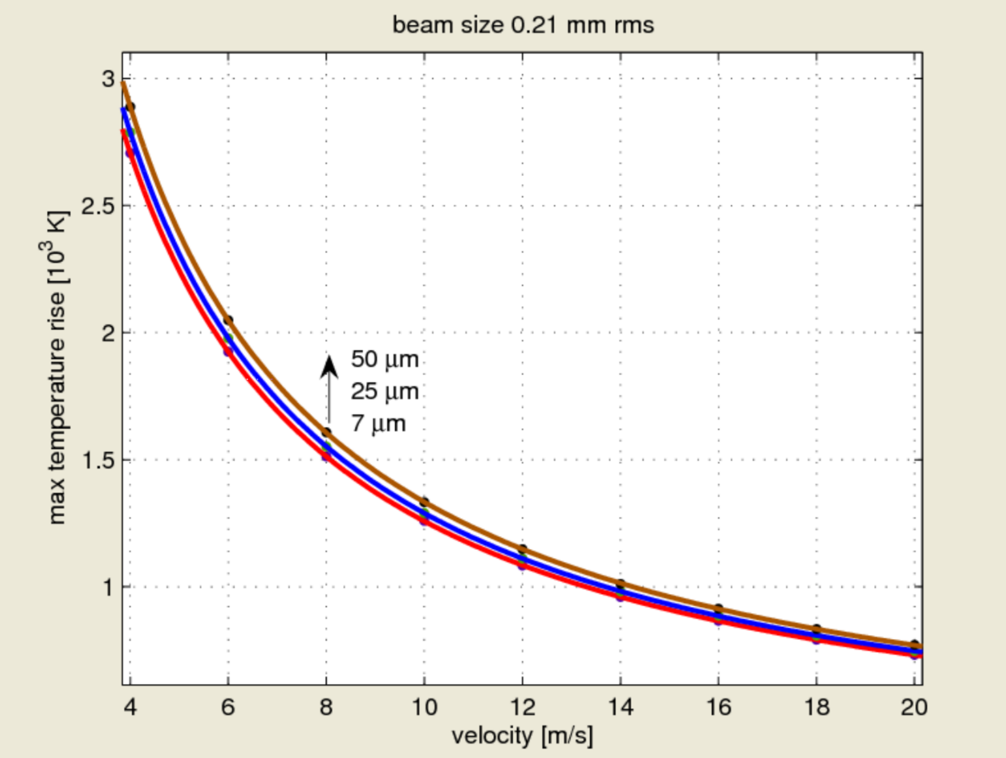

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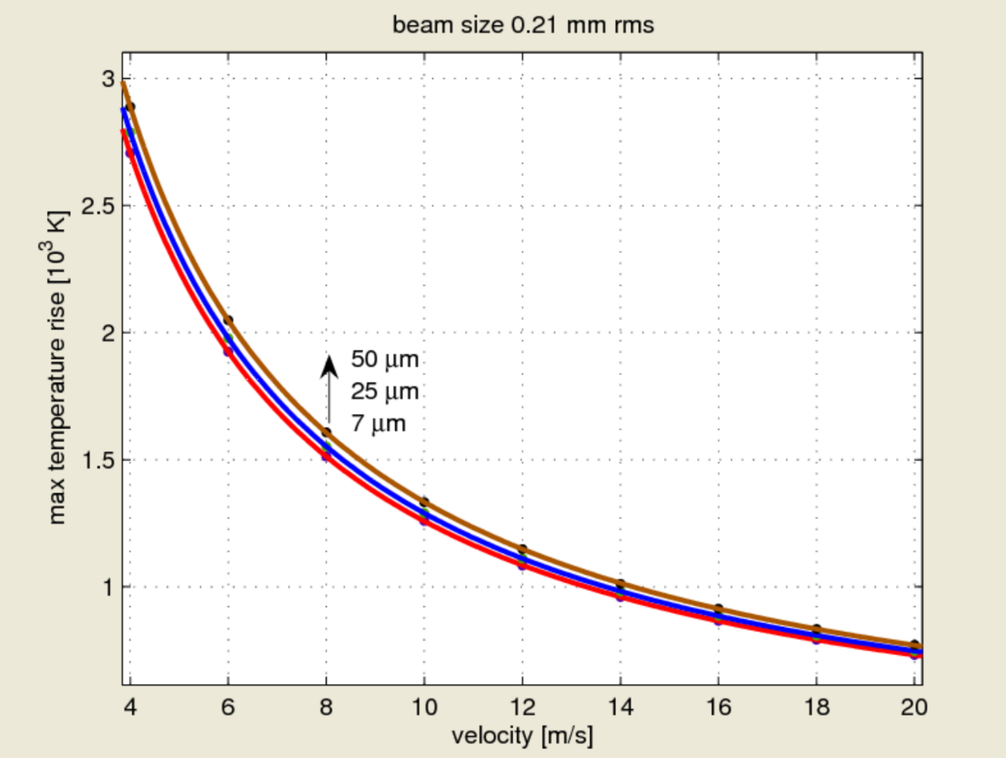

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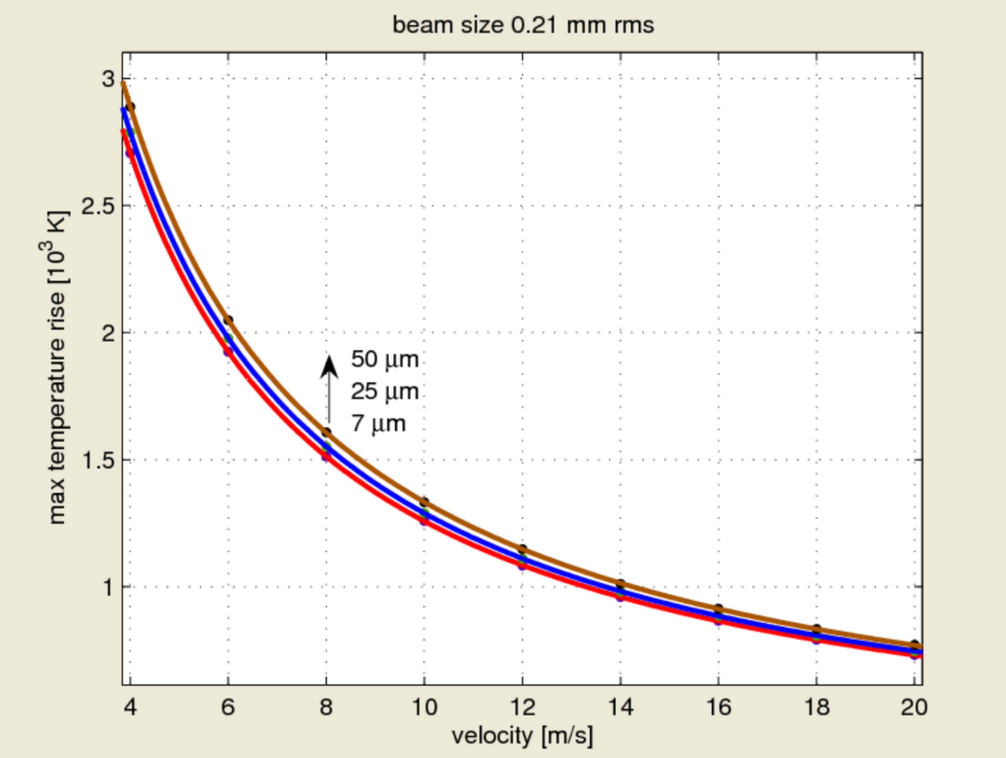

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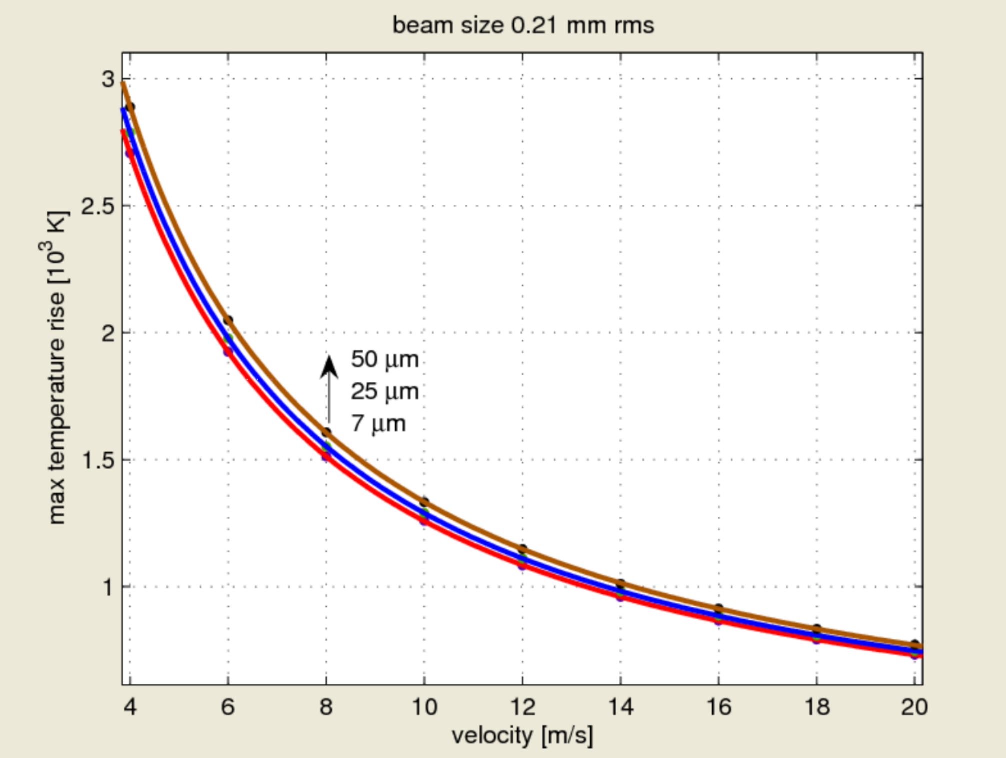
Heat capacity



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Heat capacity

Beam size
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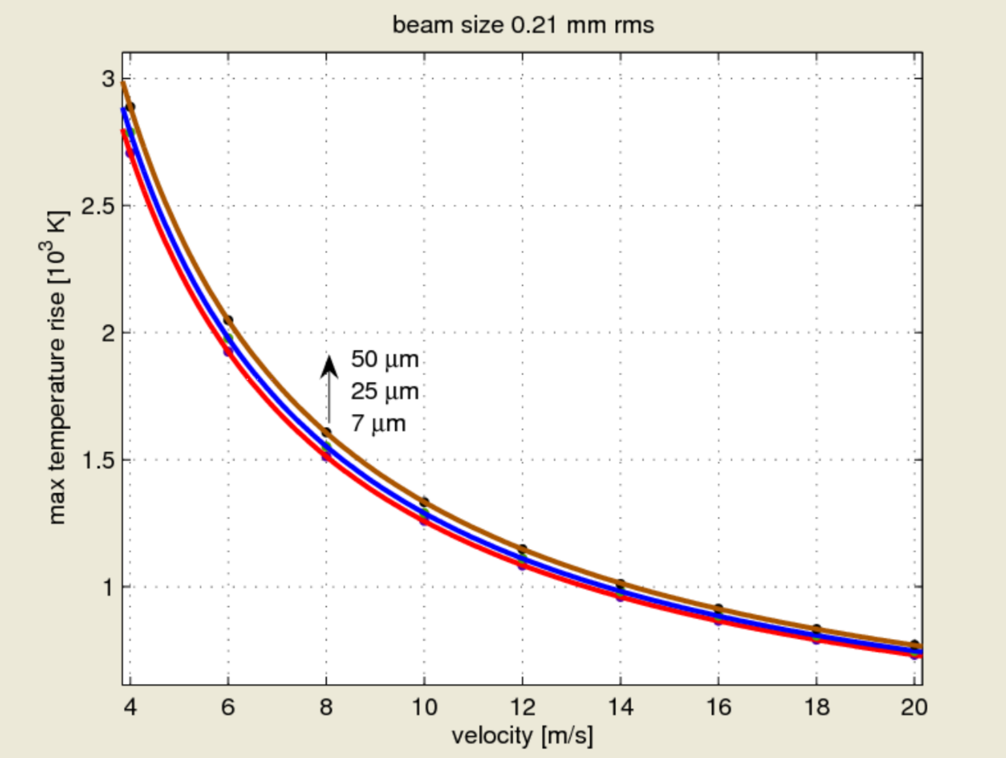

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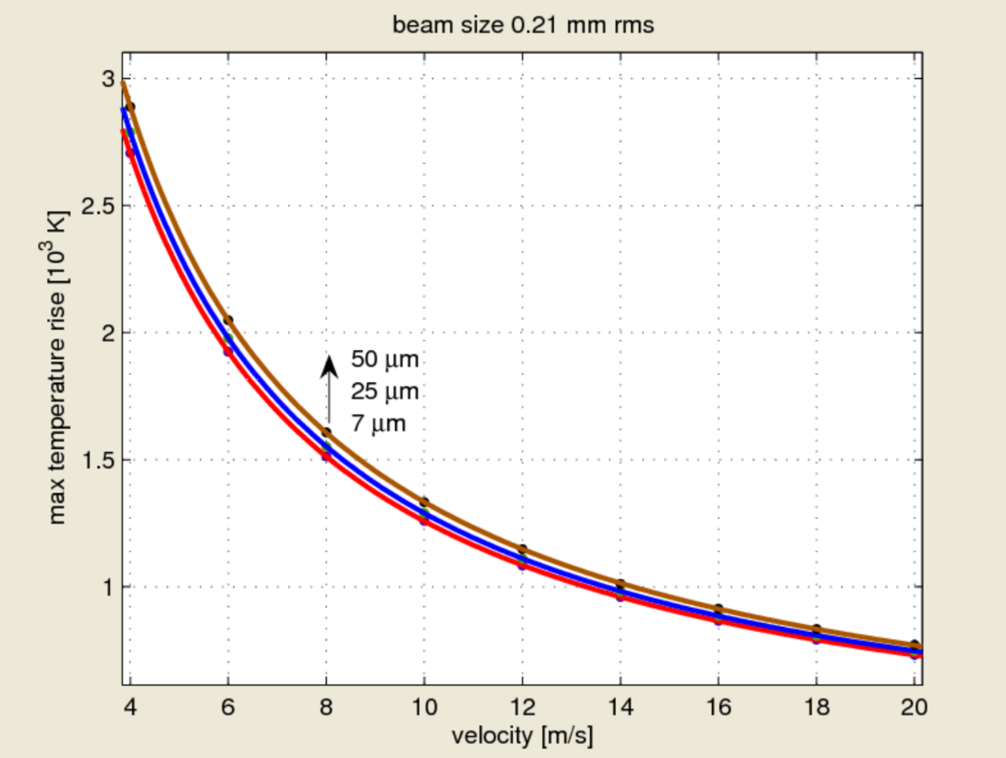

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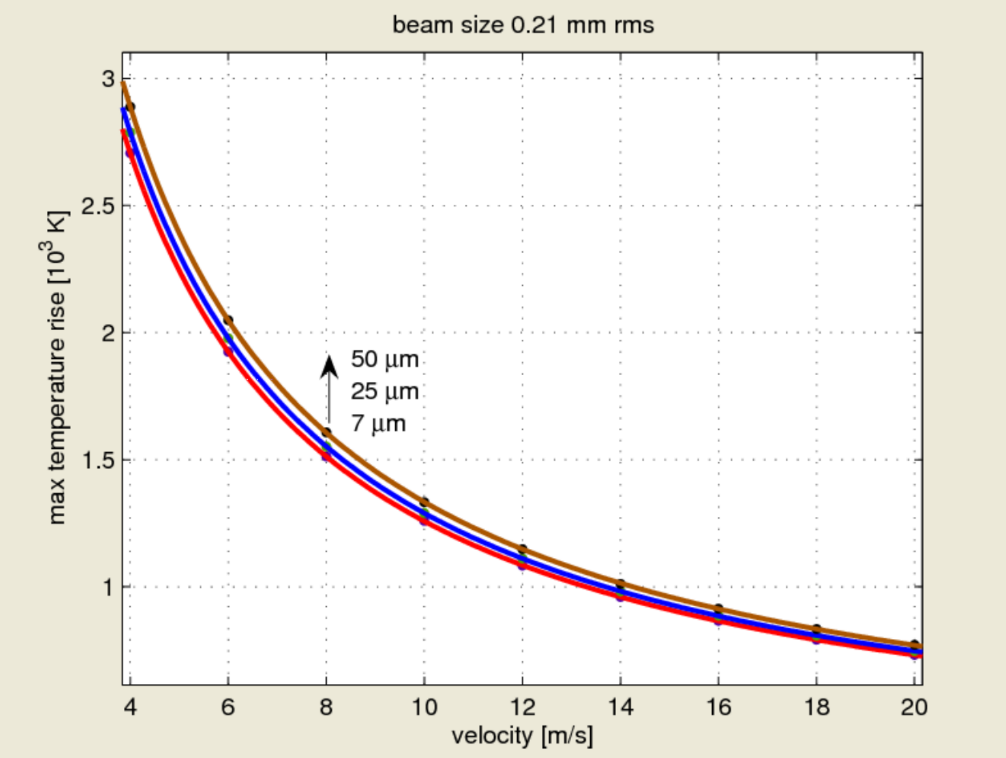

Maximum temperature reached during a single scan (simulated)

Cooling factor = 0.3

About 70% heat is lost from ejected secondary particles

K. Wittenburg from DESY, “Conventional wire scanners for Tesla”

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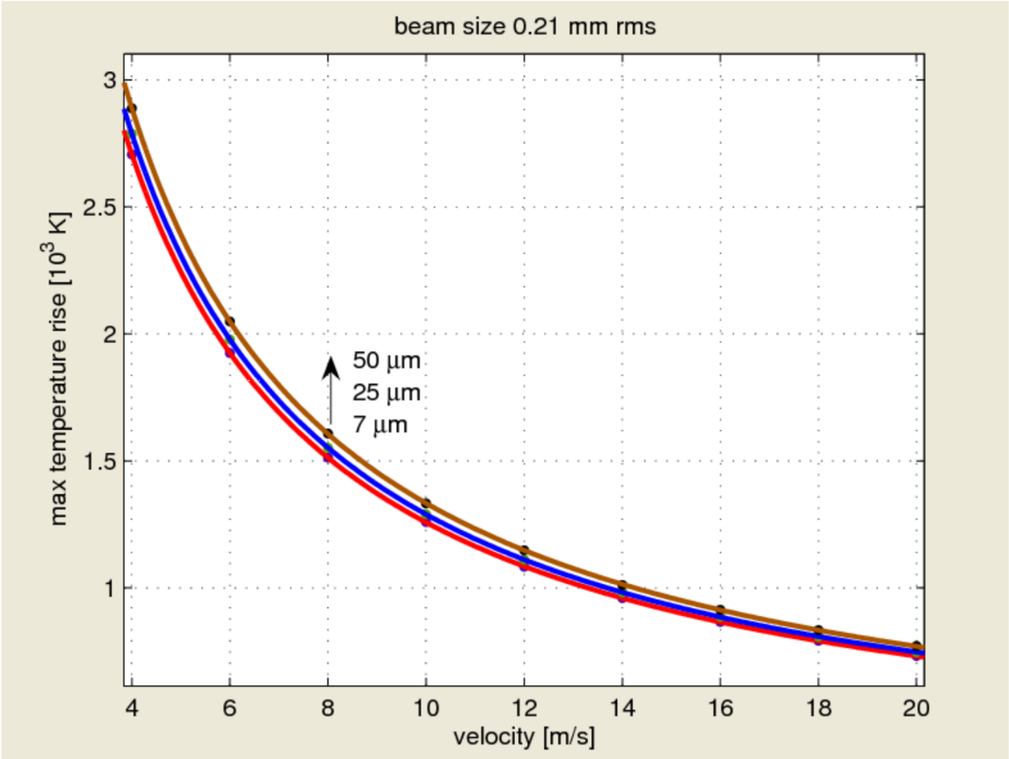

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Choosing a wire material

It's a tradeoff between heat capacity and durability.

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

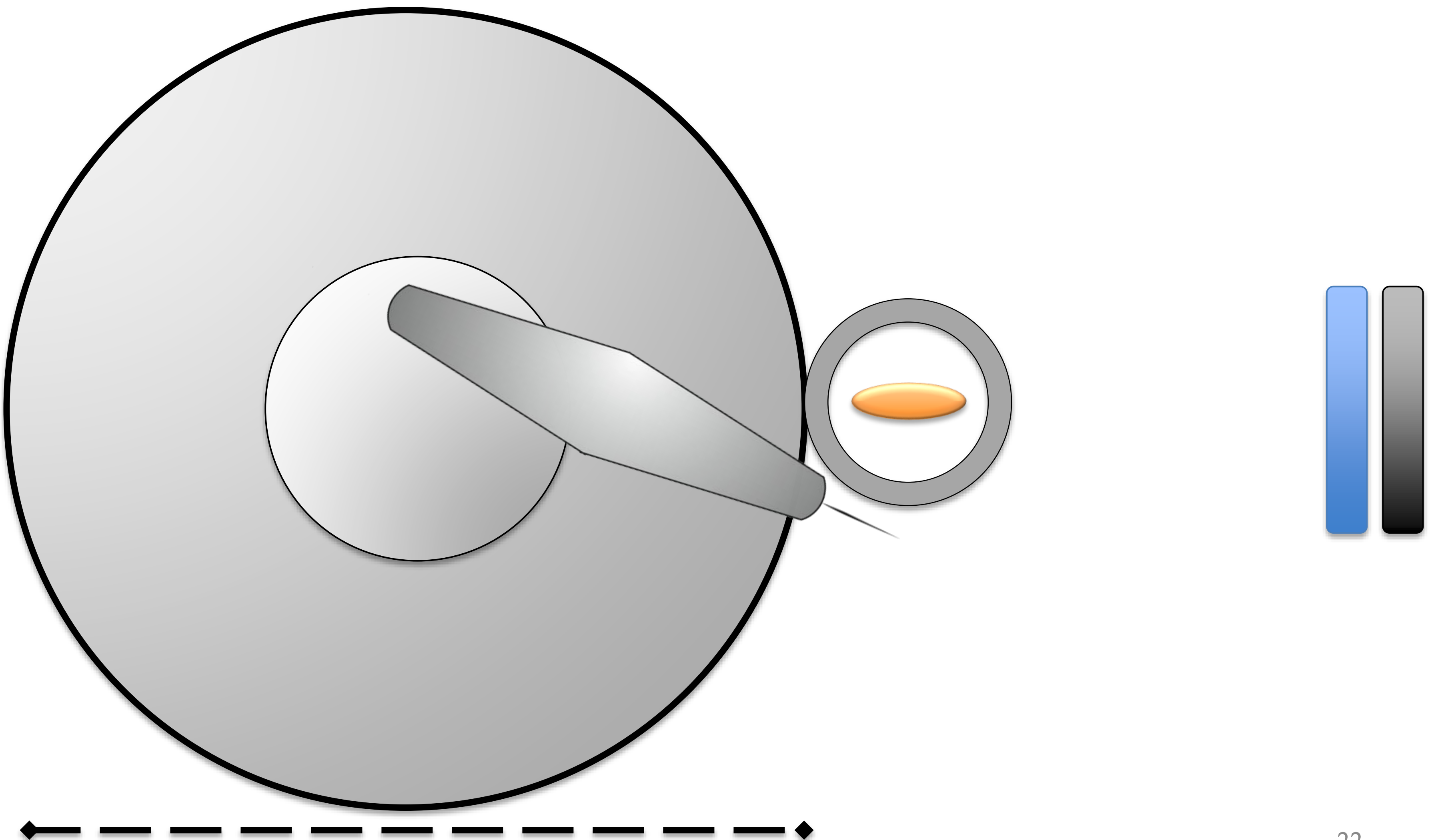
Tungsten is a good secondary choice, and is more durable.

	Carbon	Tungsten
C_p (cal / g / ˚C)	0.42*	0.055
Melting/ Sublimation (K)	3915	3695
Durability	Brittle	Durable

* C_p for Carbon scales with temperature; this is for 1000 ˚C

A cartoon of the 2 gear design

Detection



Scale: 35cm / 14”

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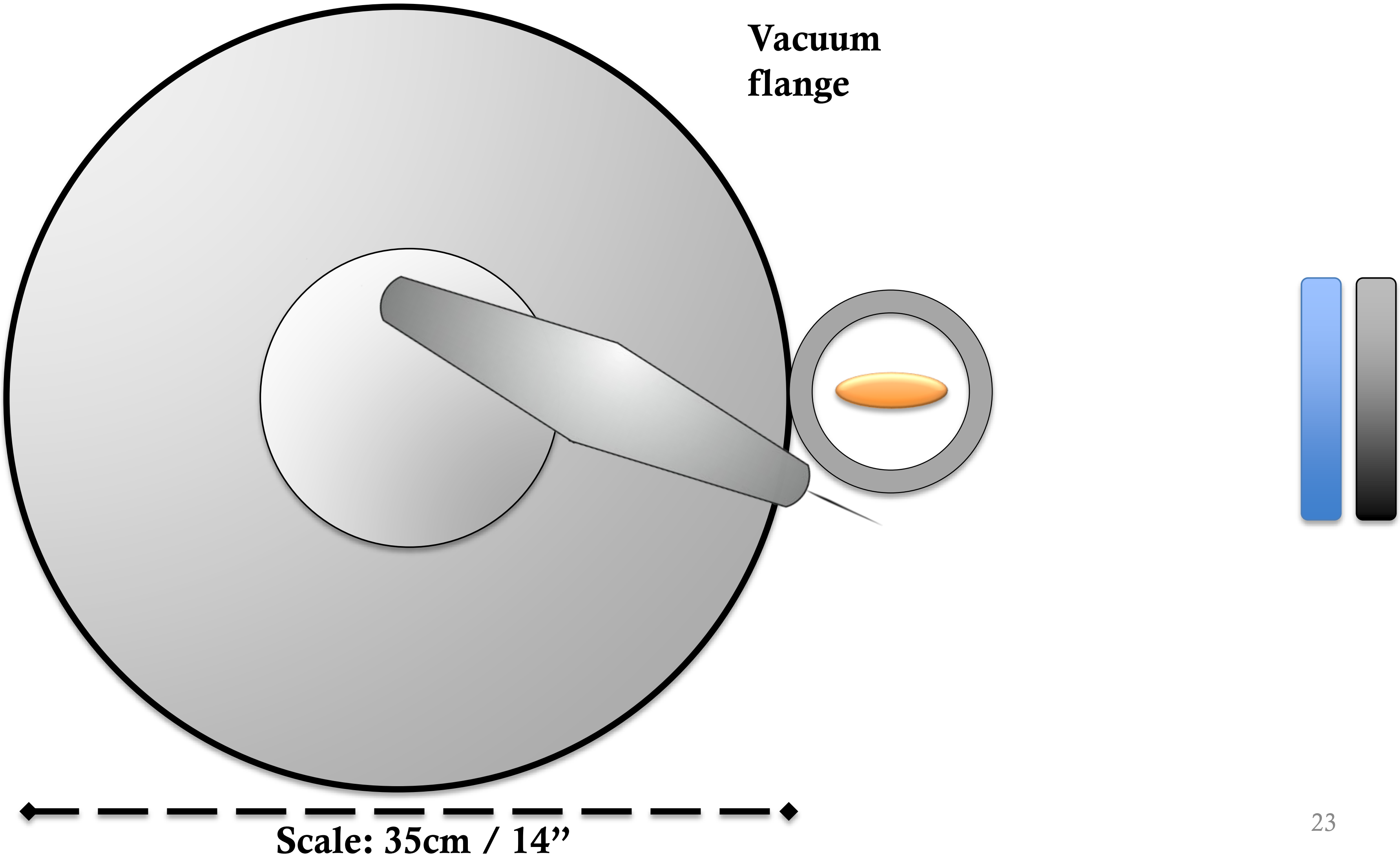

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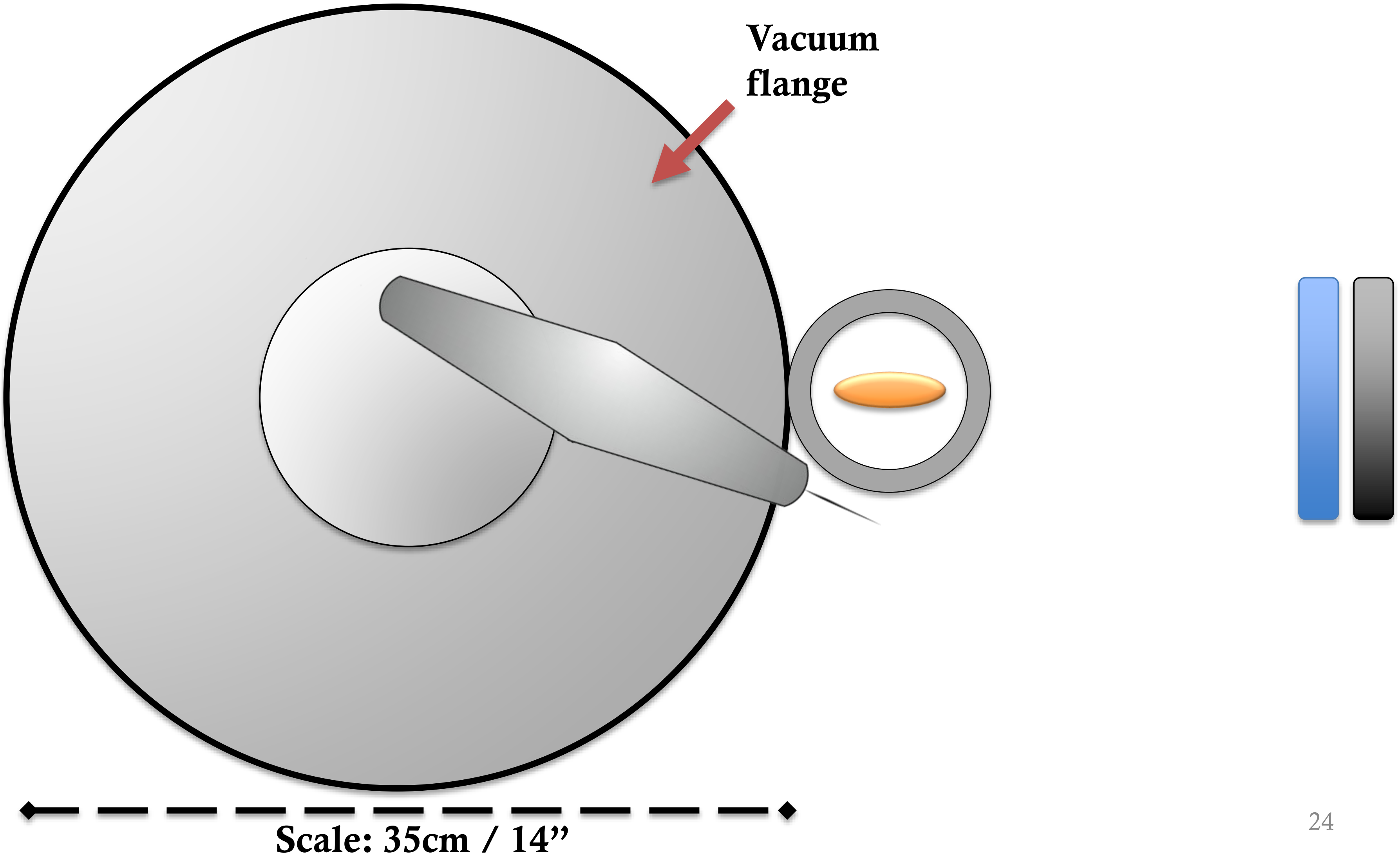

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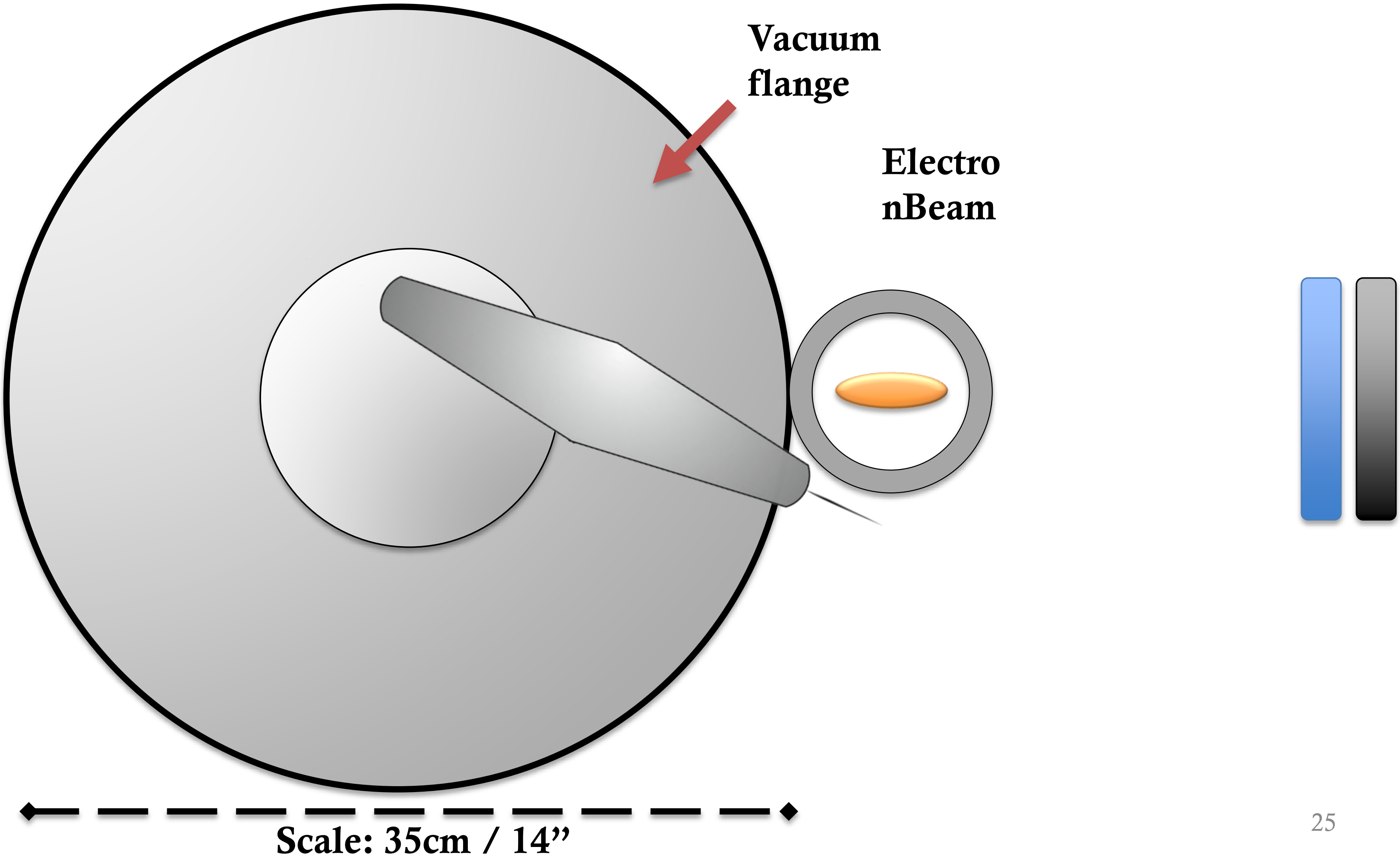

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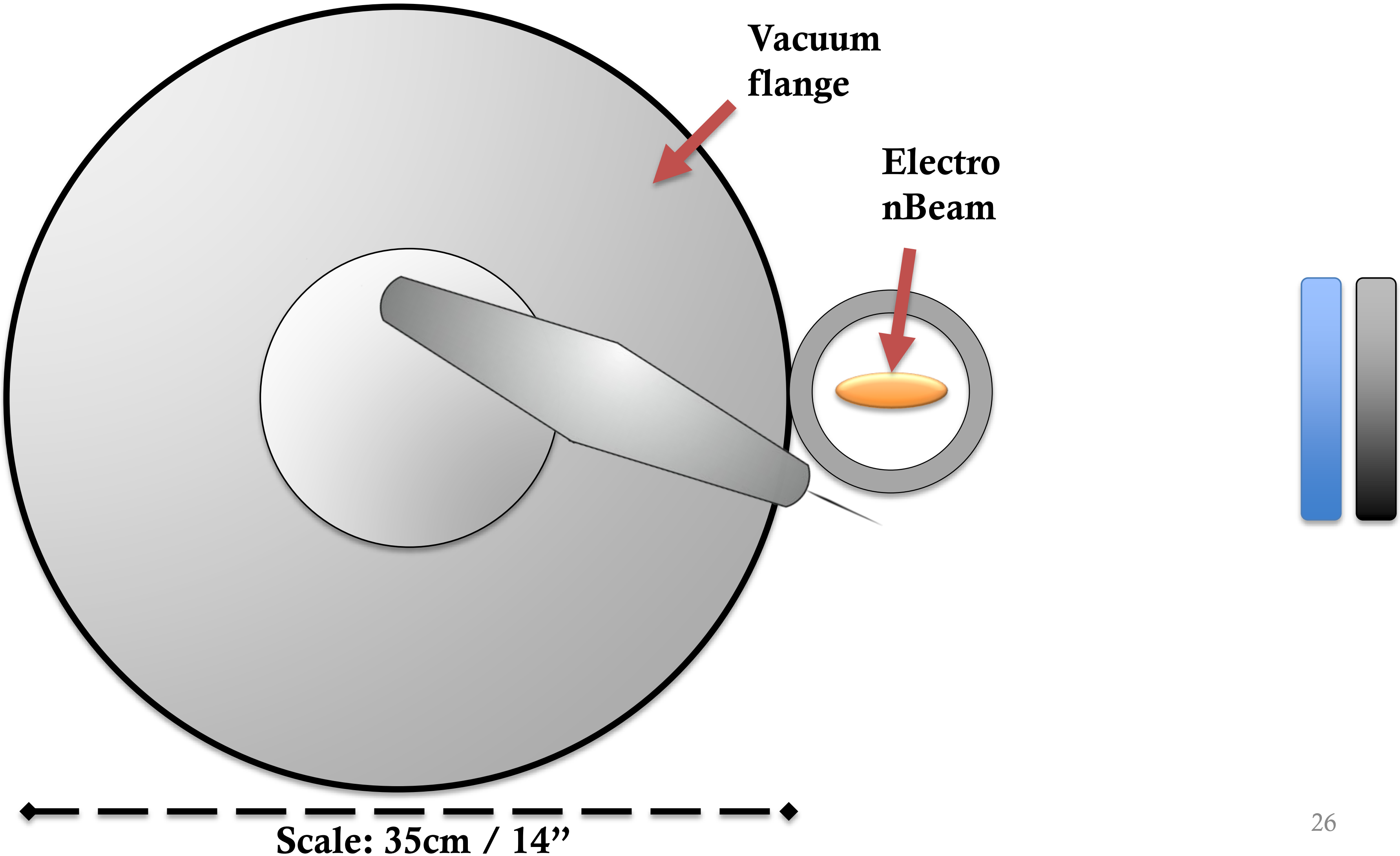

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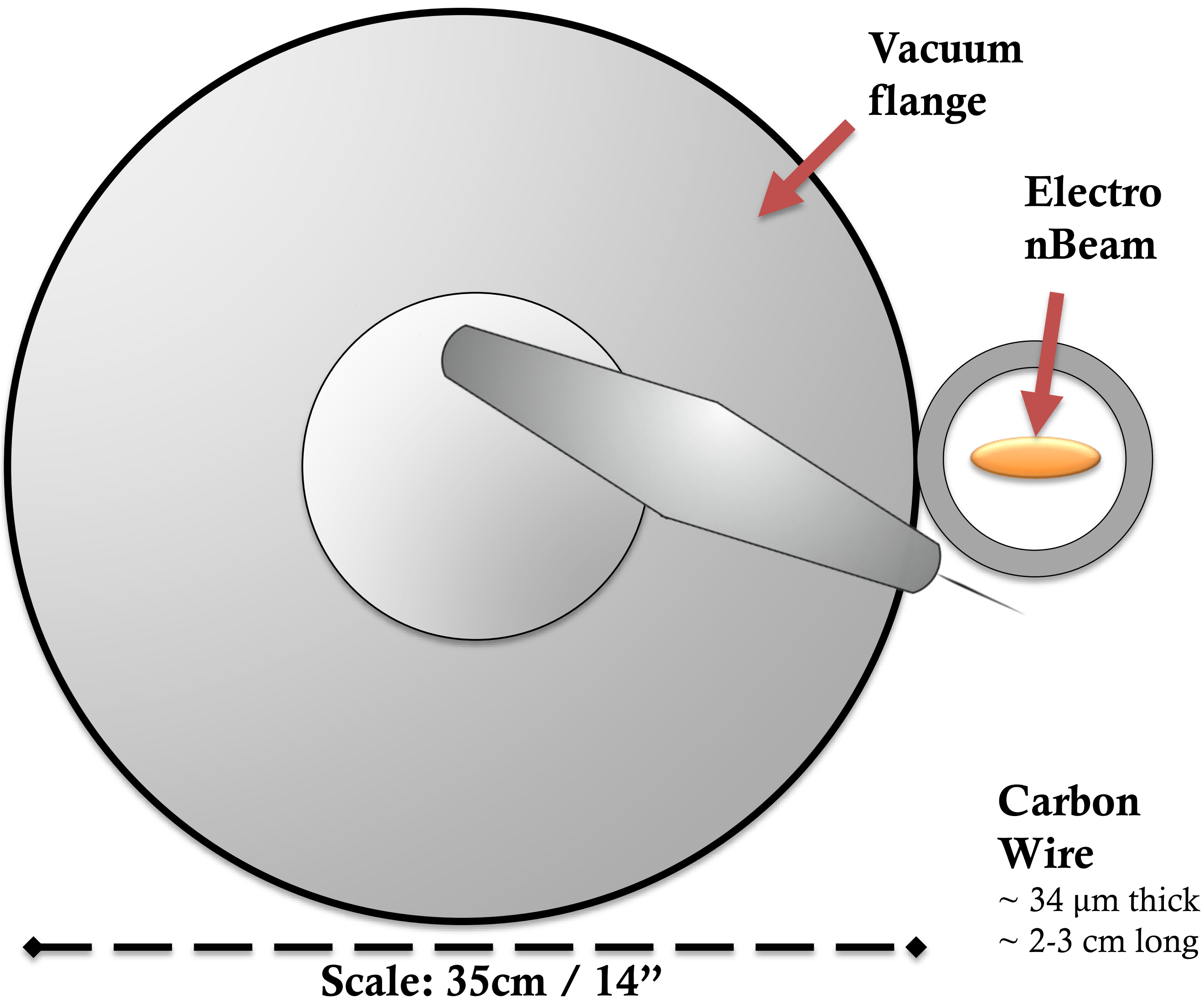

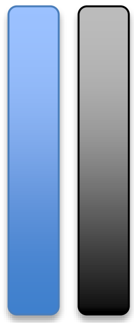

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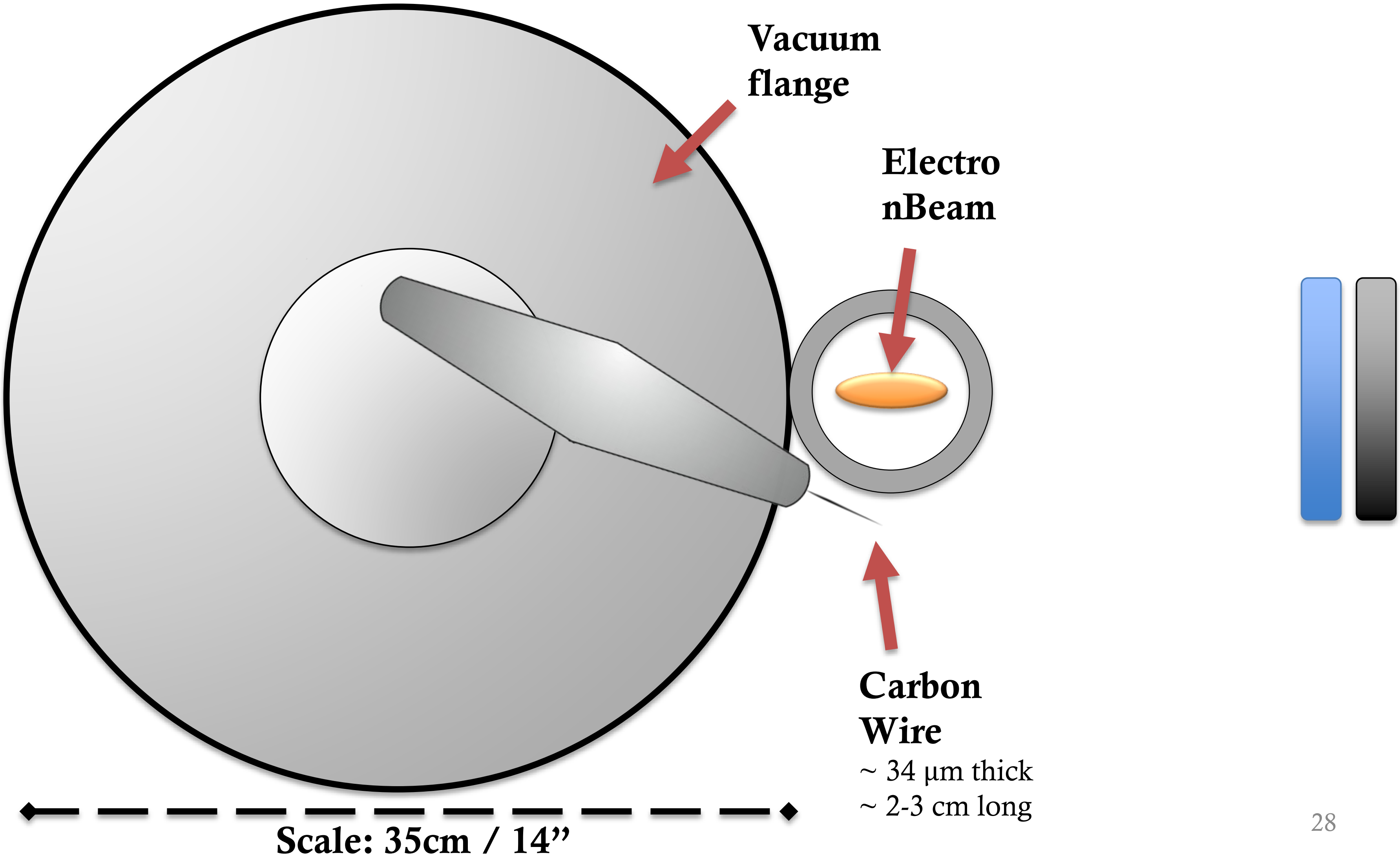

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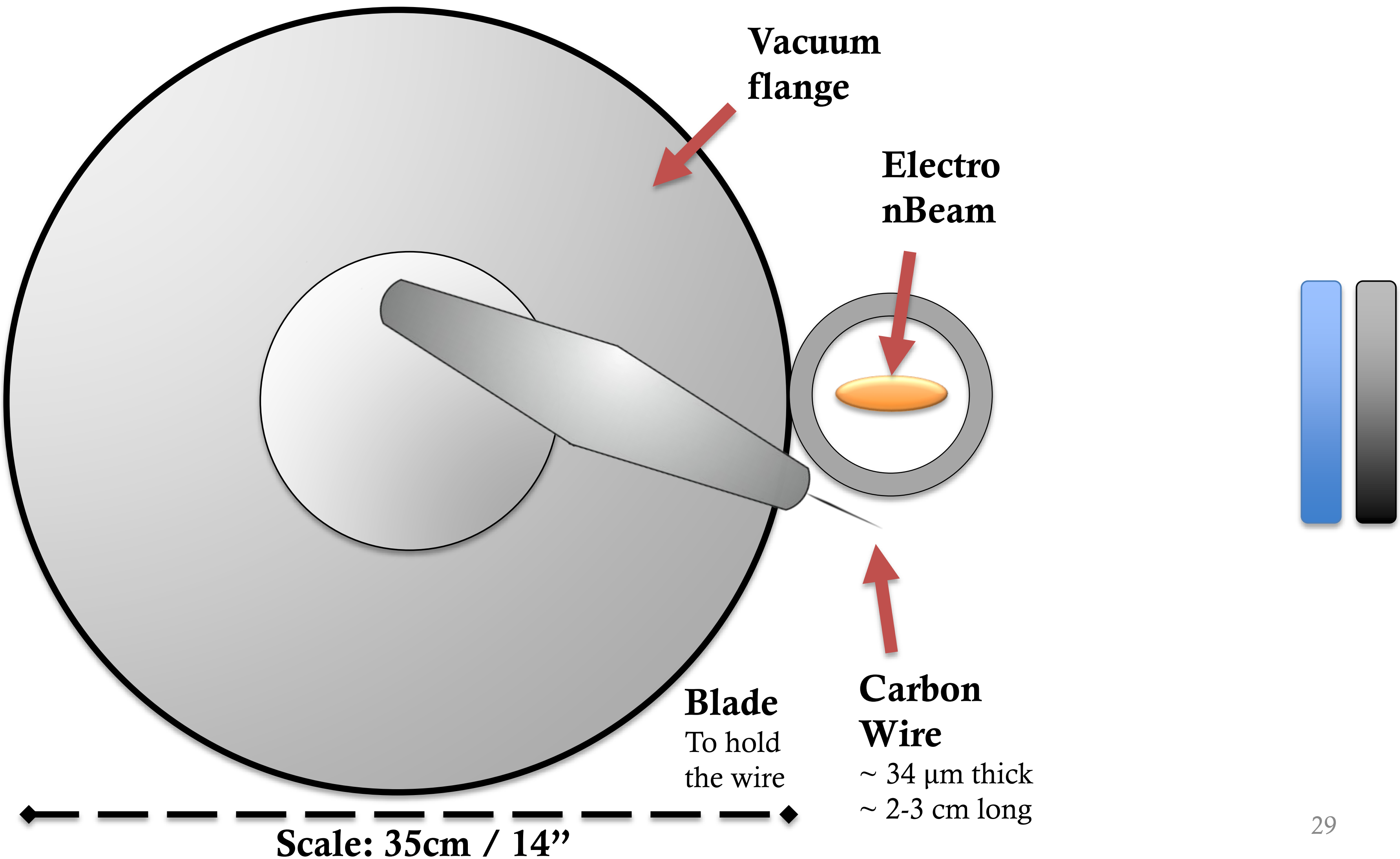

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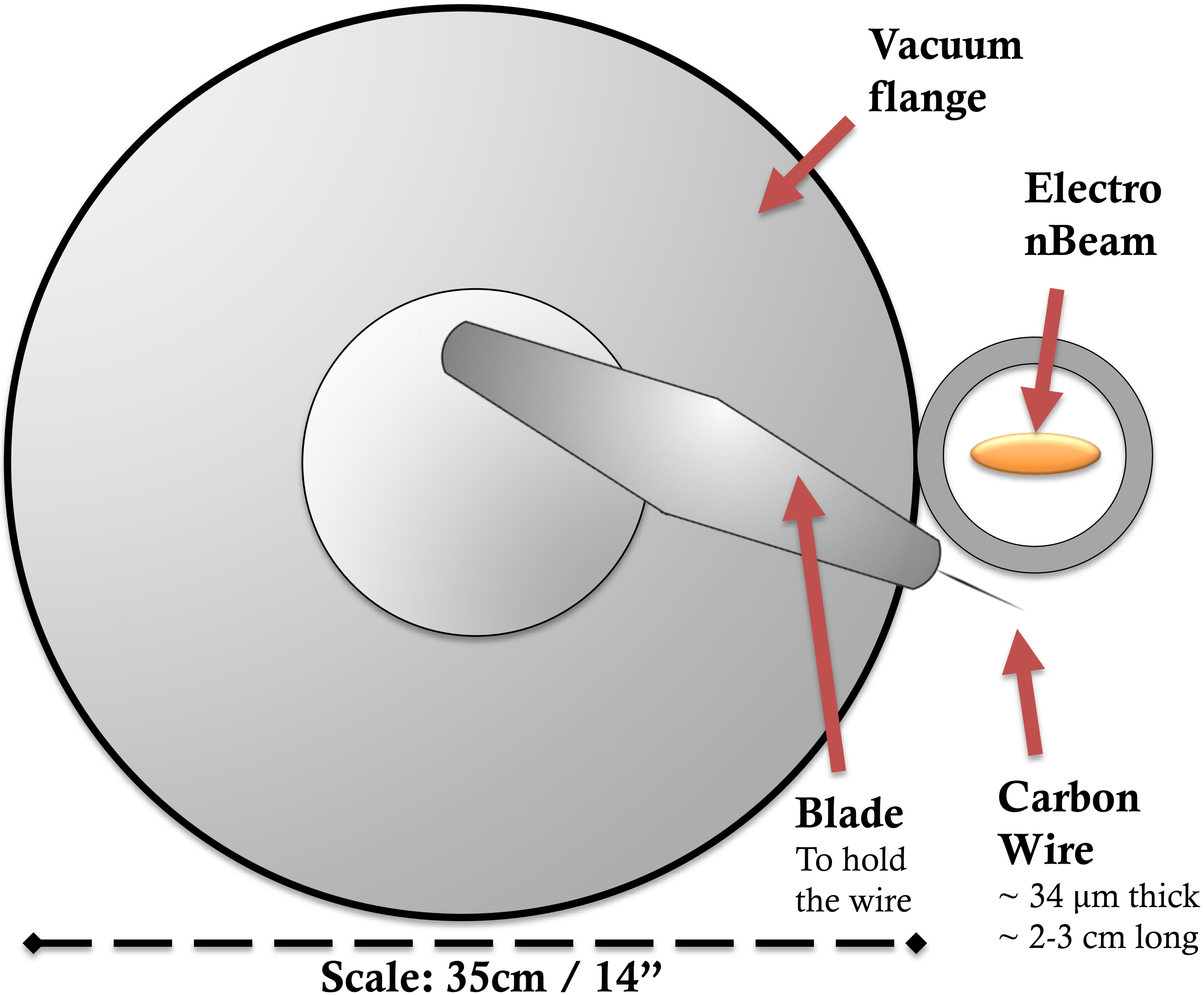

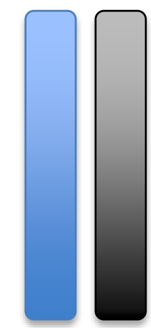

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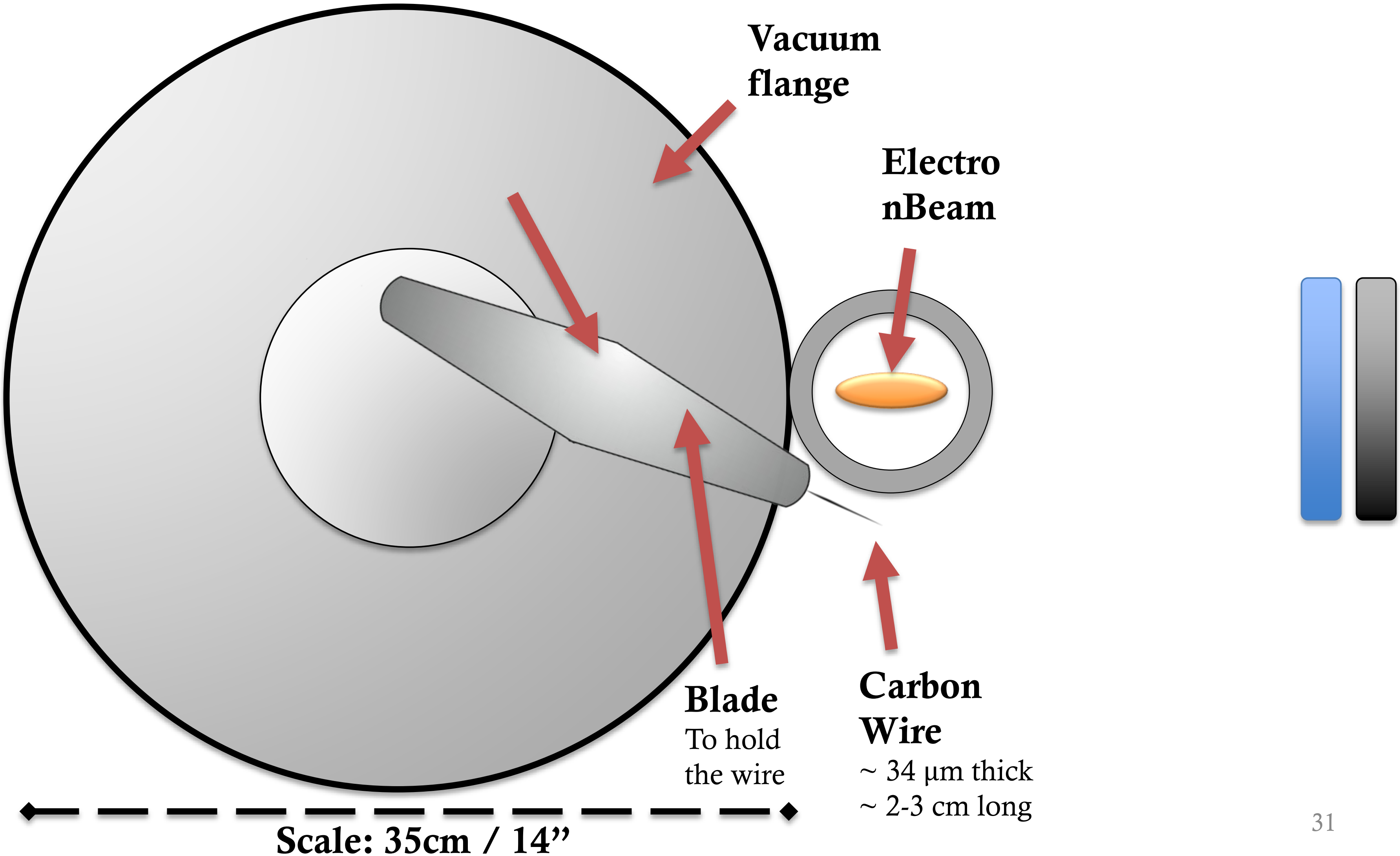

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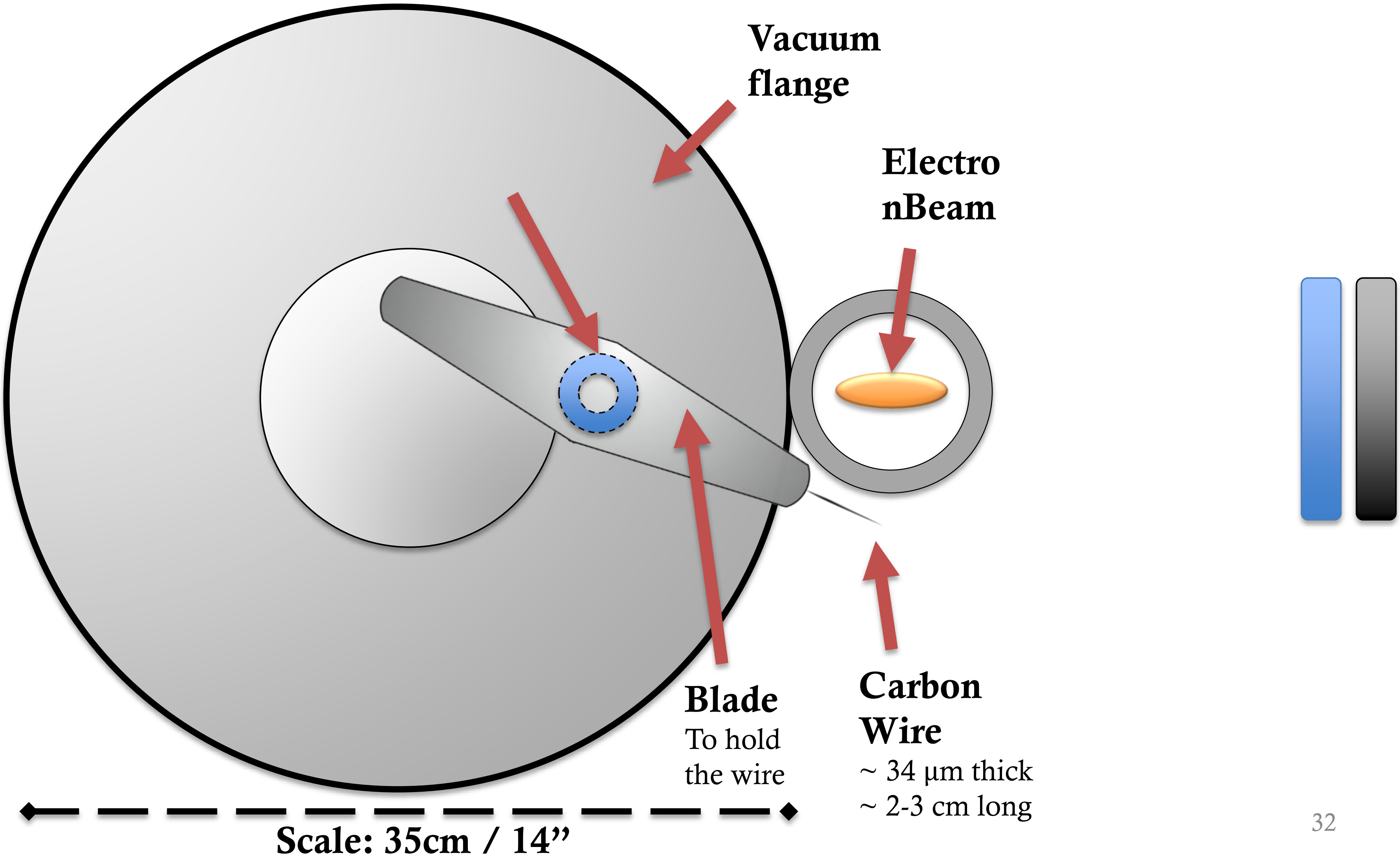

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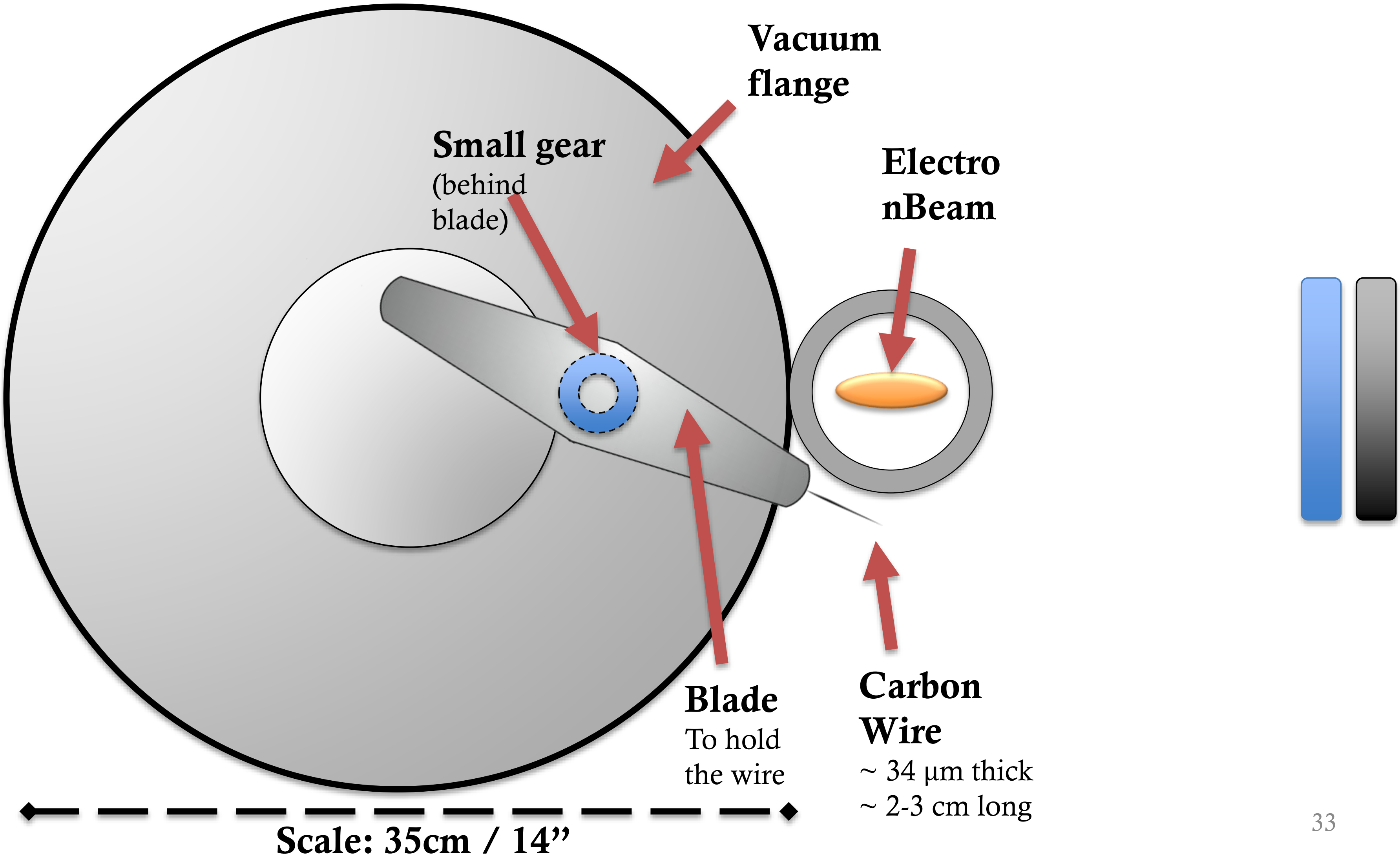

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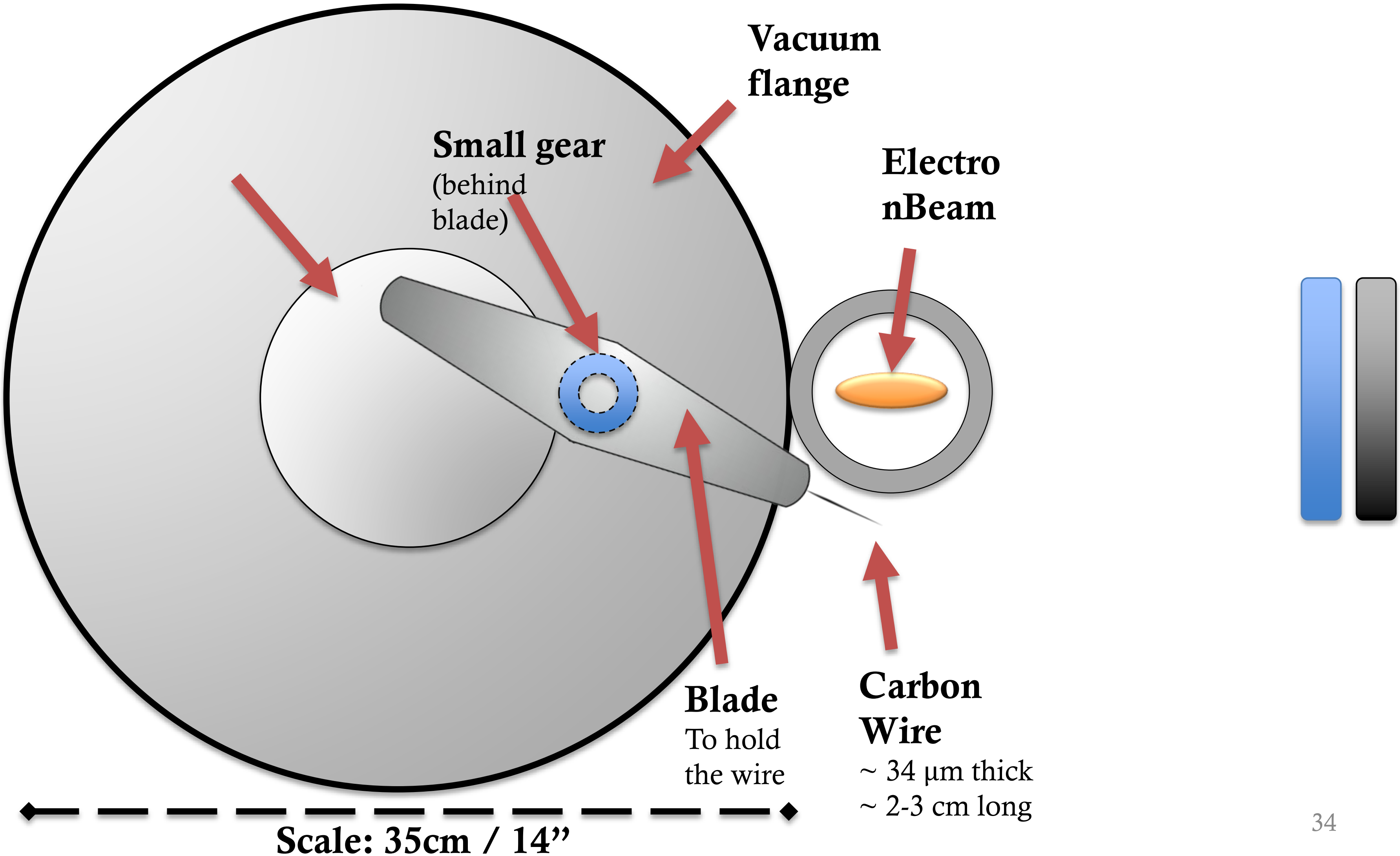

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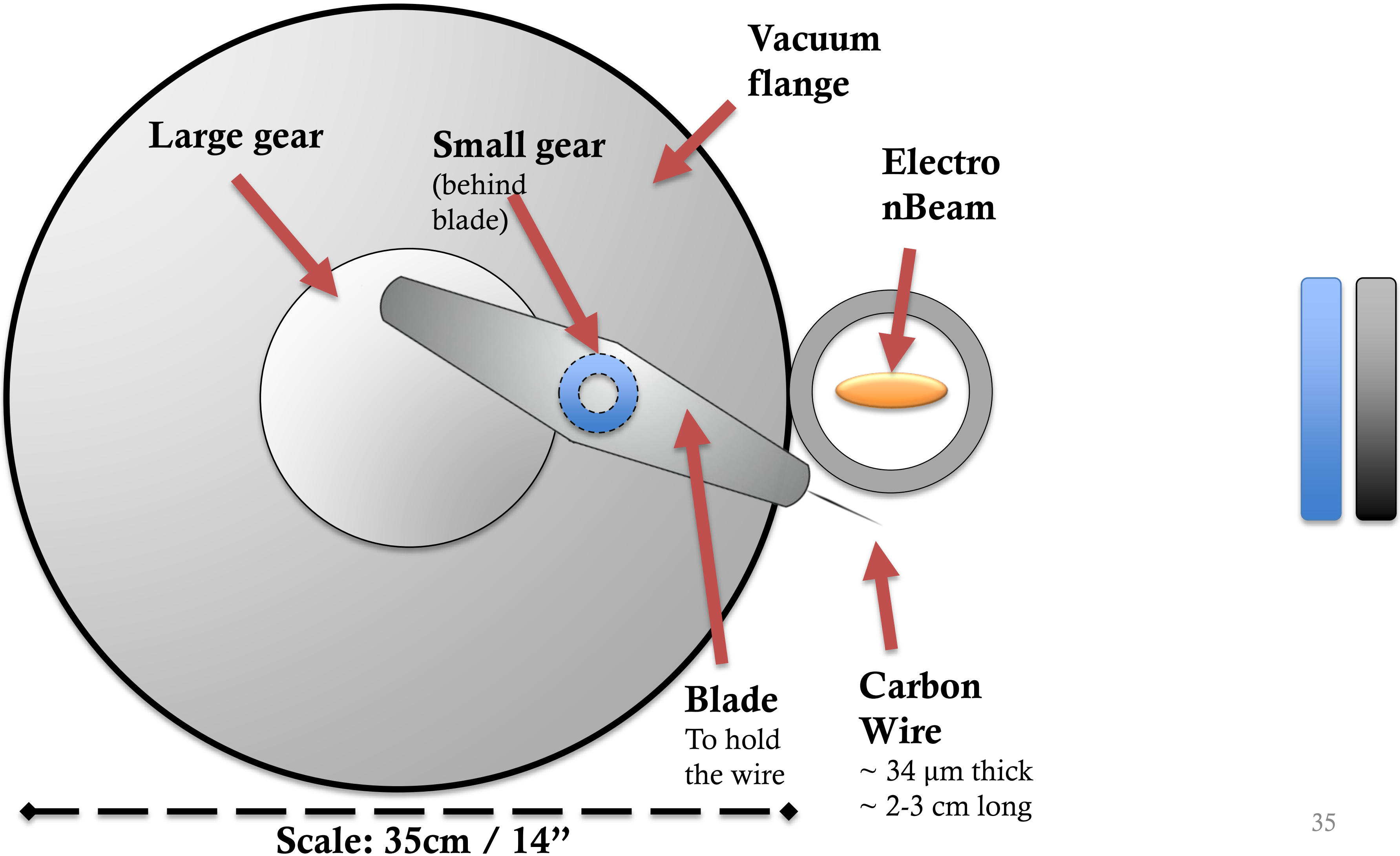

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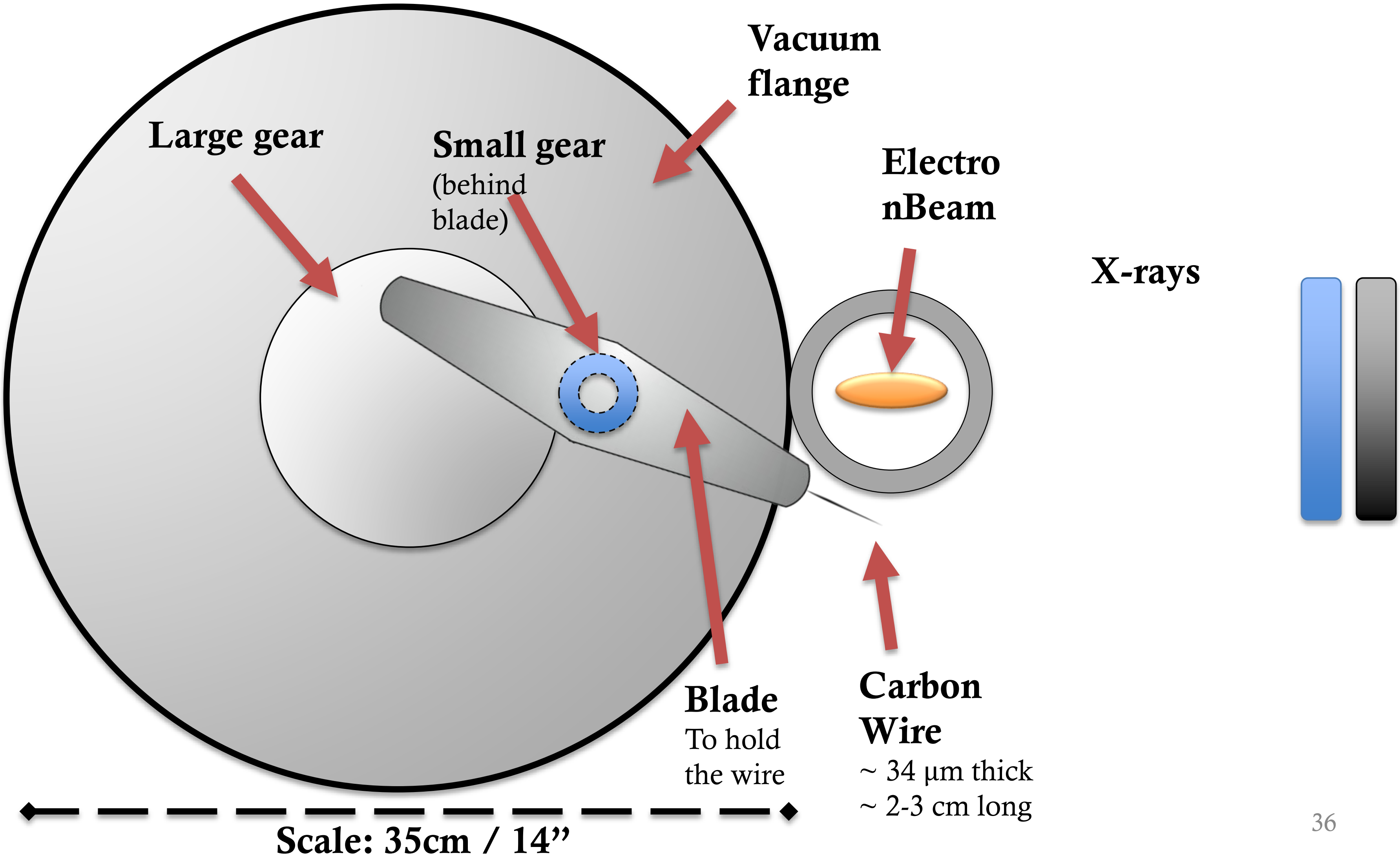

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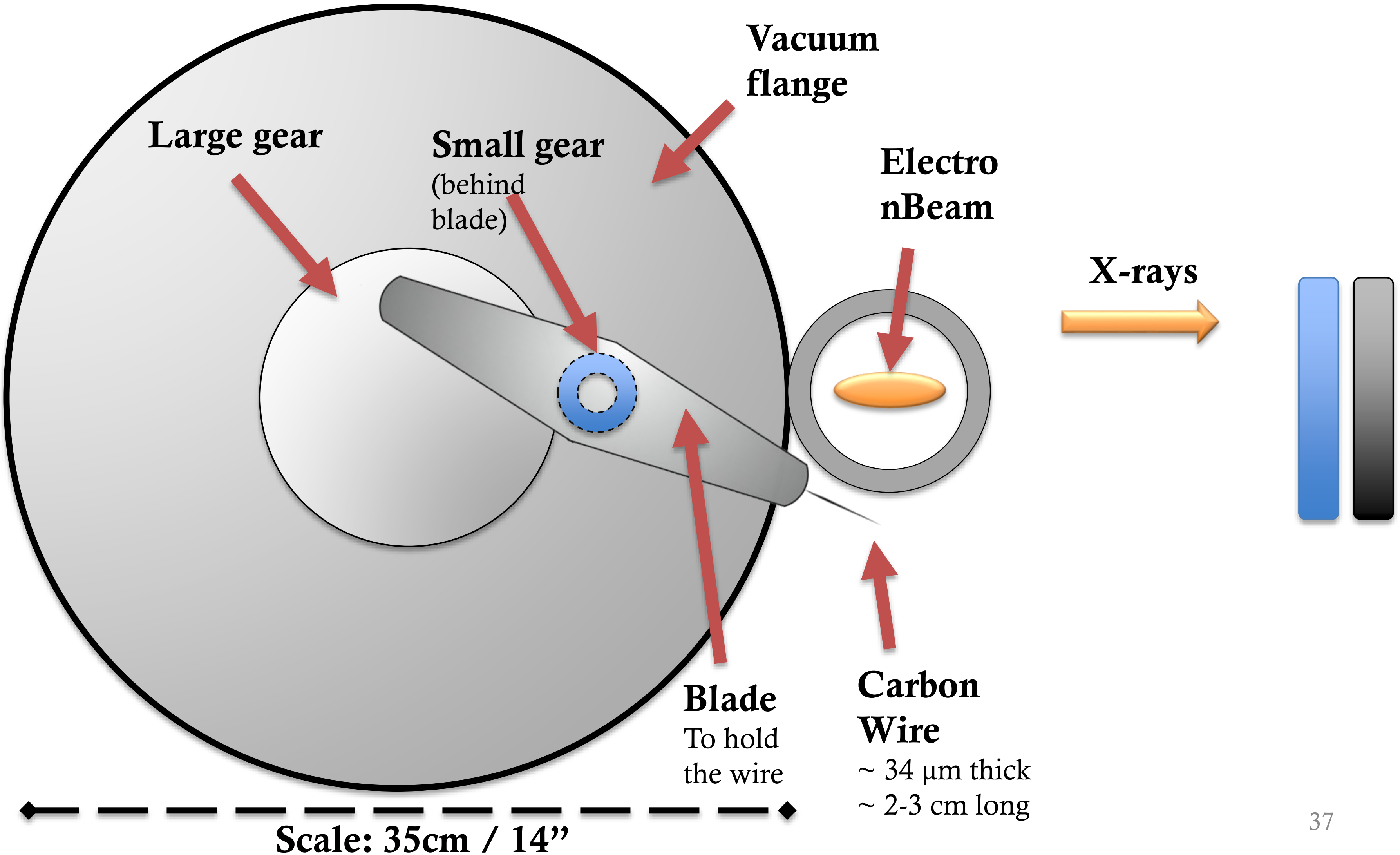

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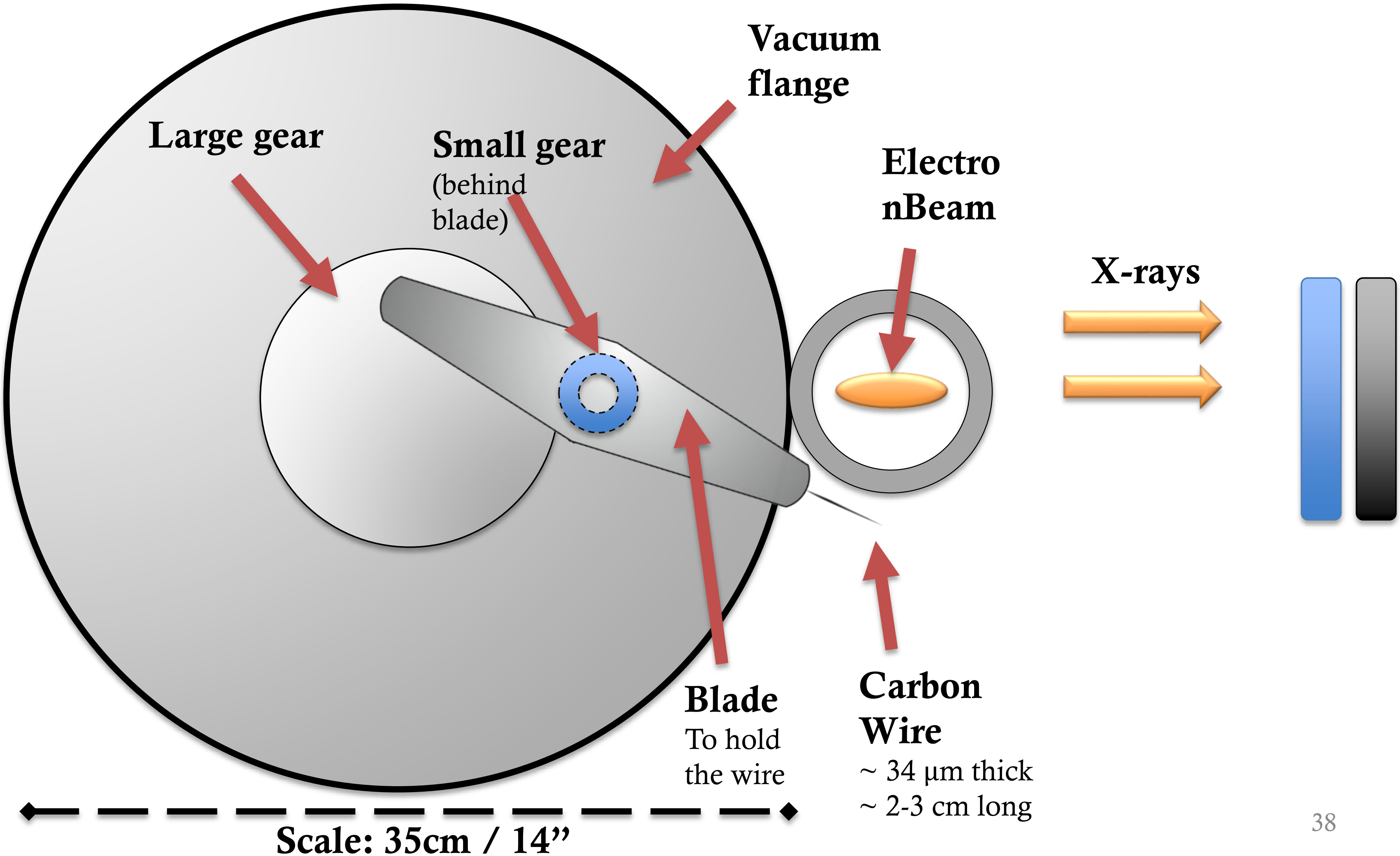

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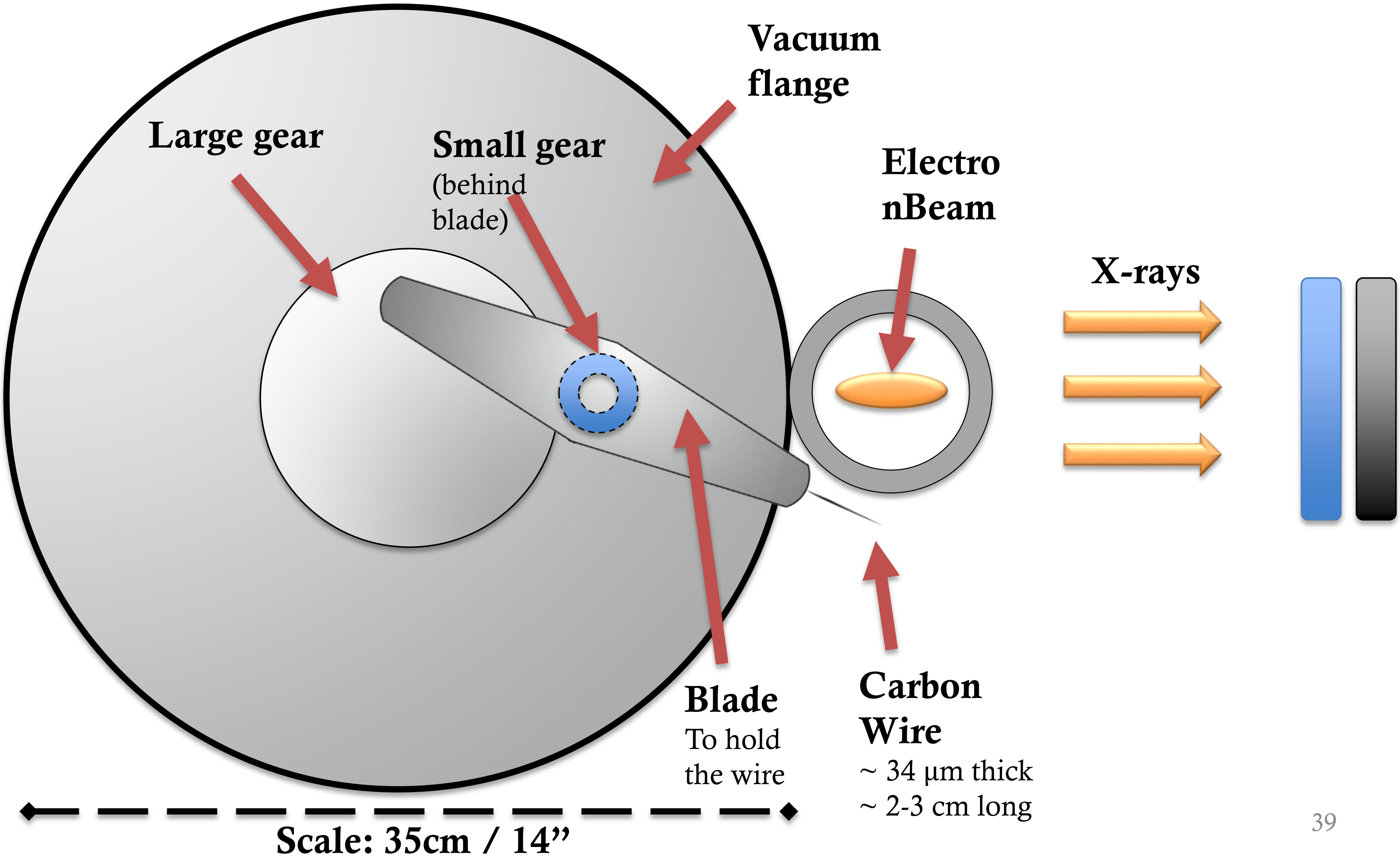

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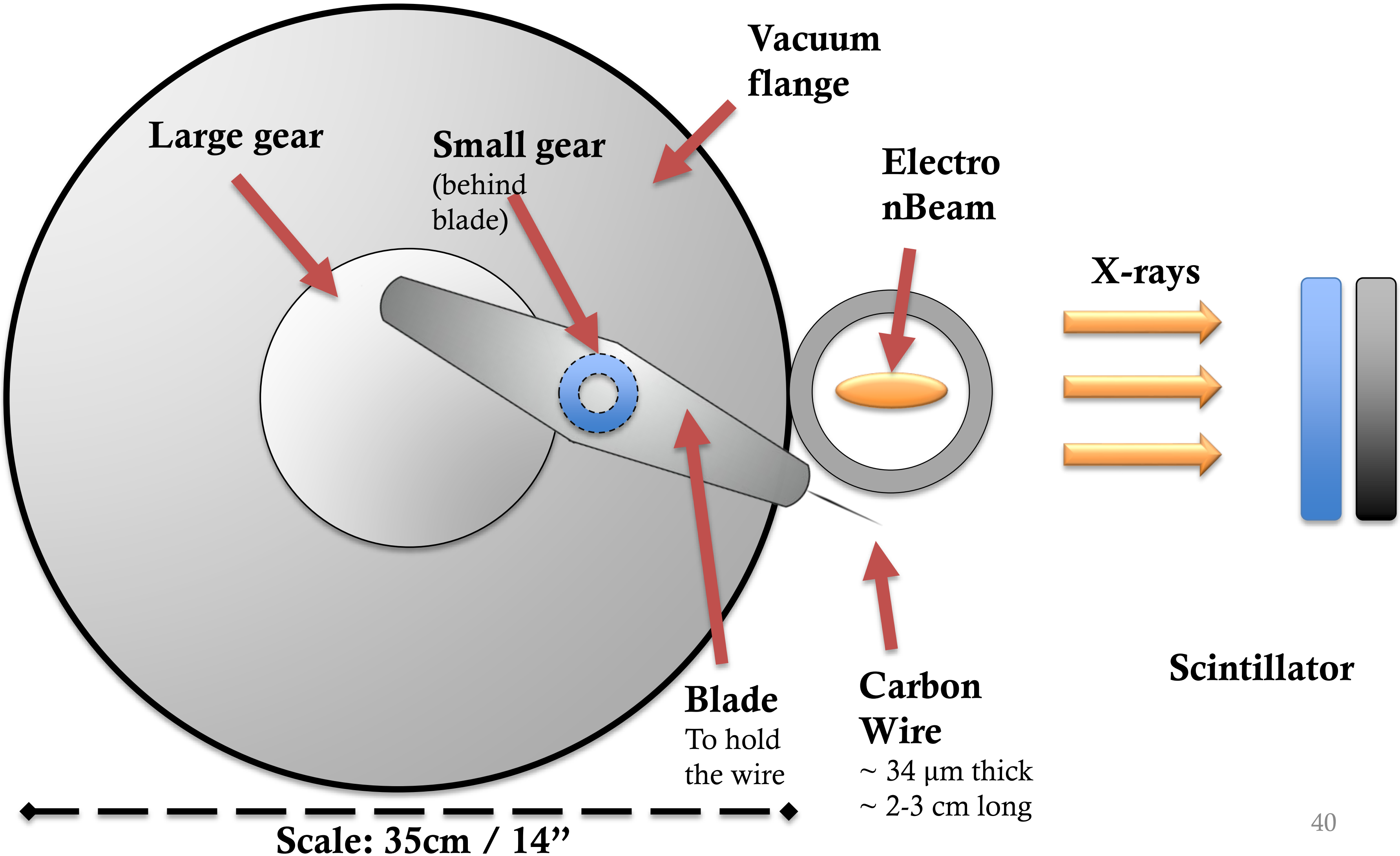

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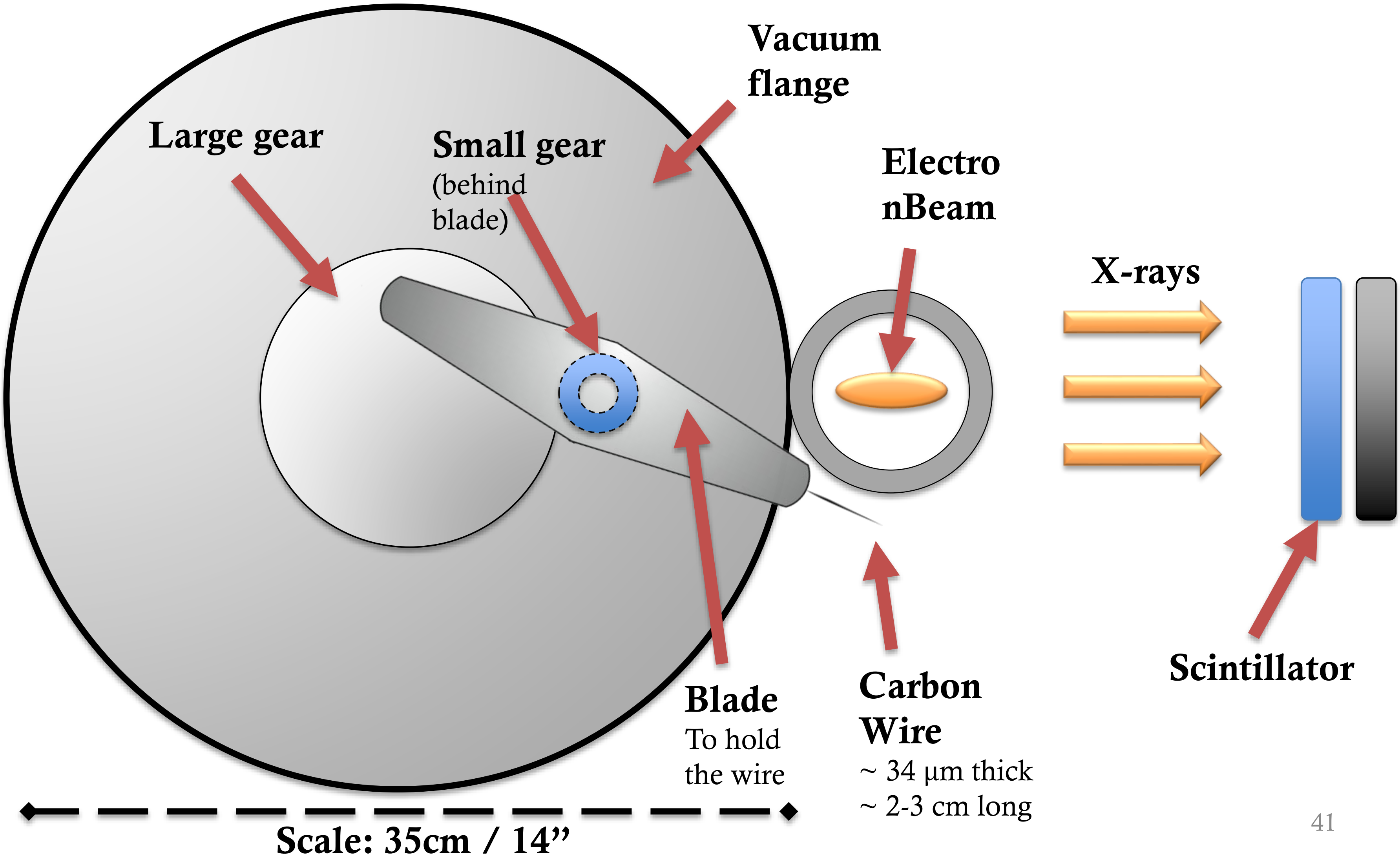

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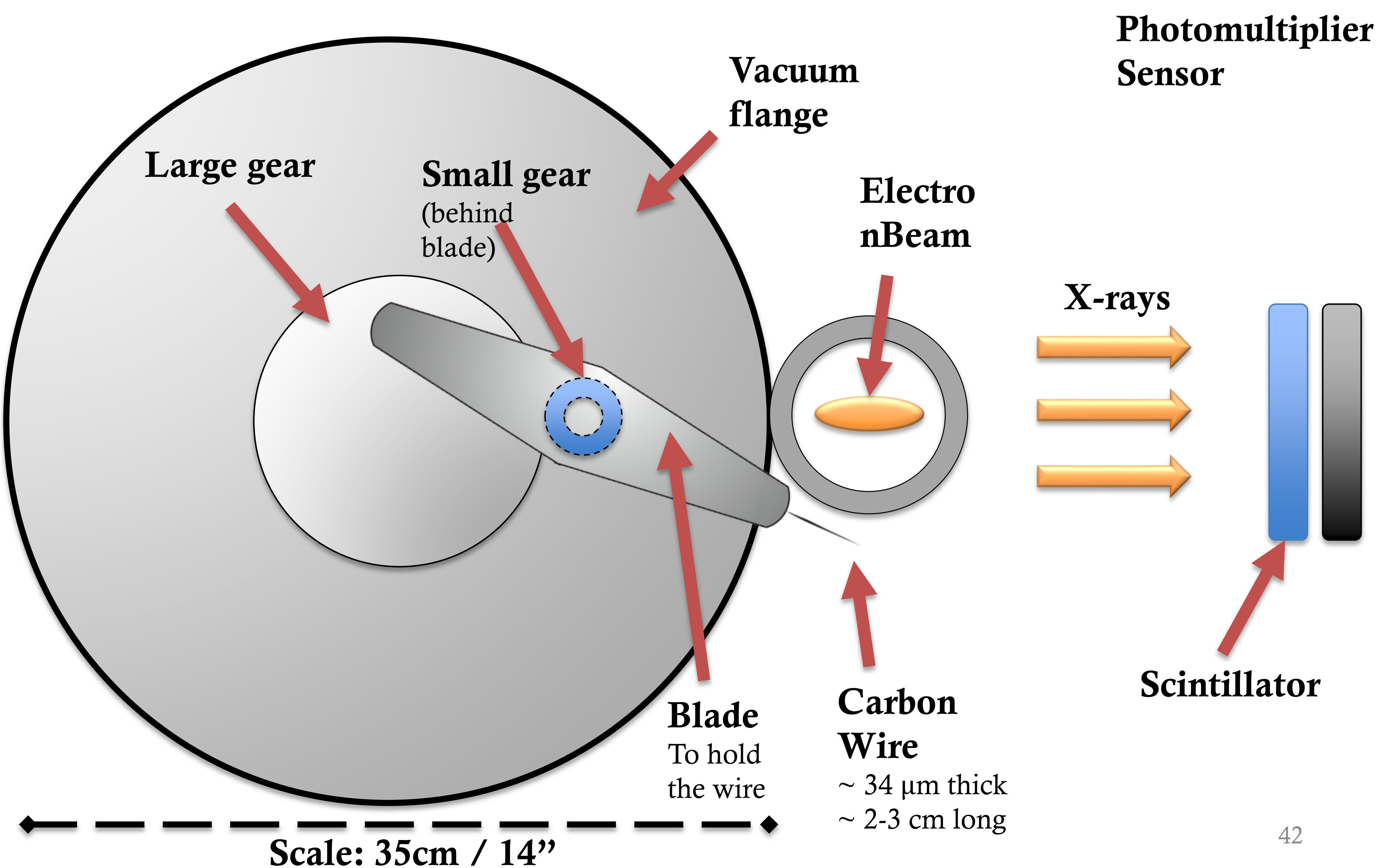

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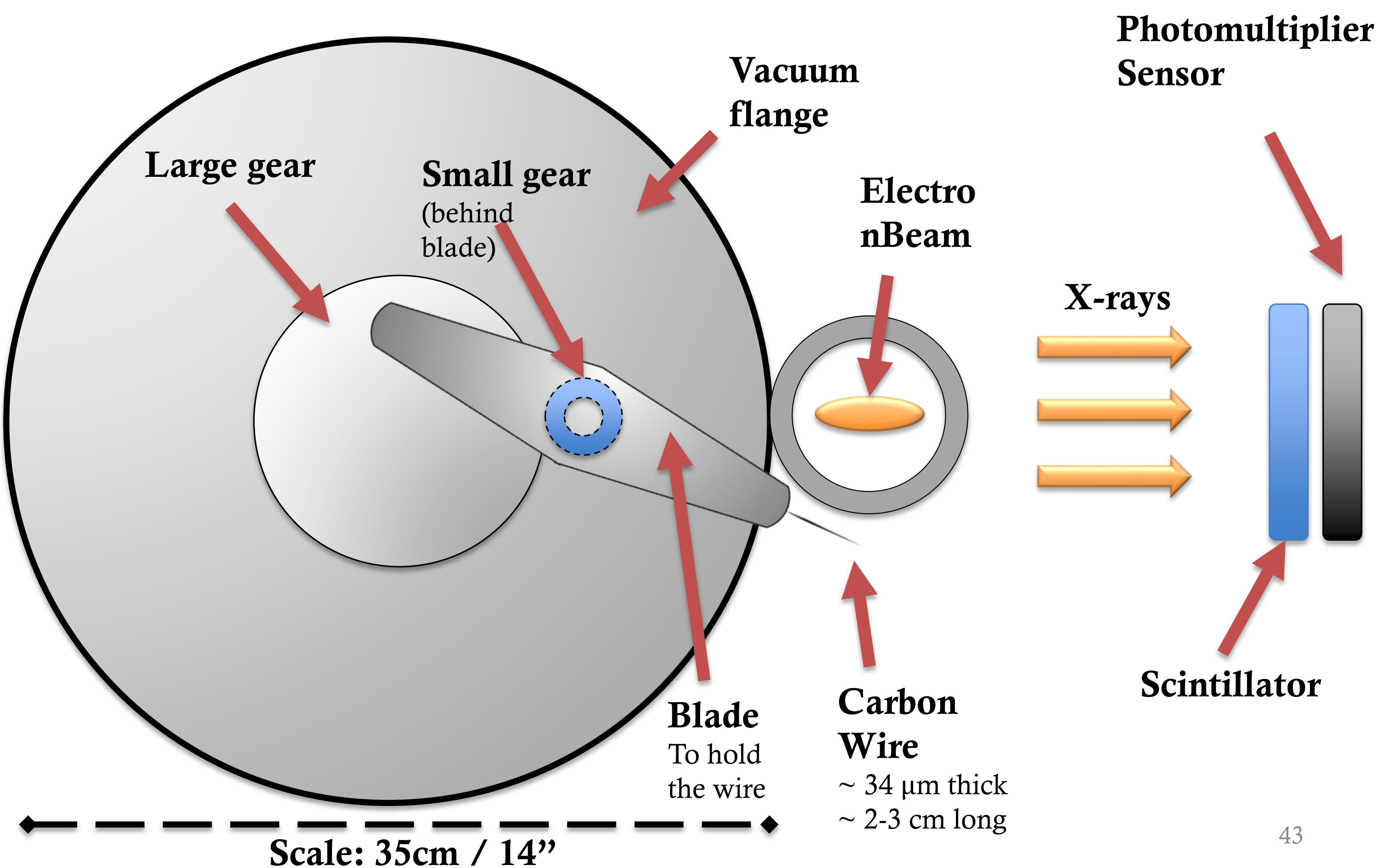

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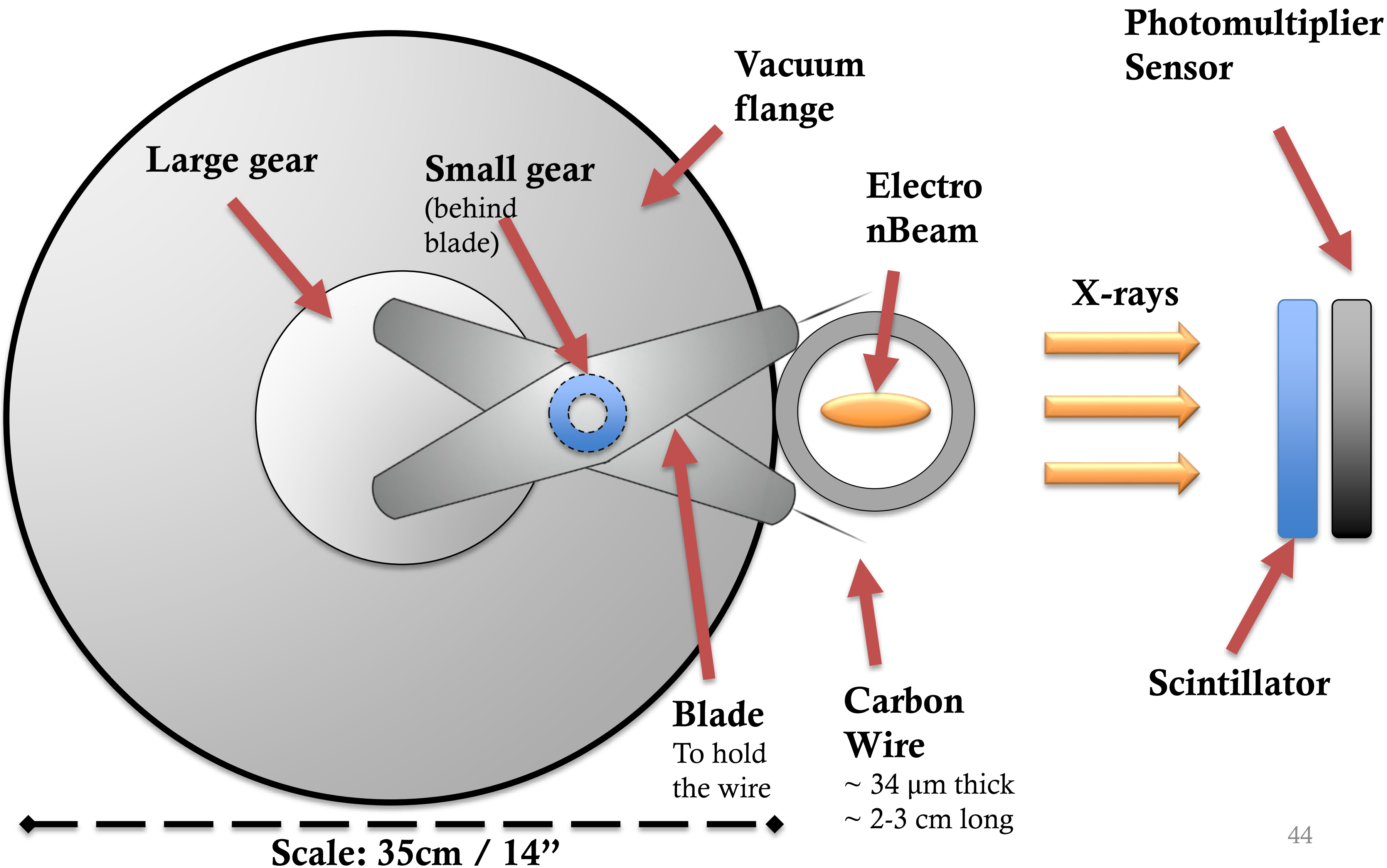

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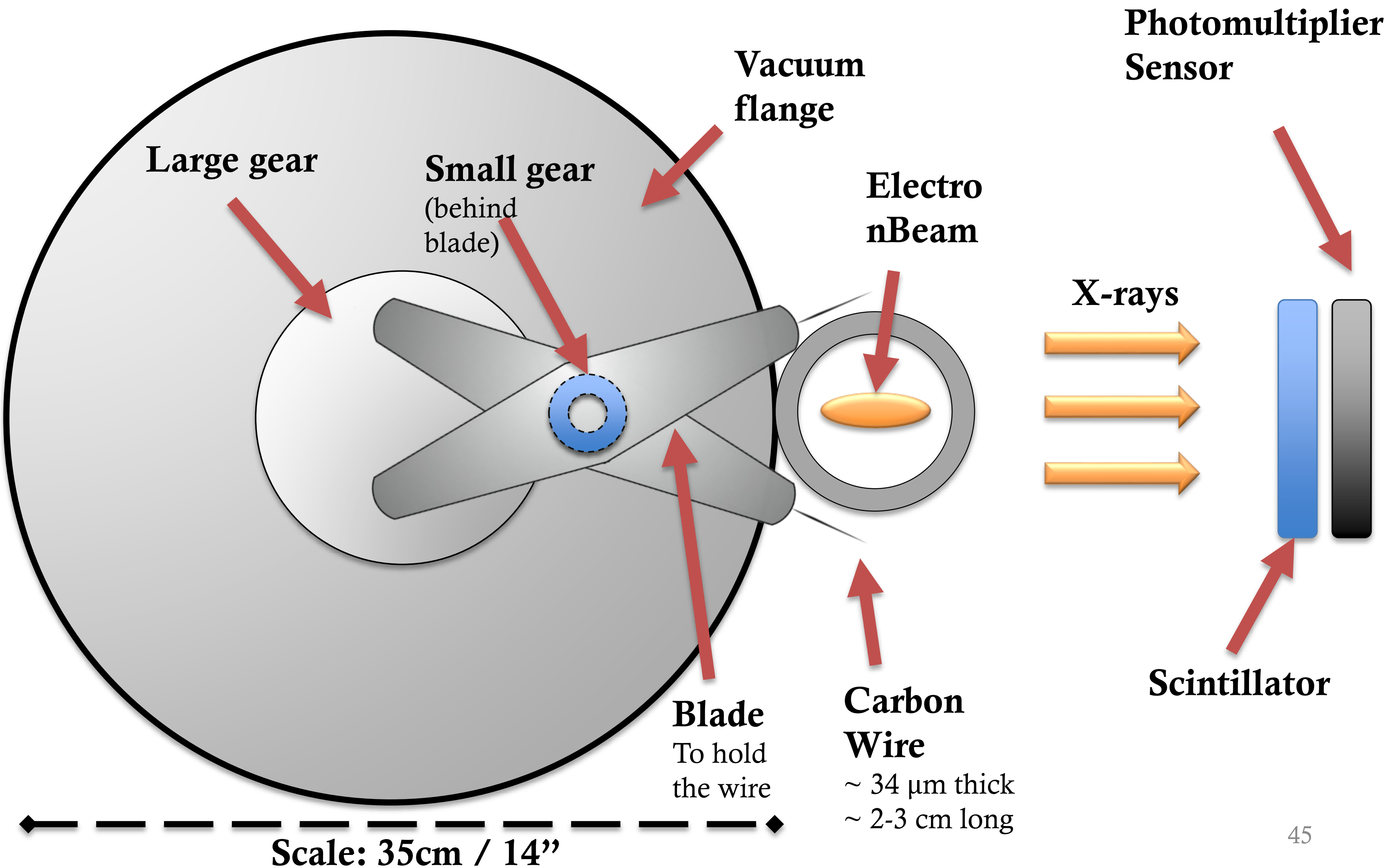

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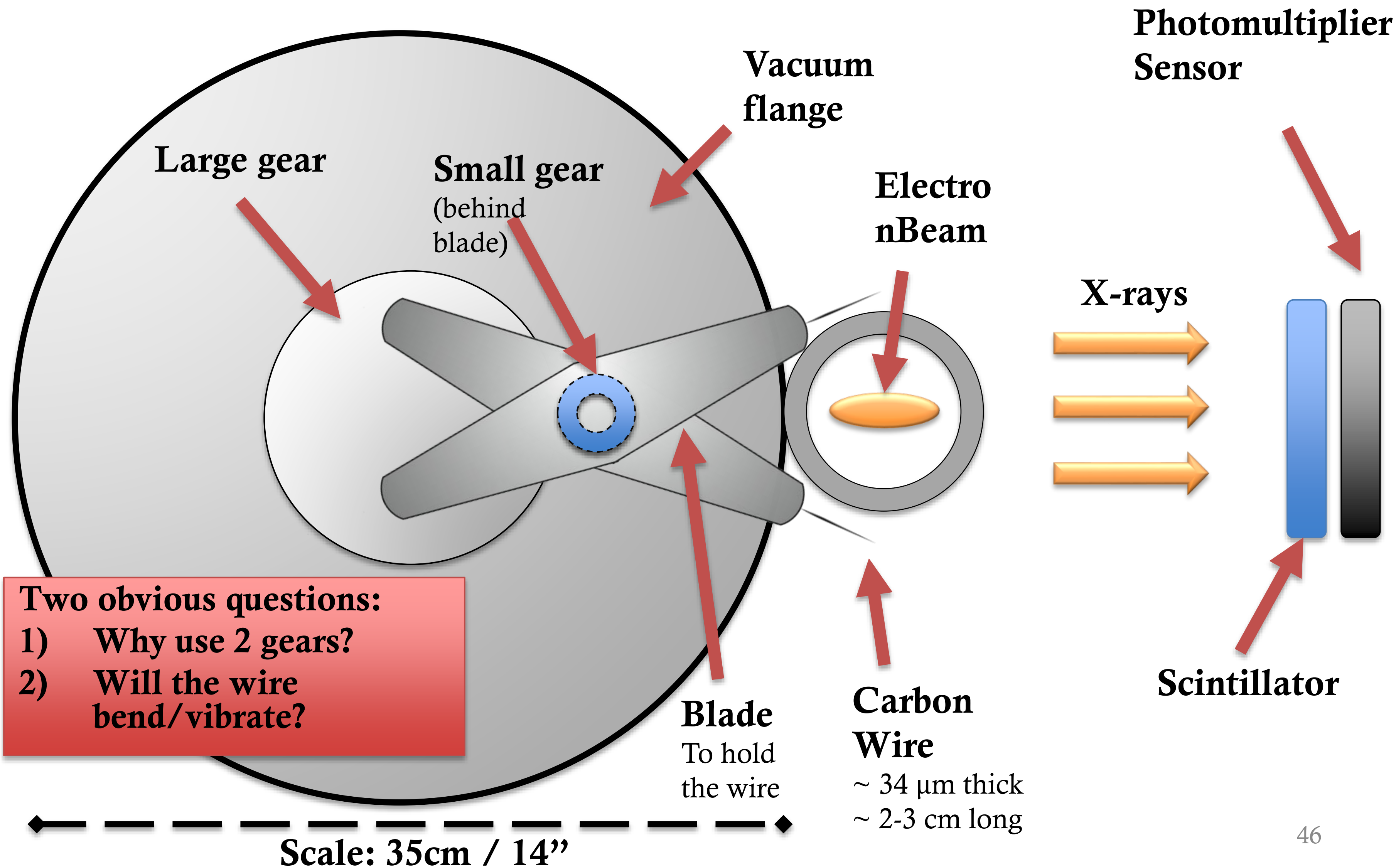
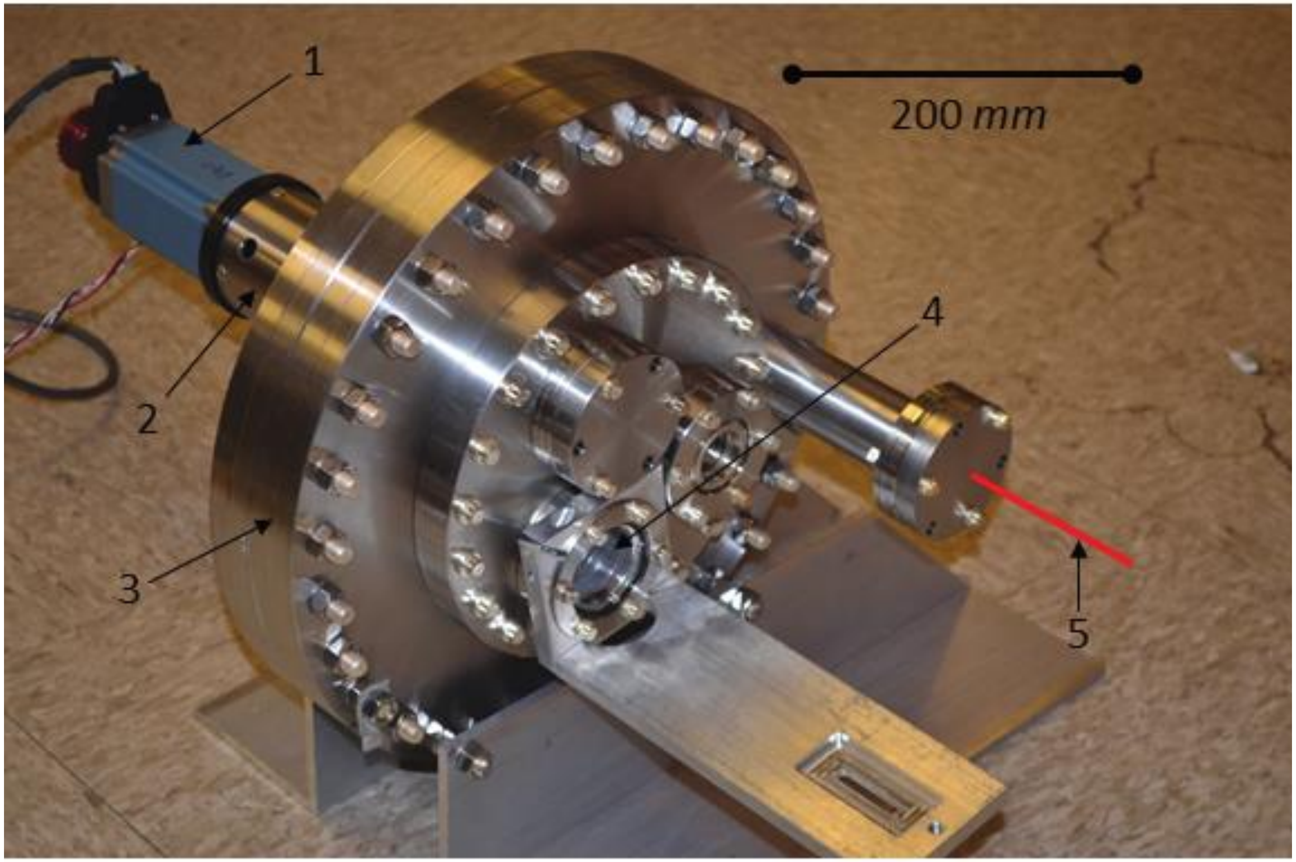


Two obvious questions:

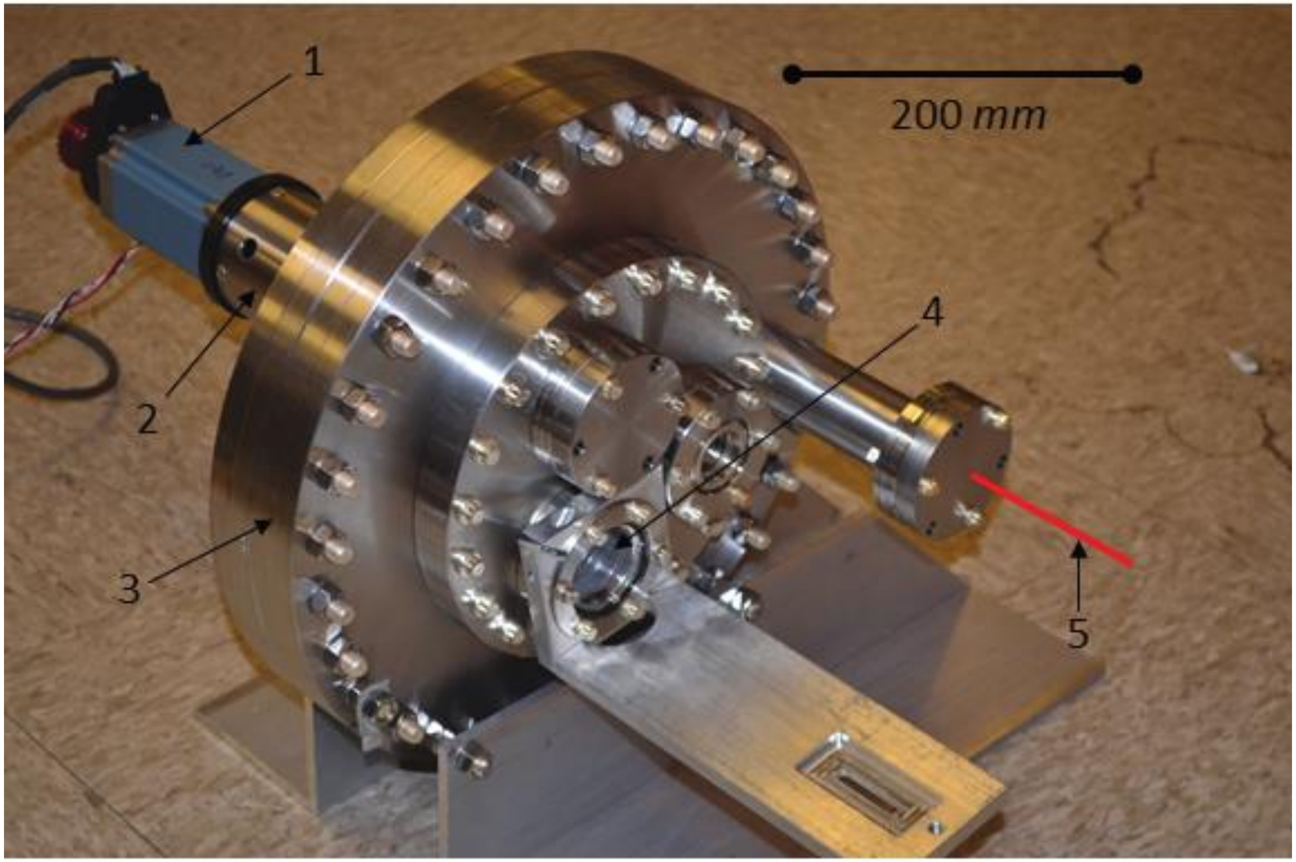
1) **Why use 2 gears?**
2) **Will the wire bend/vibrate?**

Outside view



Outside view

Stepper motor



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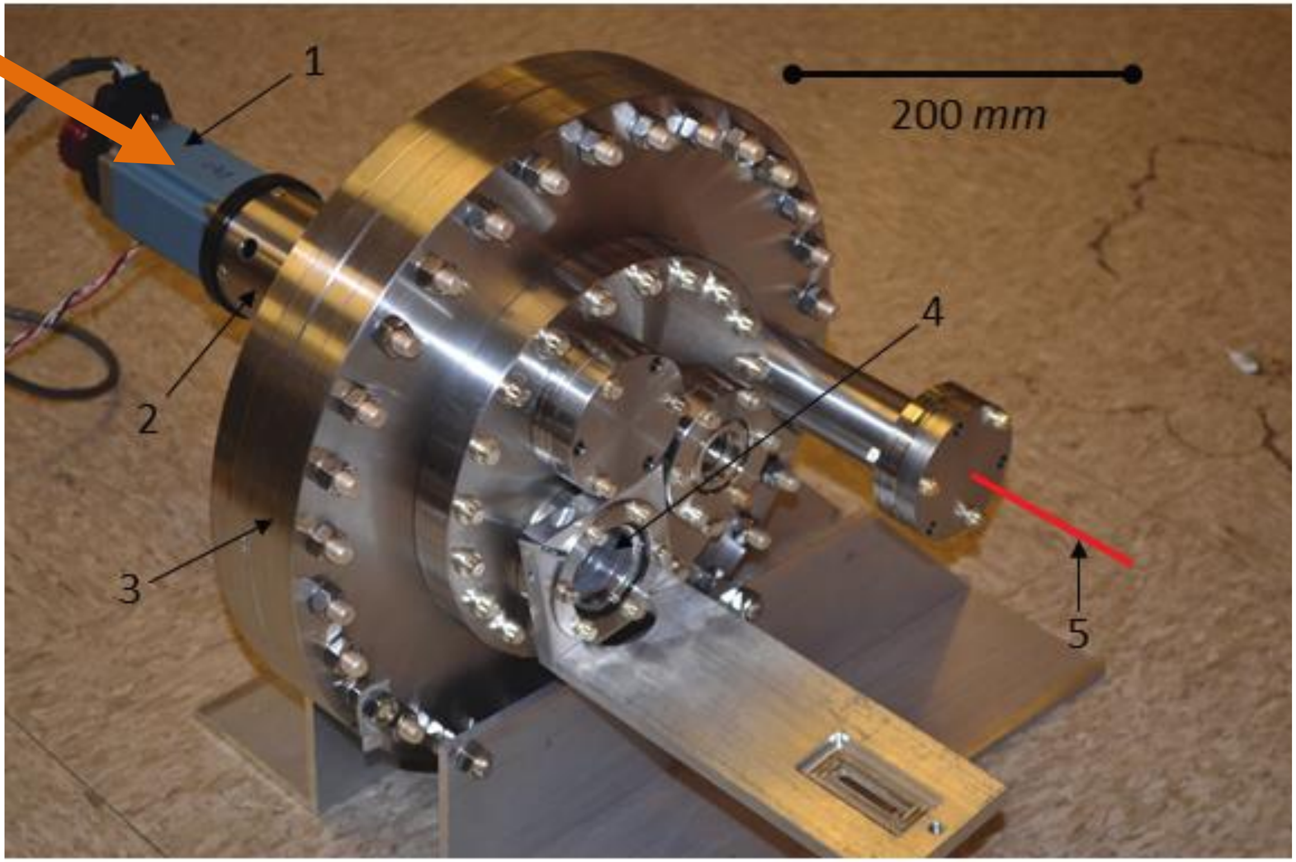

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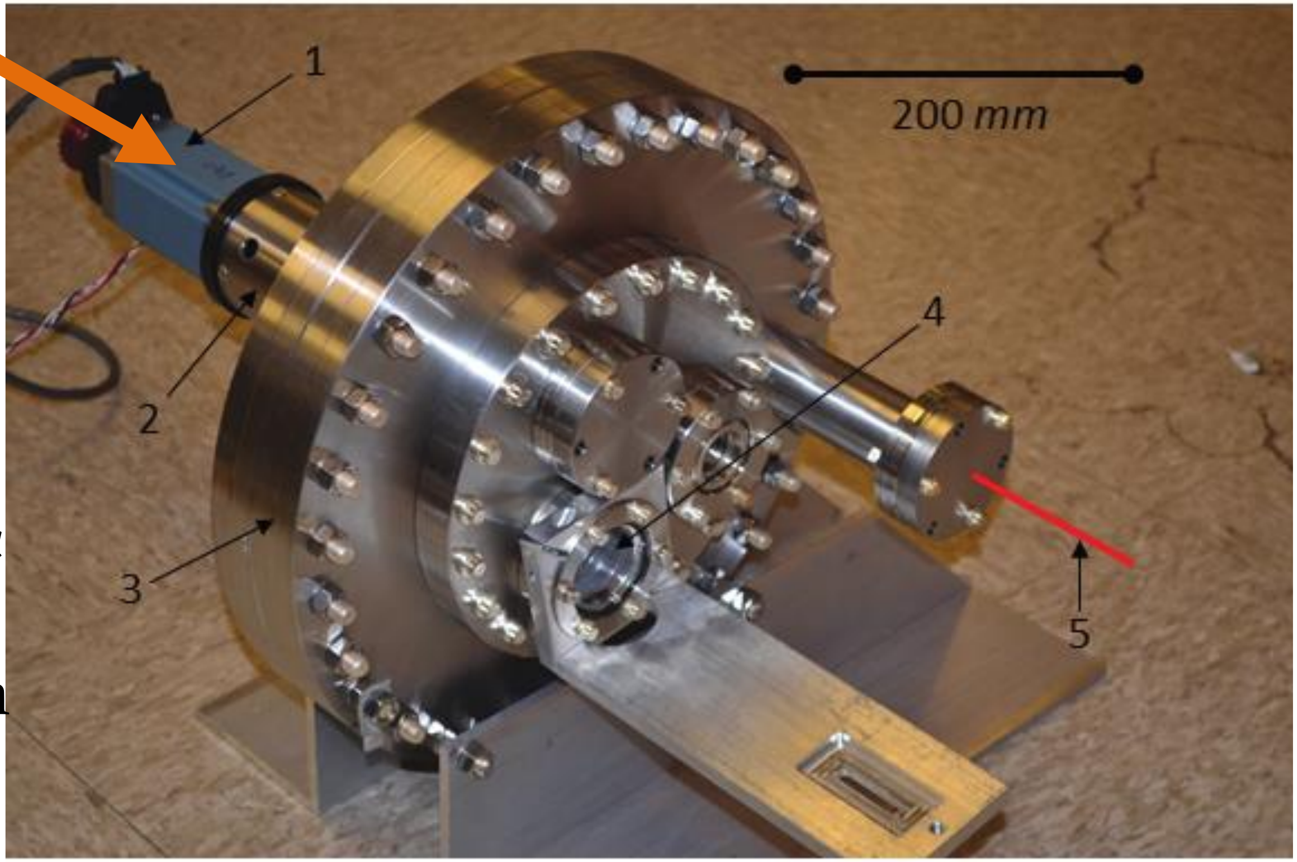
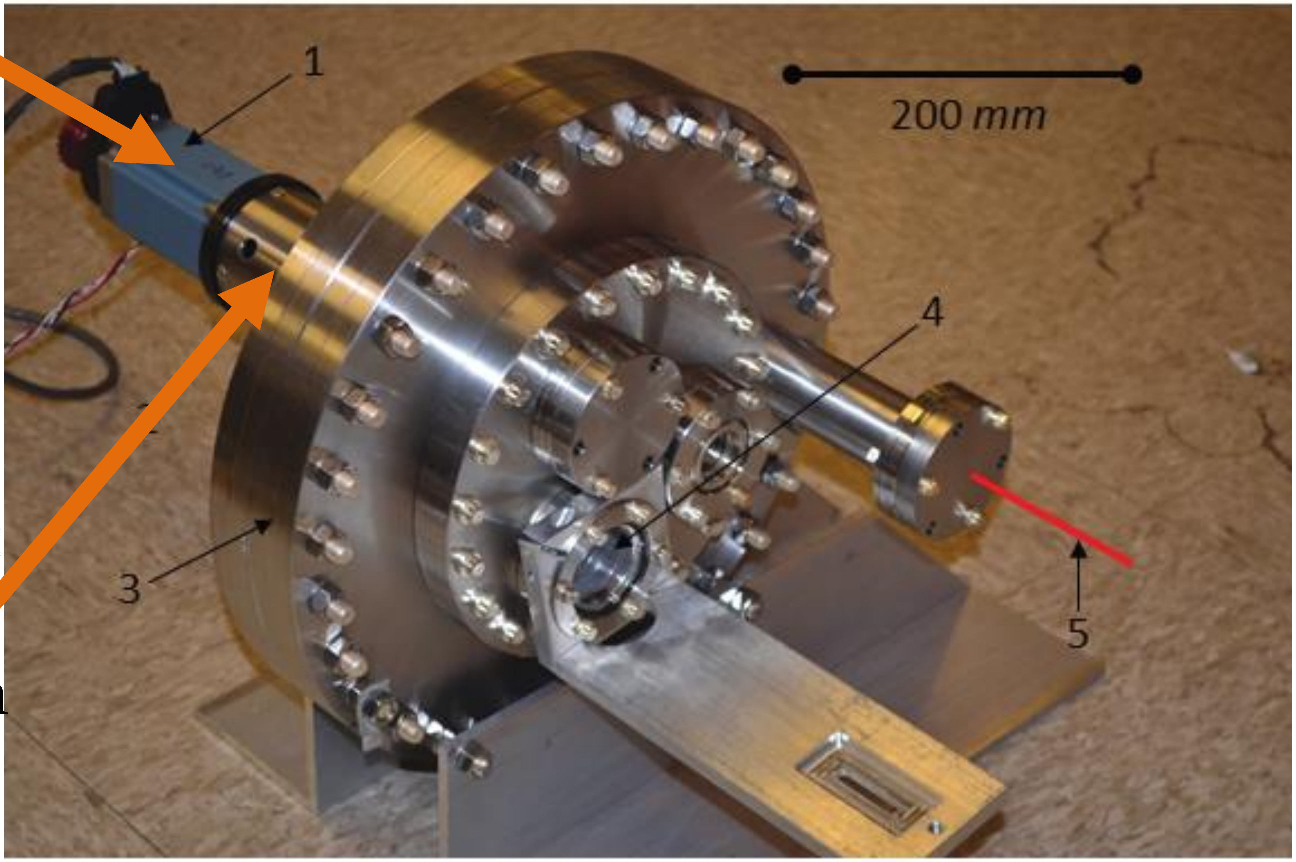


Ferrofluidic Rotary feedthrough

Outside view

Stepper motor



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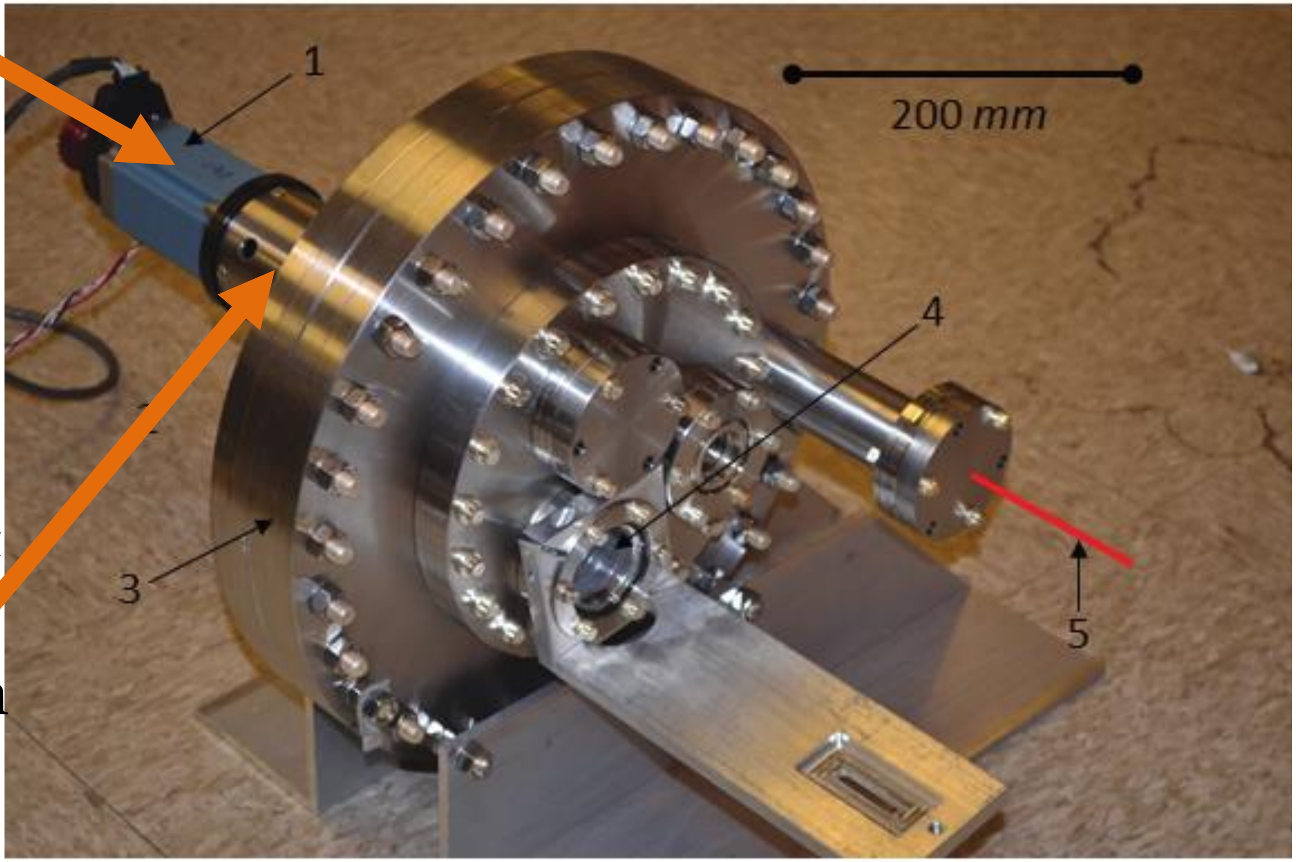

Ferrofluidic Rotary feedthrough

Vacuum flanges

Outside view

Stepper motor

Ferrofluidic Rotary feedthrough

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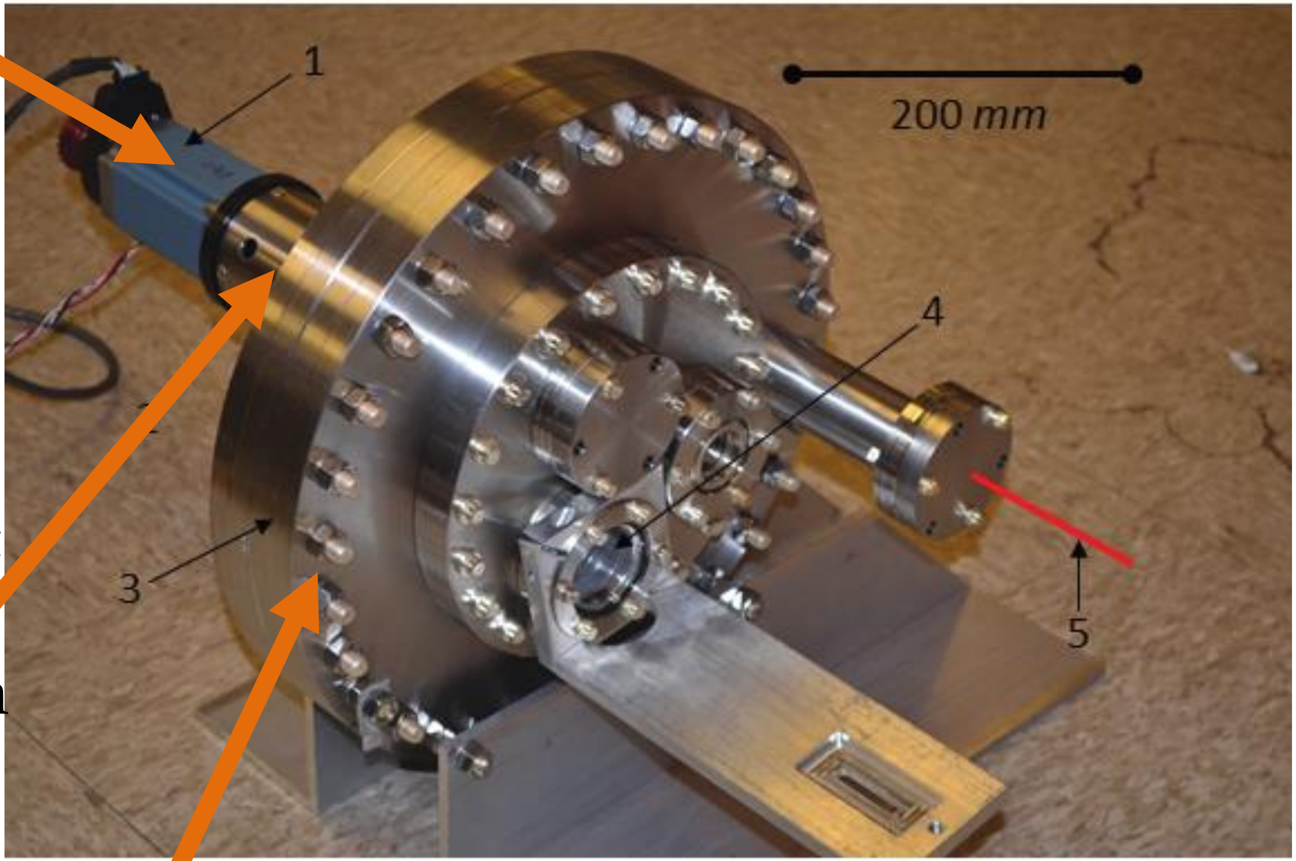
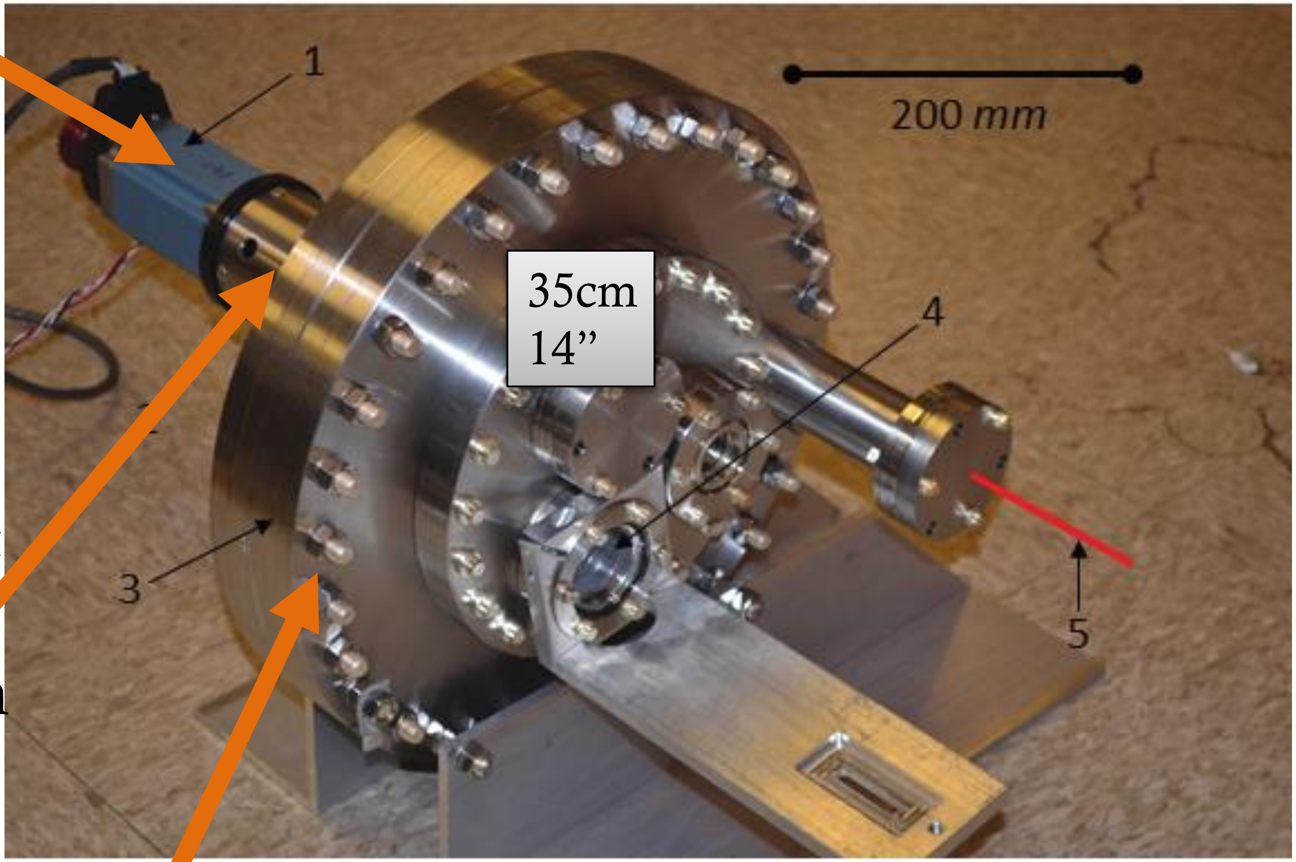


Outside view

Stepper motor



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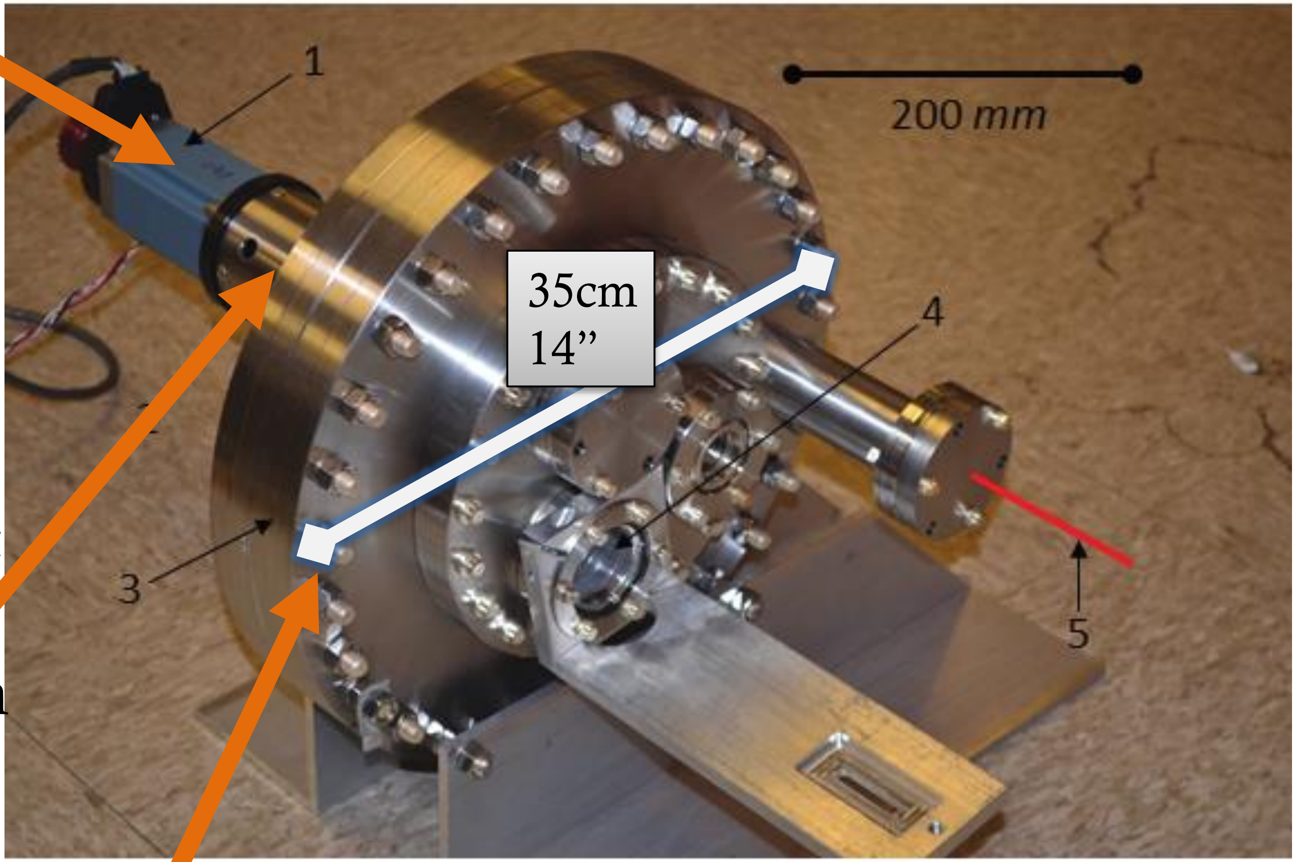

Vacuum flanges

Outside view

Stepper motor

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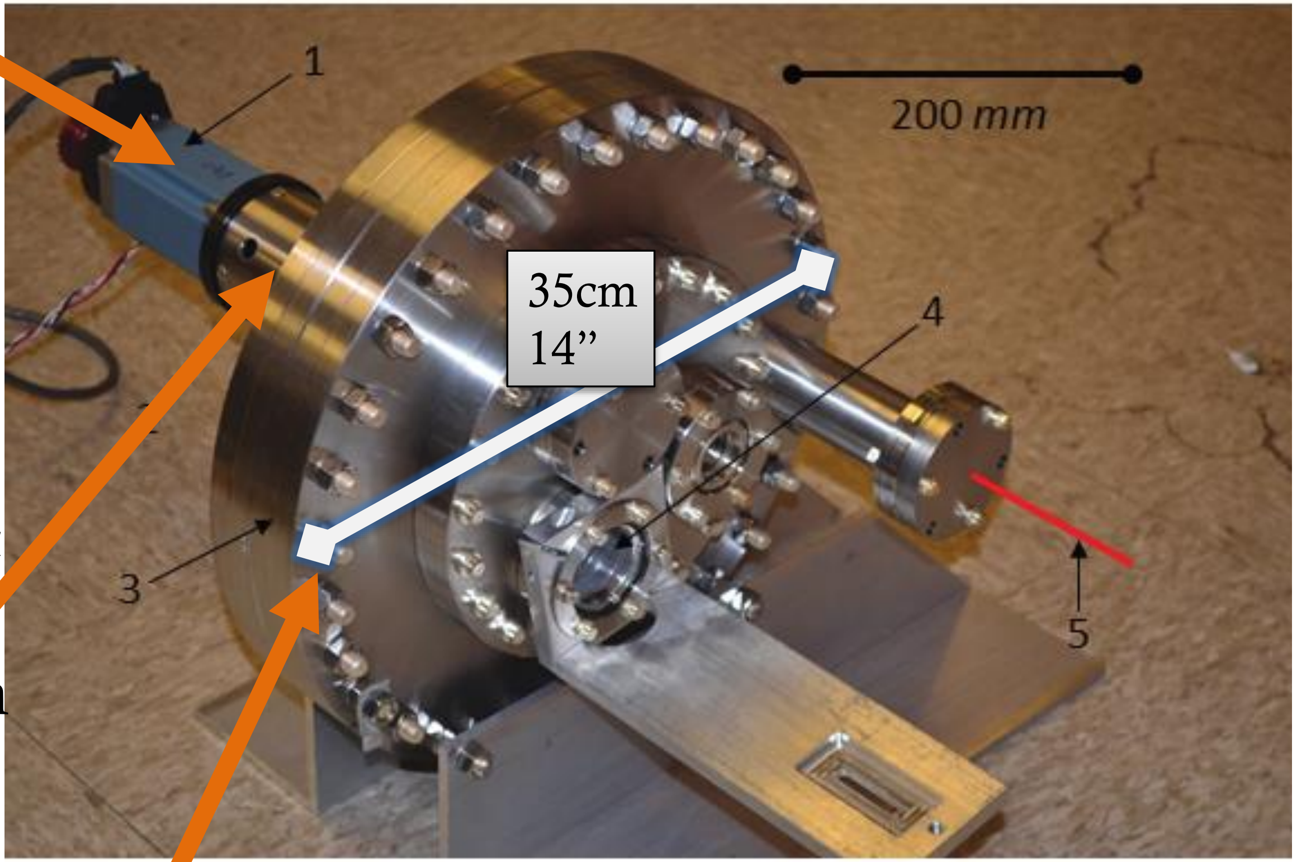


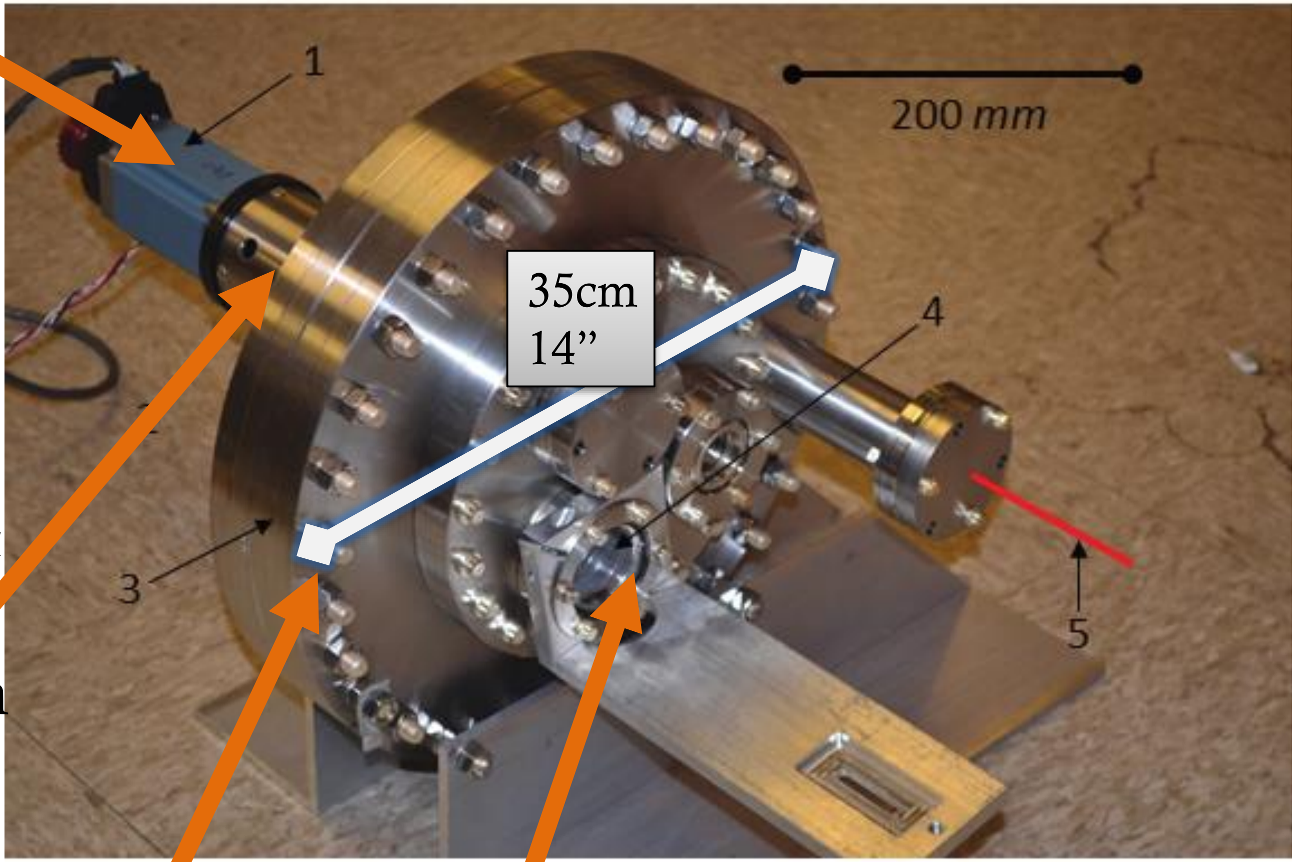
Vacuum flanges

Viewports

Outside view

Stepper motor

Ferrofluidic Rotary feedthrough



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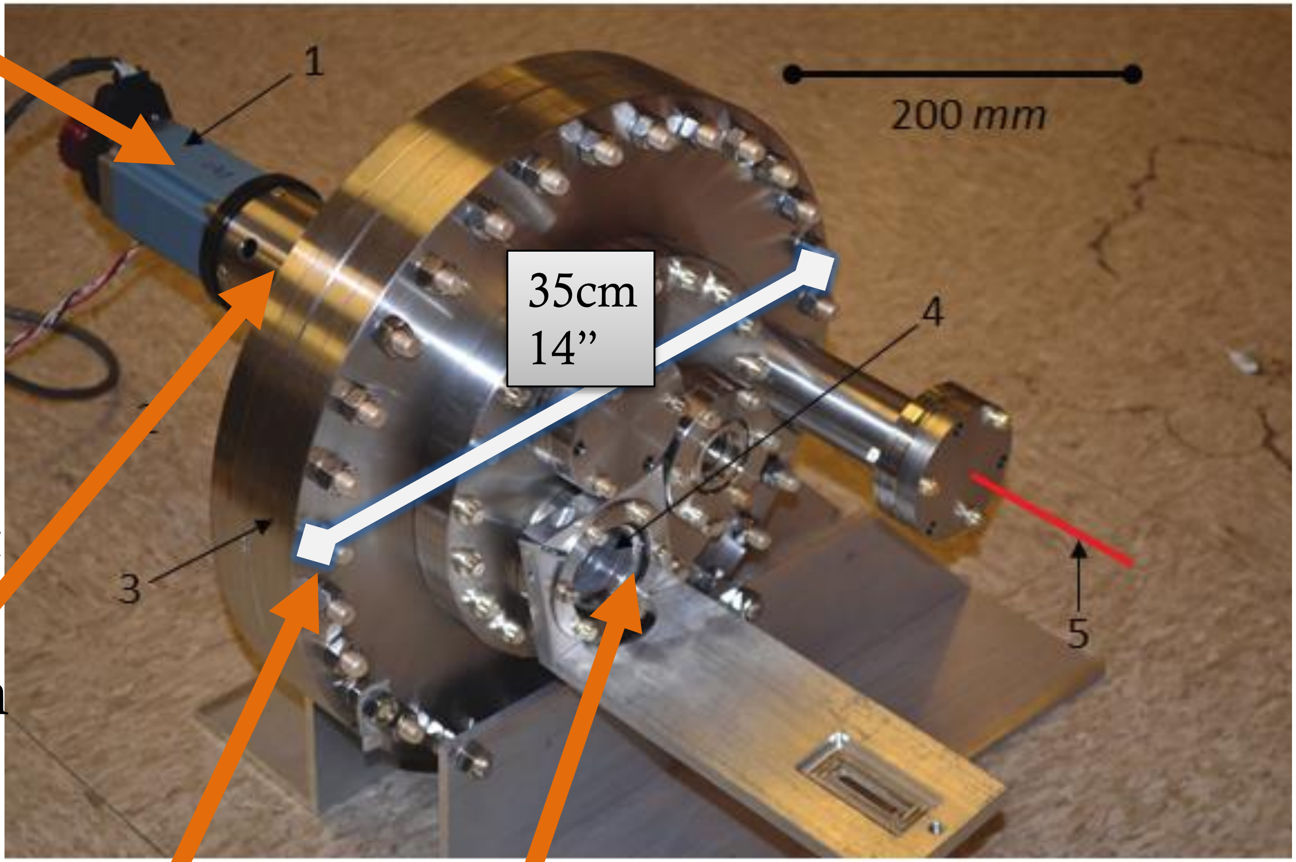


Ferrofluidic Rotary feedthrough

Vacuum flanges

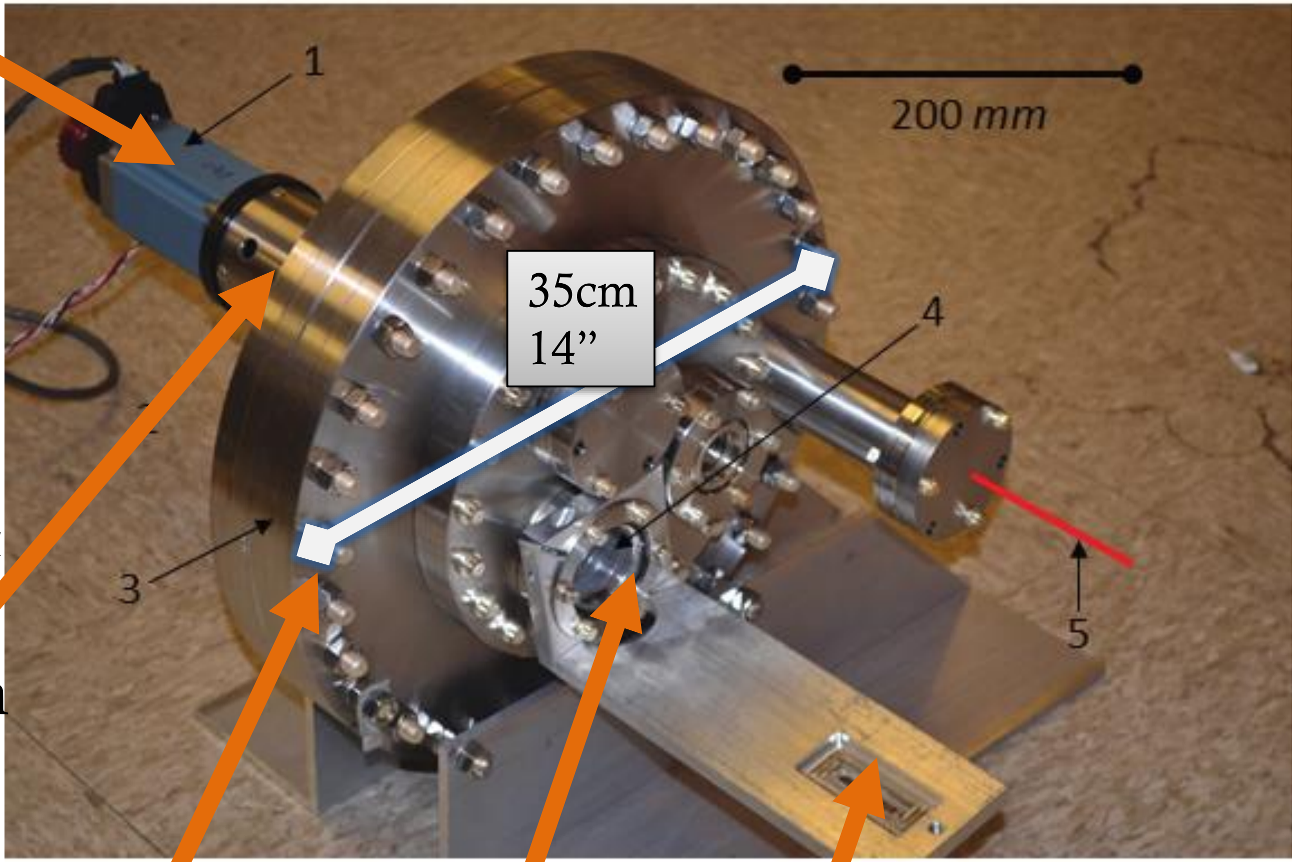
Viewports

Camera mount

Outside view

Stepper motor

Ferrofluidic Rotary feedthrough



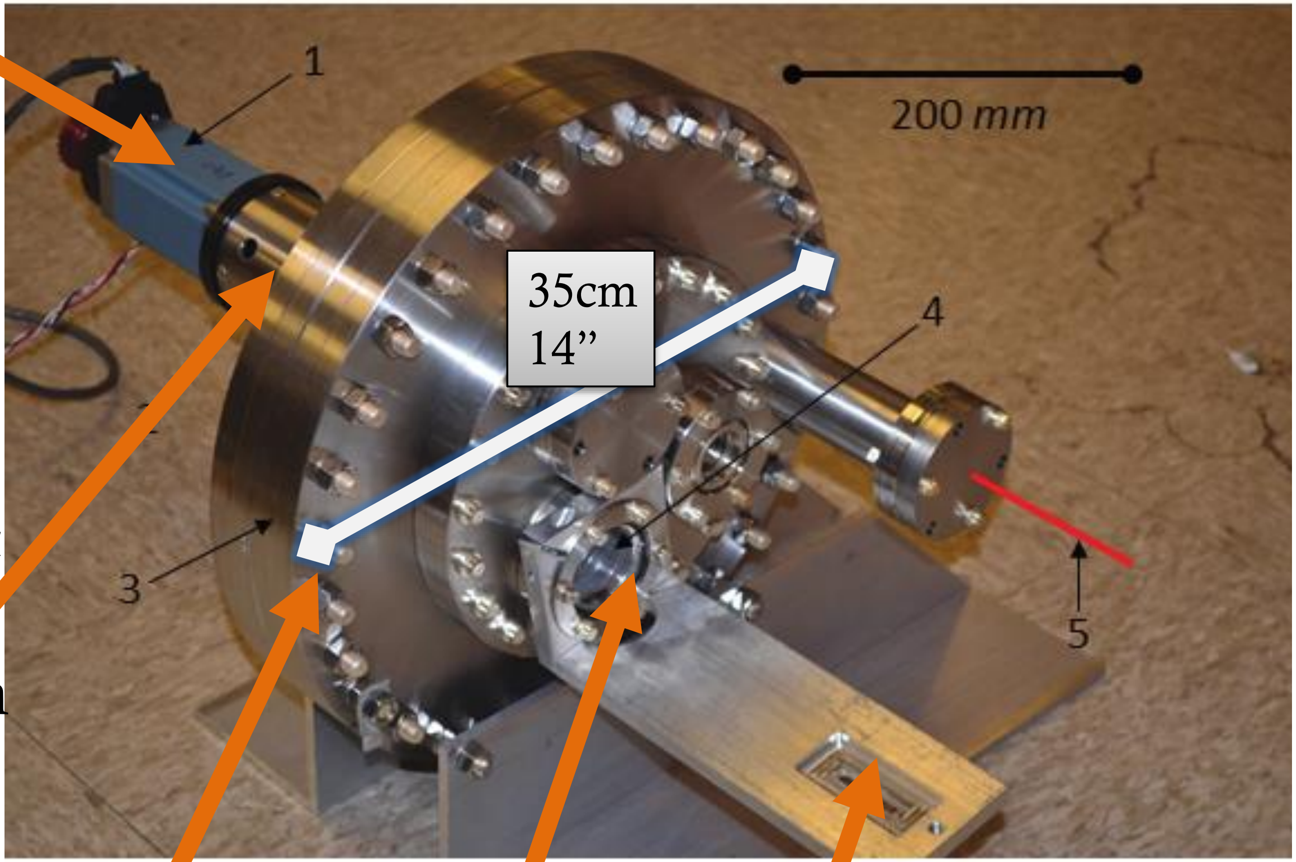
Vacuum flanges

Viewports

Camera mount

Outside view

Stepper motor



Ferrofluidic Rotary feedthrough

Beam pipe

Vacuum flanges

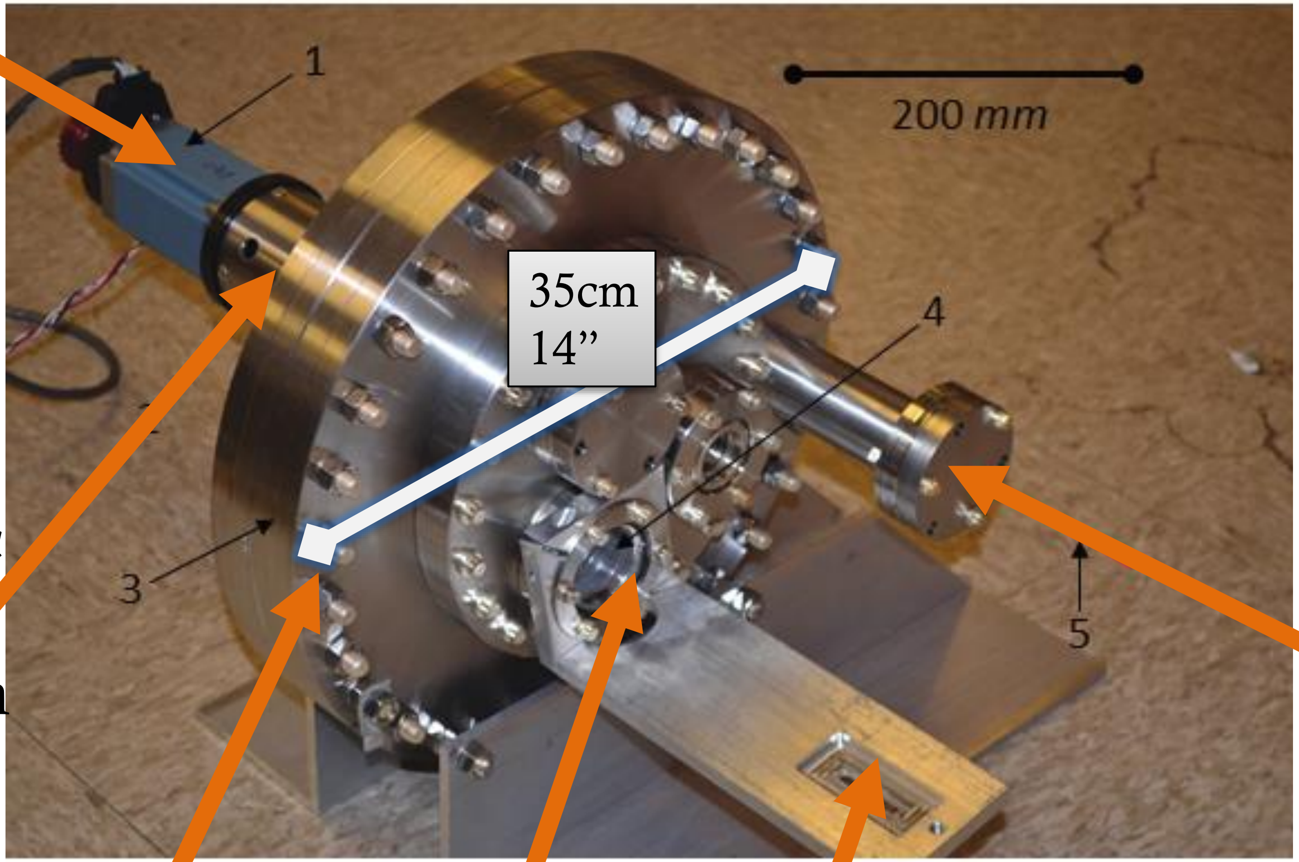
Viewports

Camera mount

Outside view

Stepper motor

Ferrofluidic Rotary feedthrough



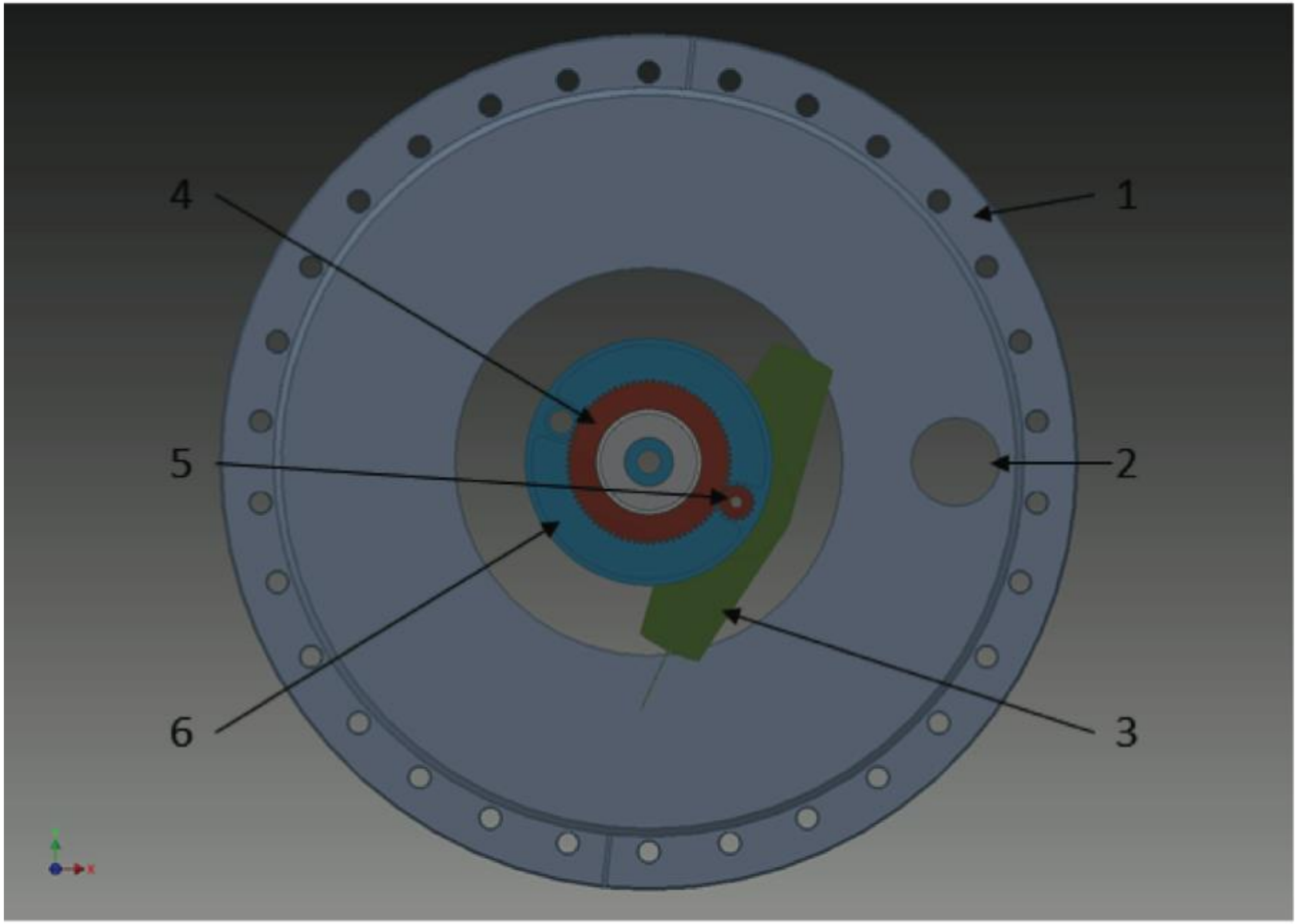
Beam pipe

Vacuum flanges

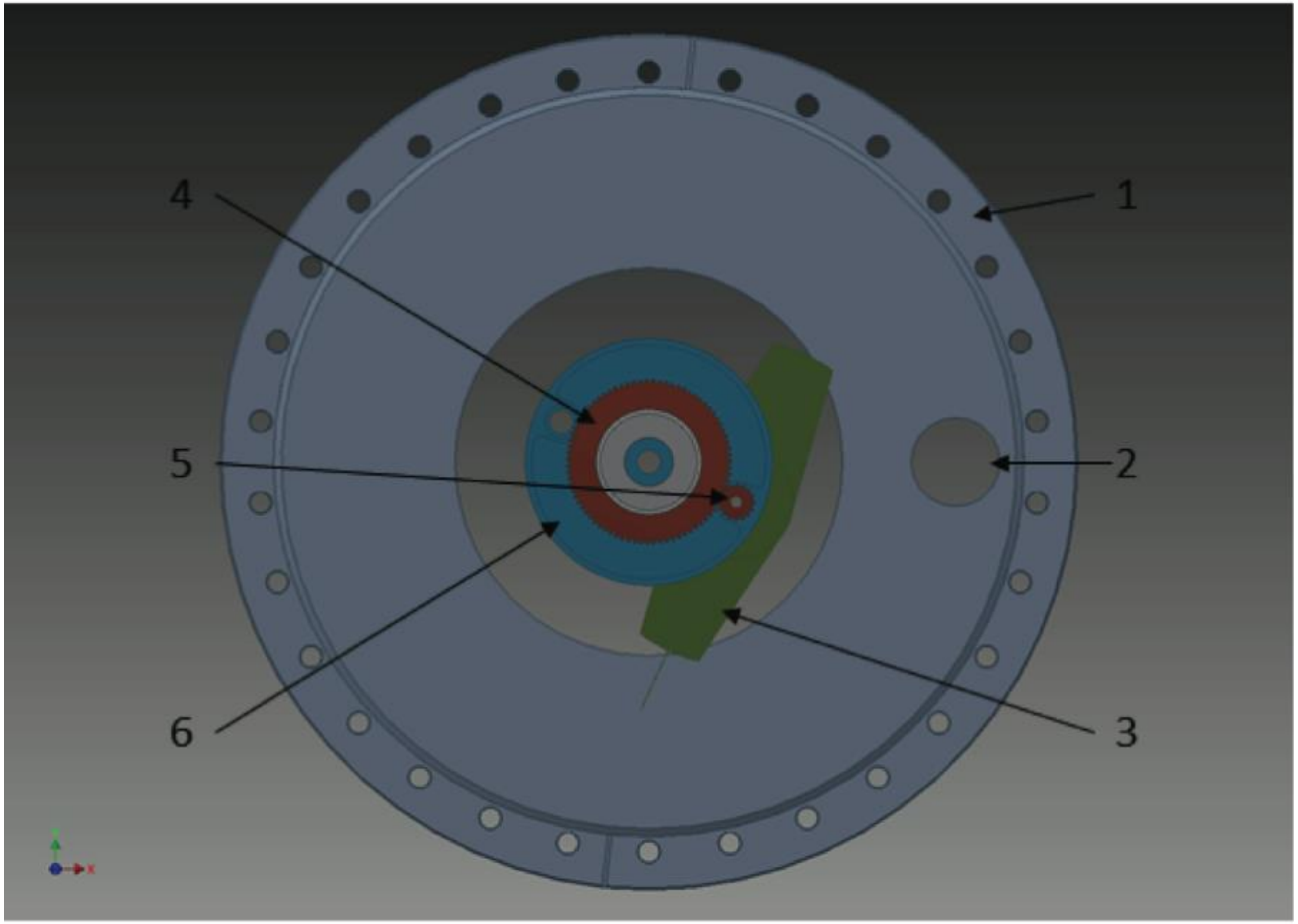
Viewports

Camera mount

3D model of the design

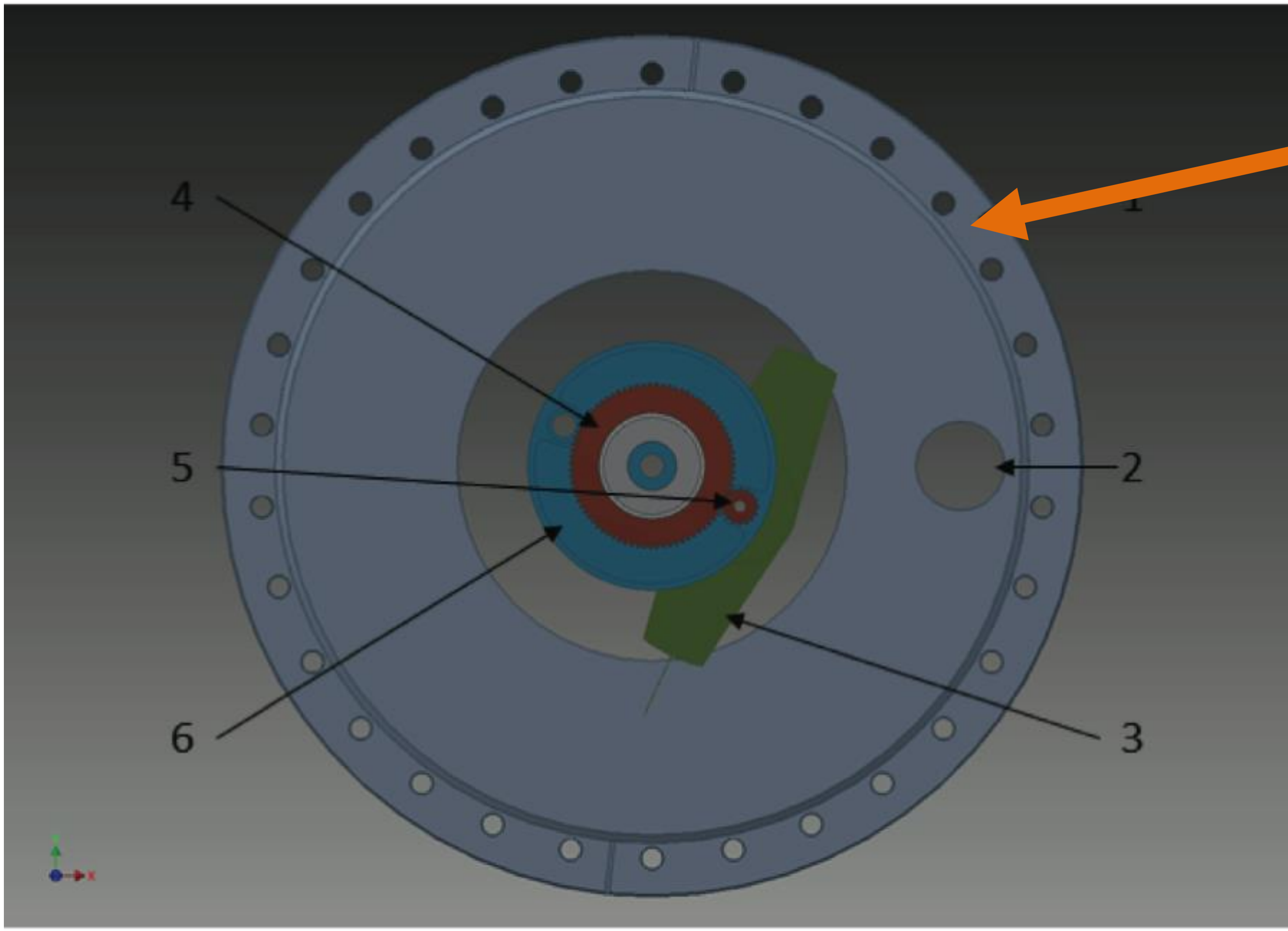


3D model of the design



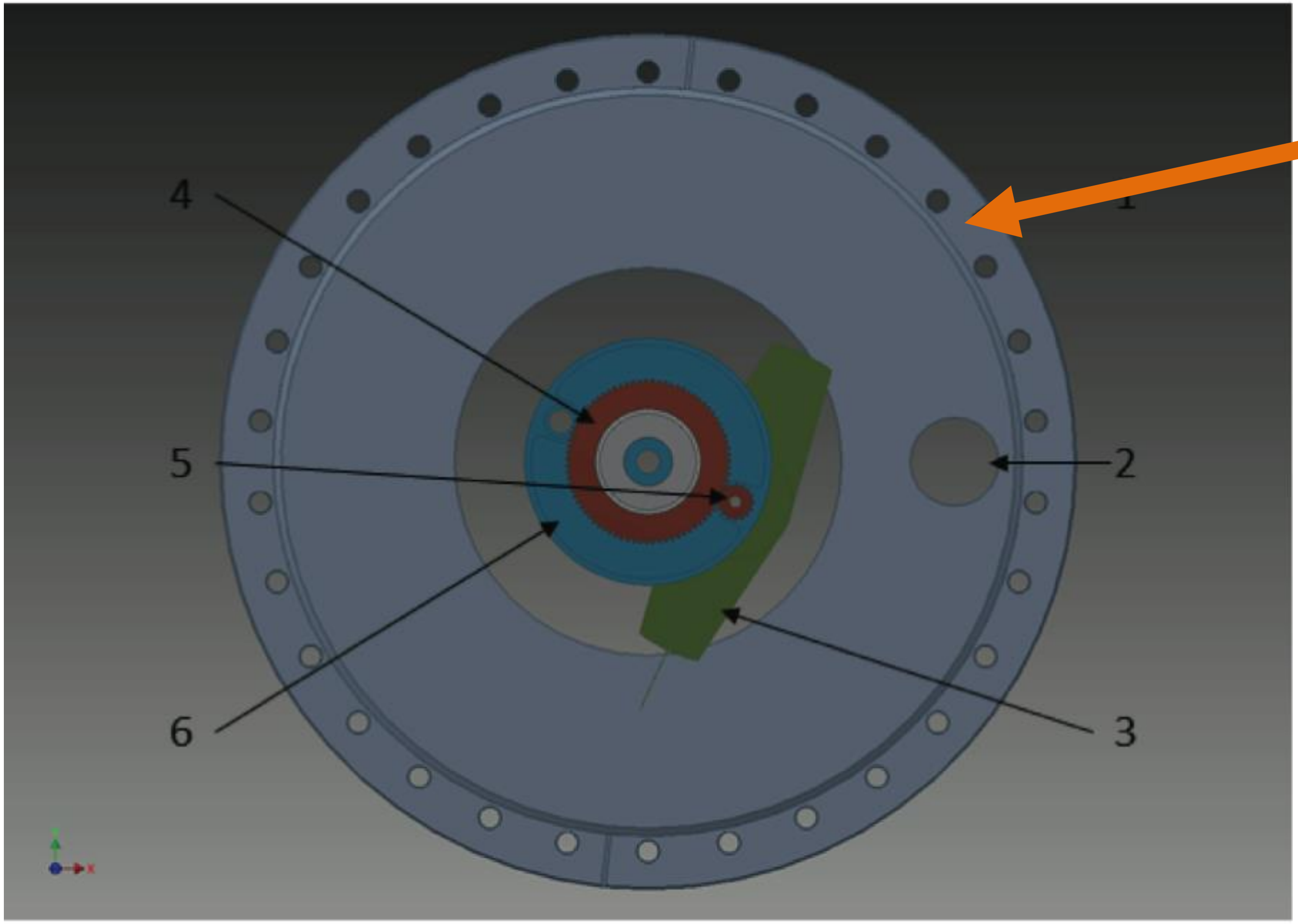
Vacuum Flange

3D model of the design



Vacuum
Flange

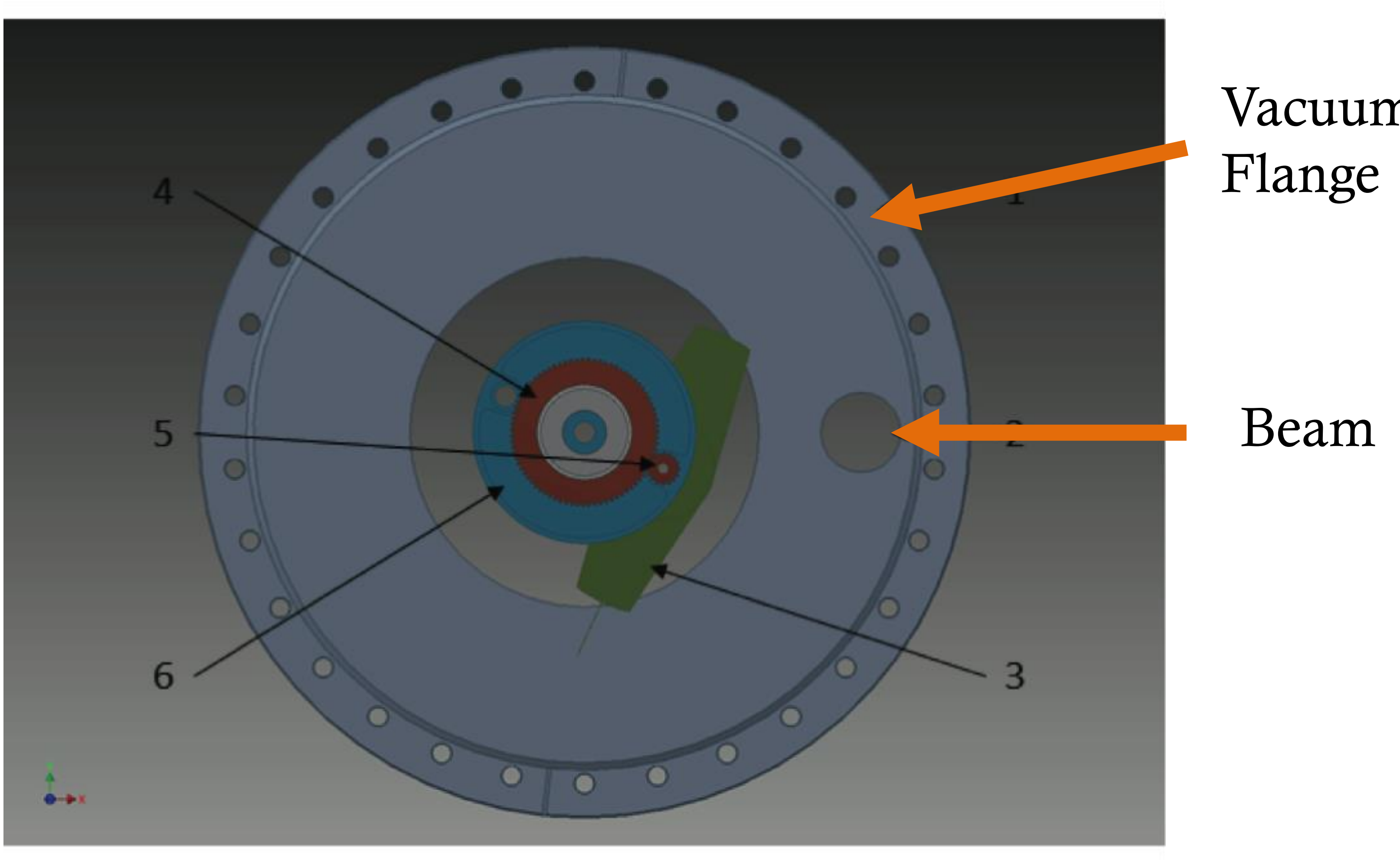
3D model of the design



Vacuum Flange

Beam

3D model of the design



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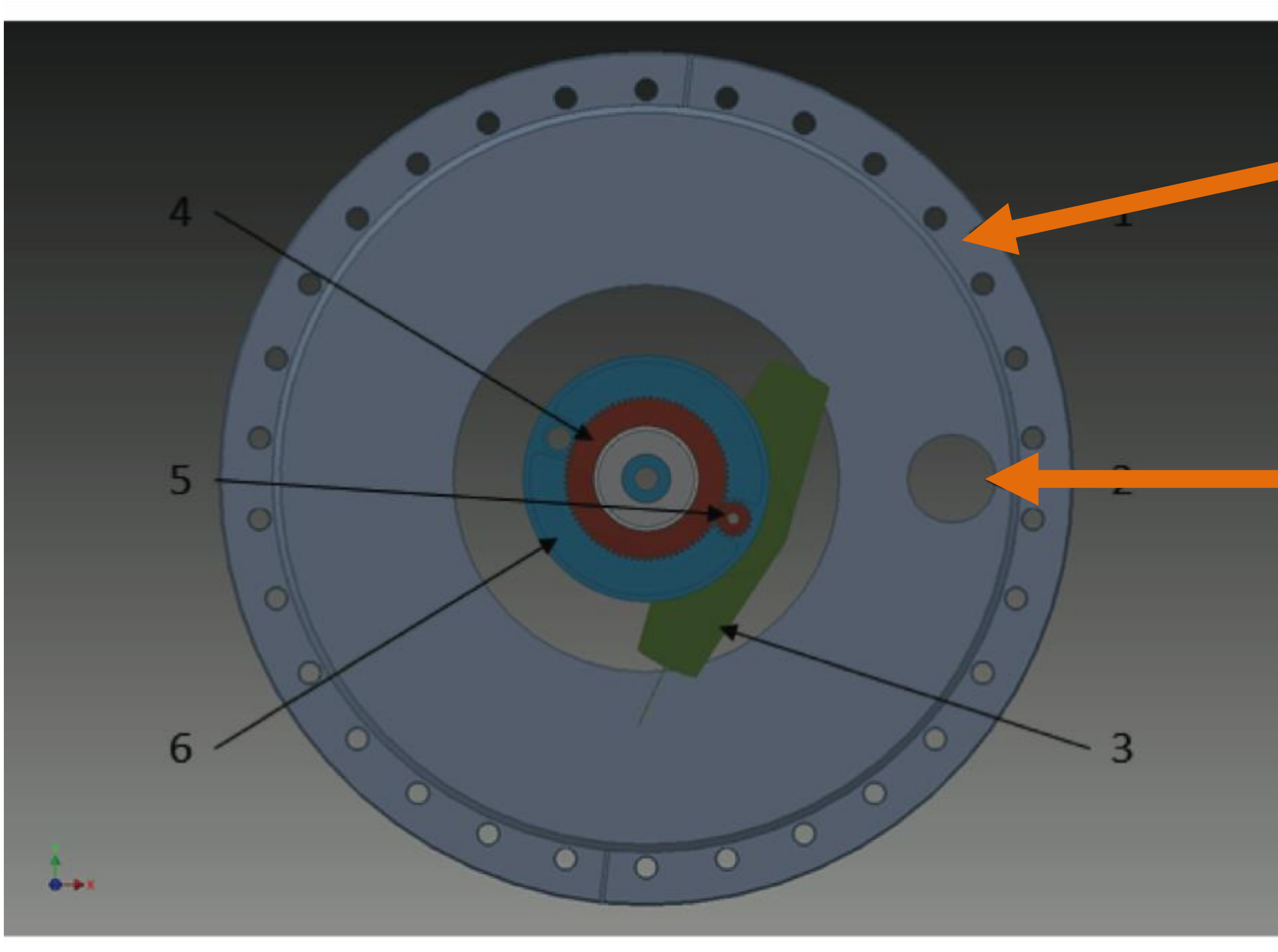
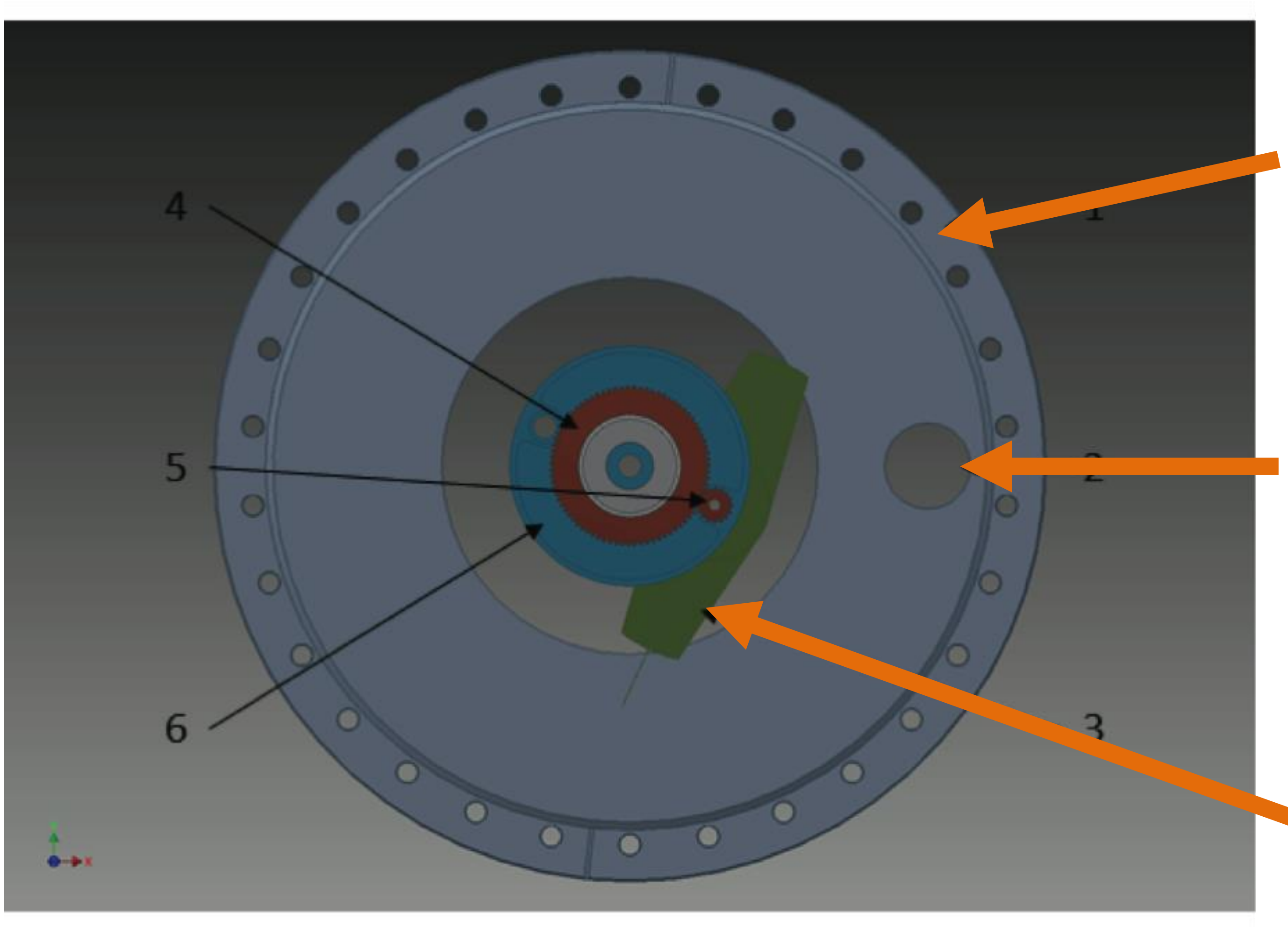


Vacuum Flange

Beam

Blade + carbon wire attached

3D model of the design



Vacuum Flange

Beam

Blade + carbon wire attached

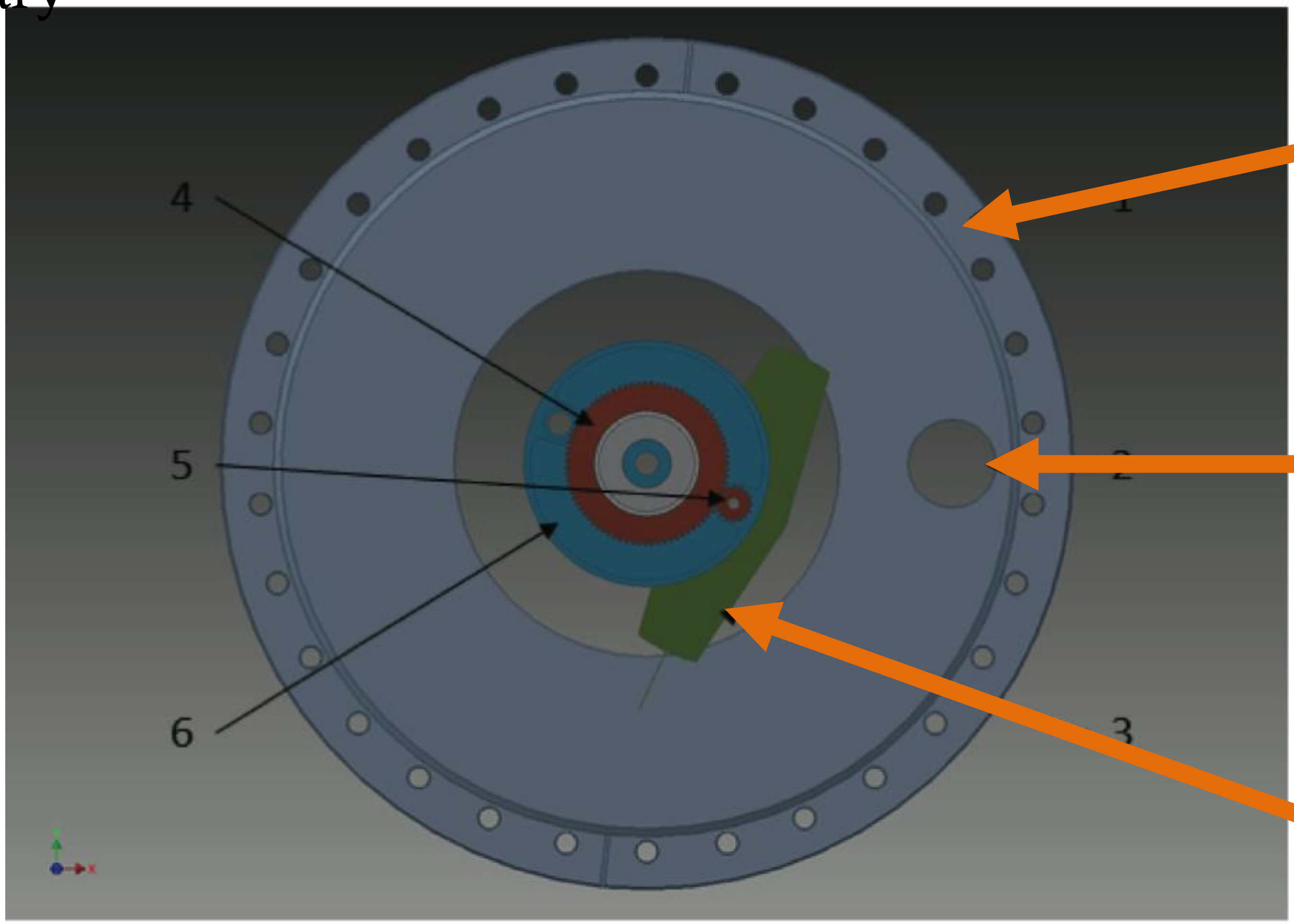
3D model of the design

Large stationary gear

Vacuum Flange

Beam

Blade + carbon wire attached



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Large stationary gear

Vacuum Flange

Beam

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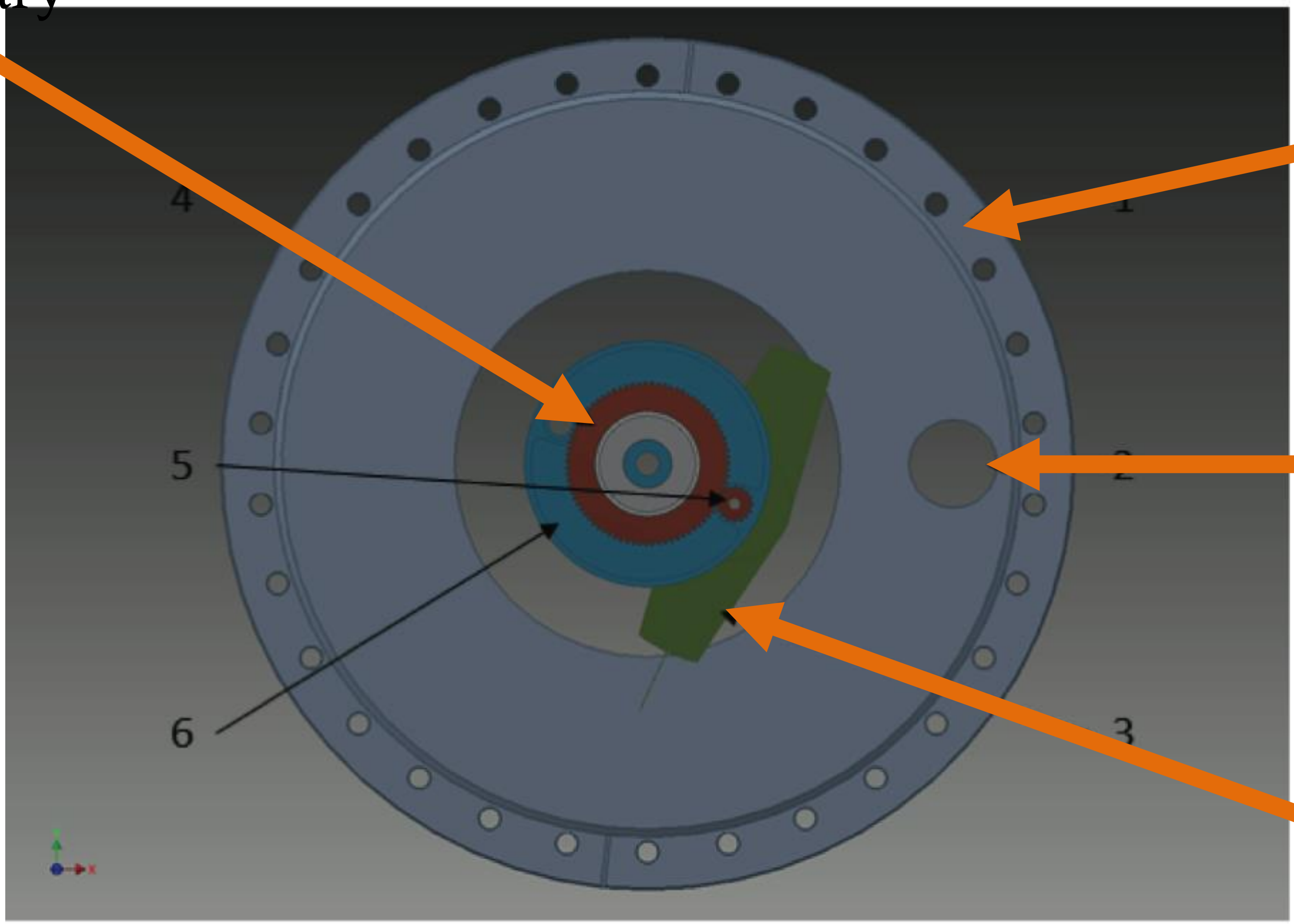
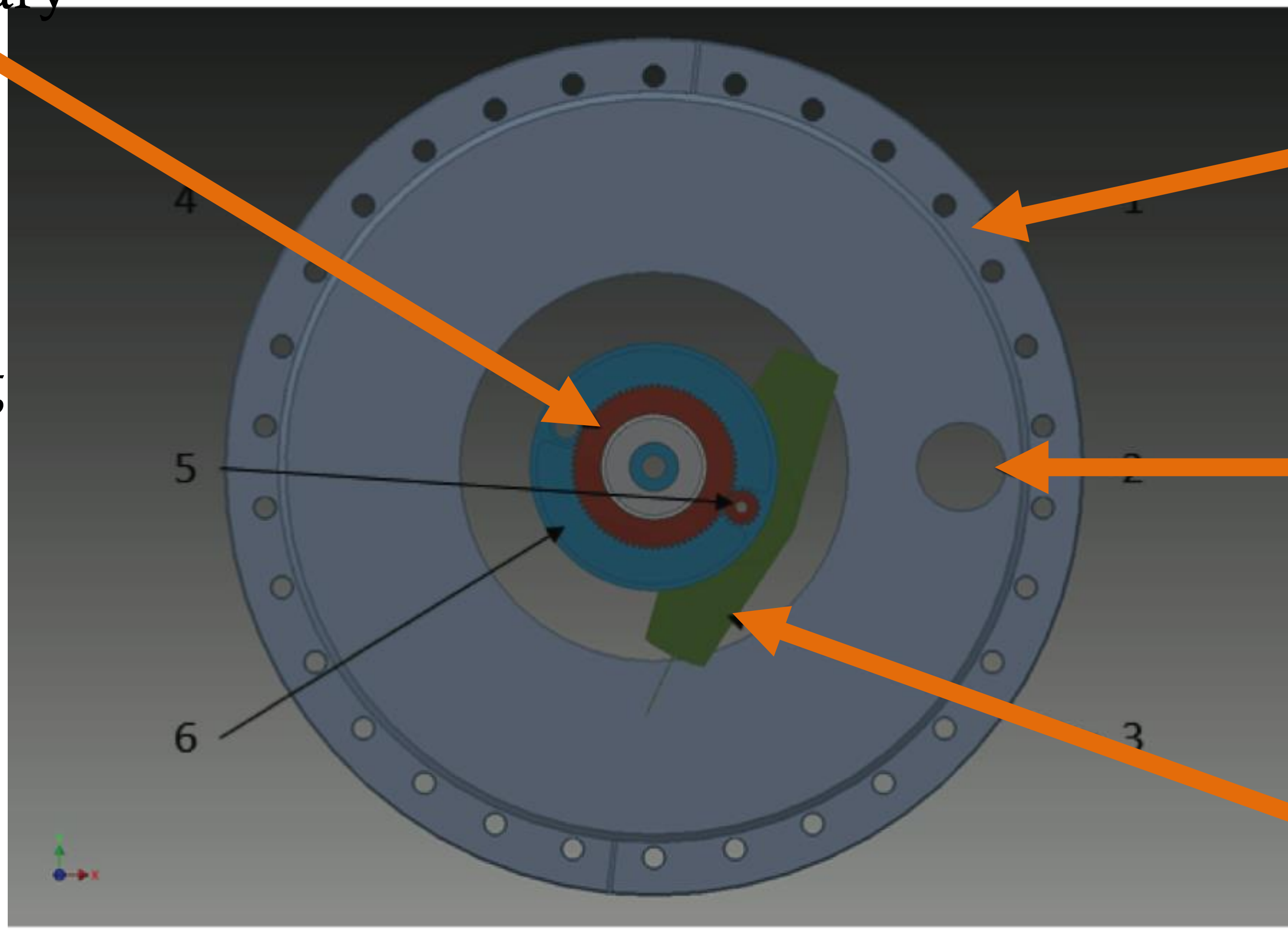


3D model of the design

Large stationary gear

Small rotating gear



Vacuum Flange

Beam

Blade + carbon wire attached

3D model of the design

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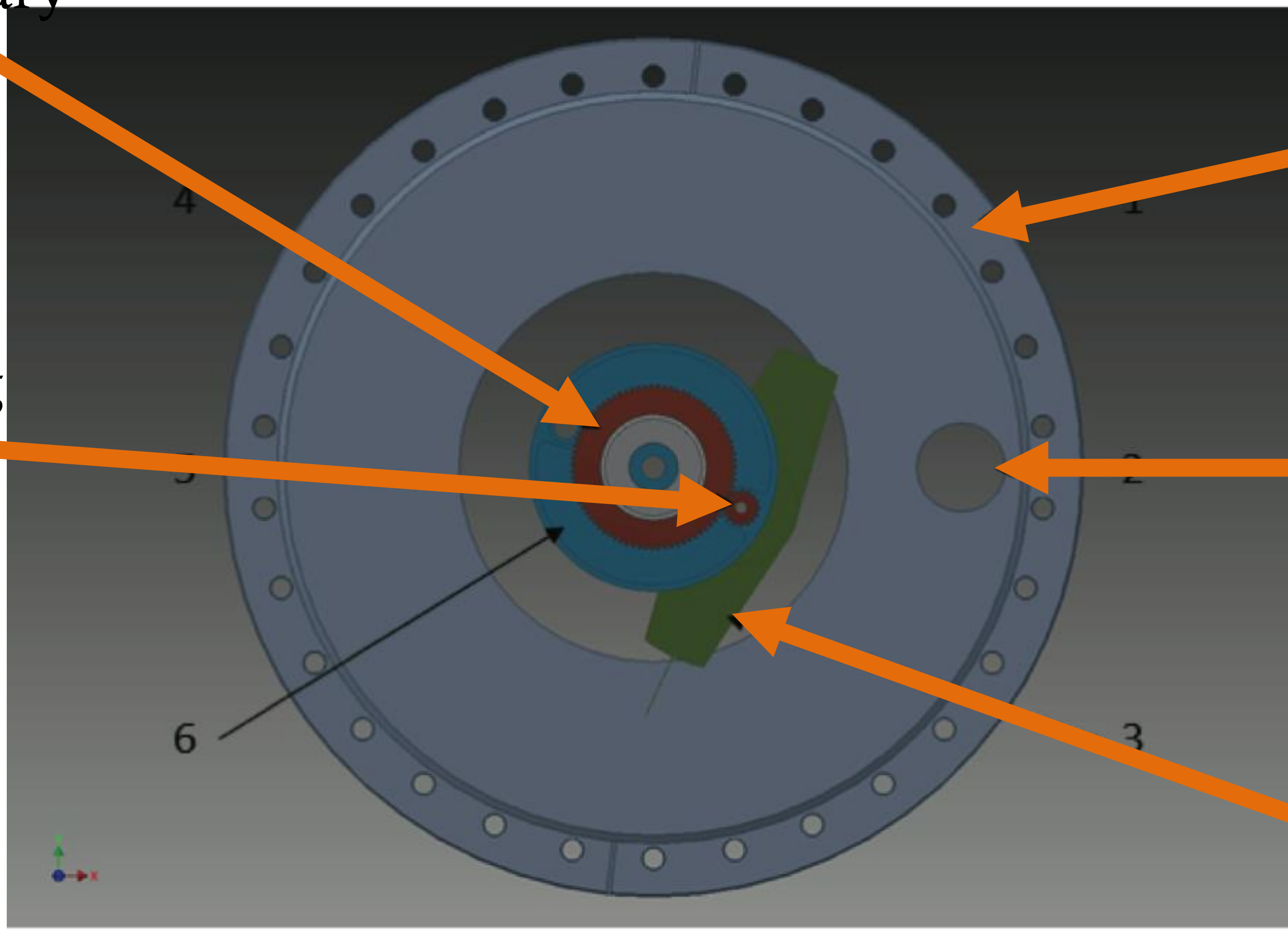
Small rotating gear



Vacuum Flange

Beam

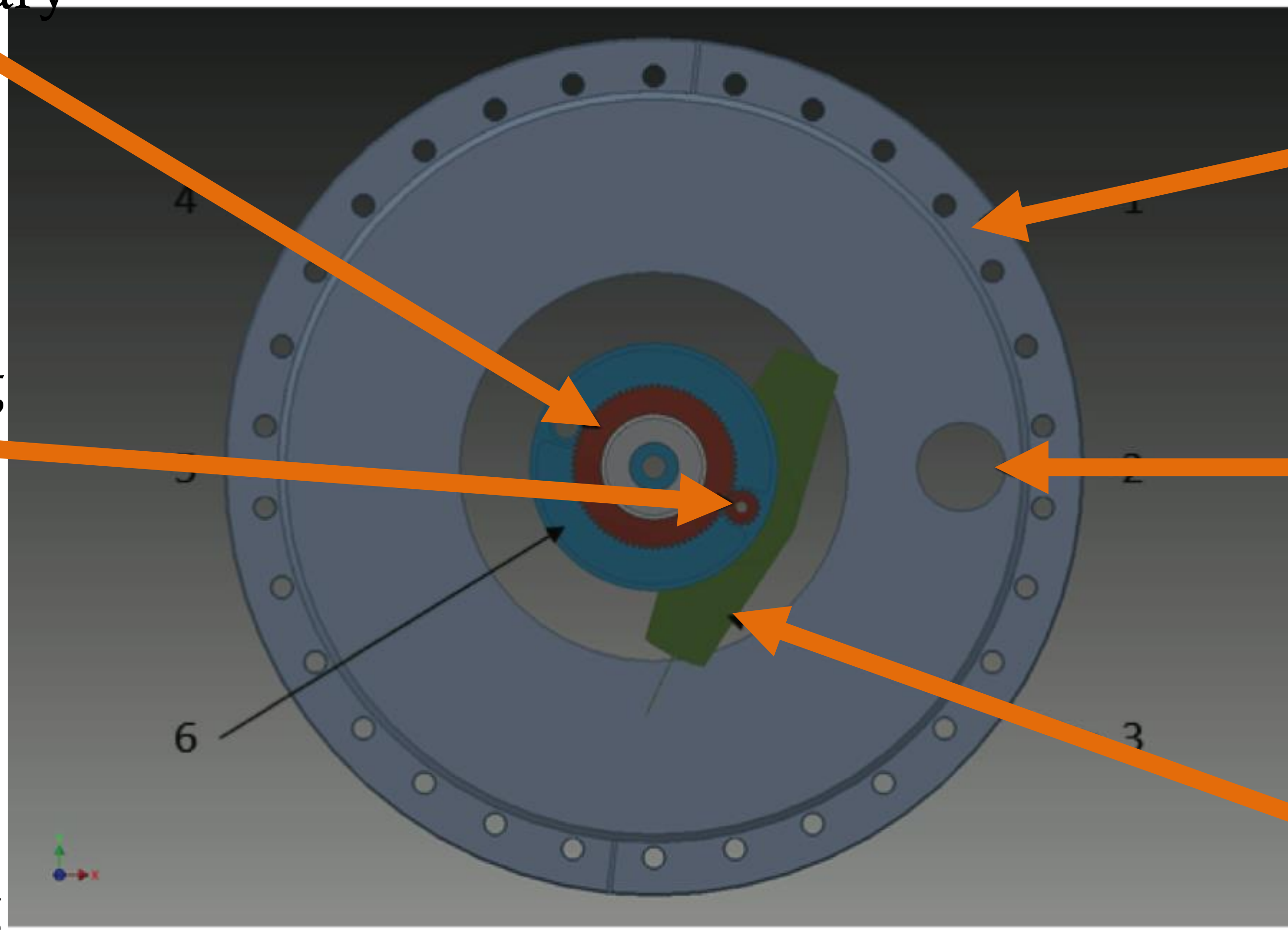
Blade + carbon wire attached

3D model of the design

Large stationary gear

Small rotating gear

Rotating Gear box



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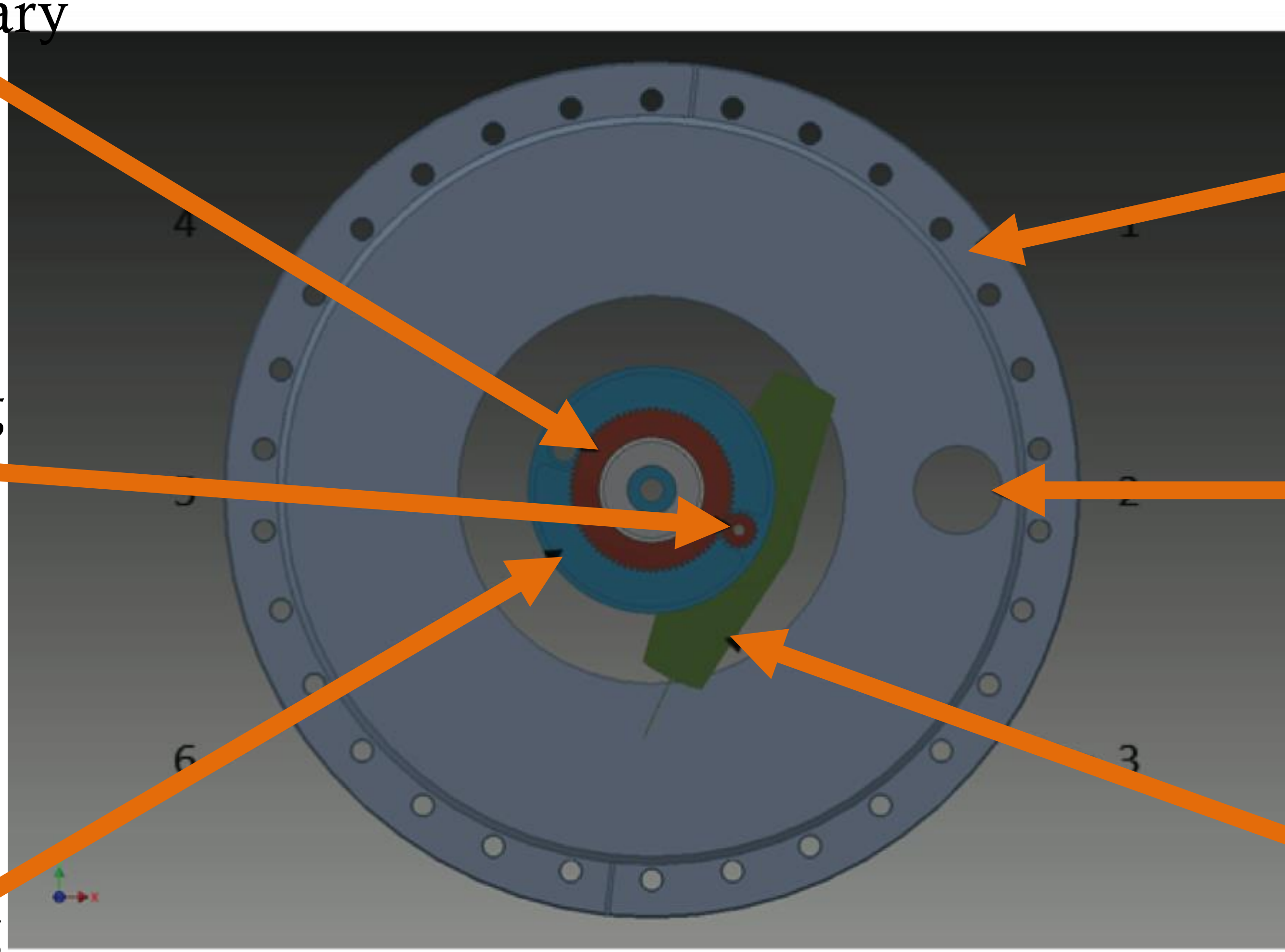

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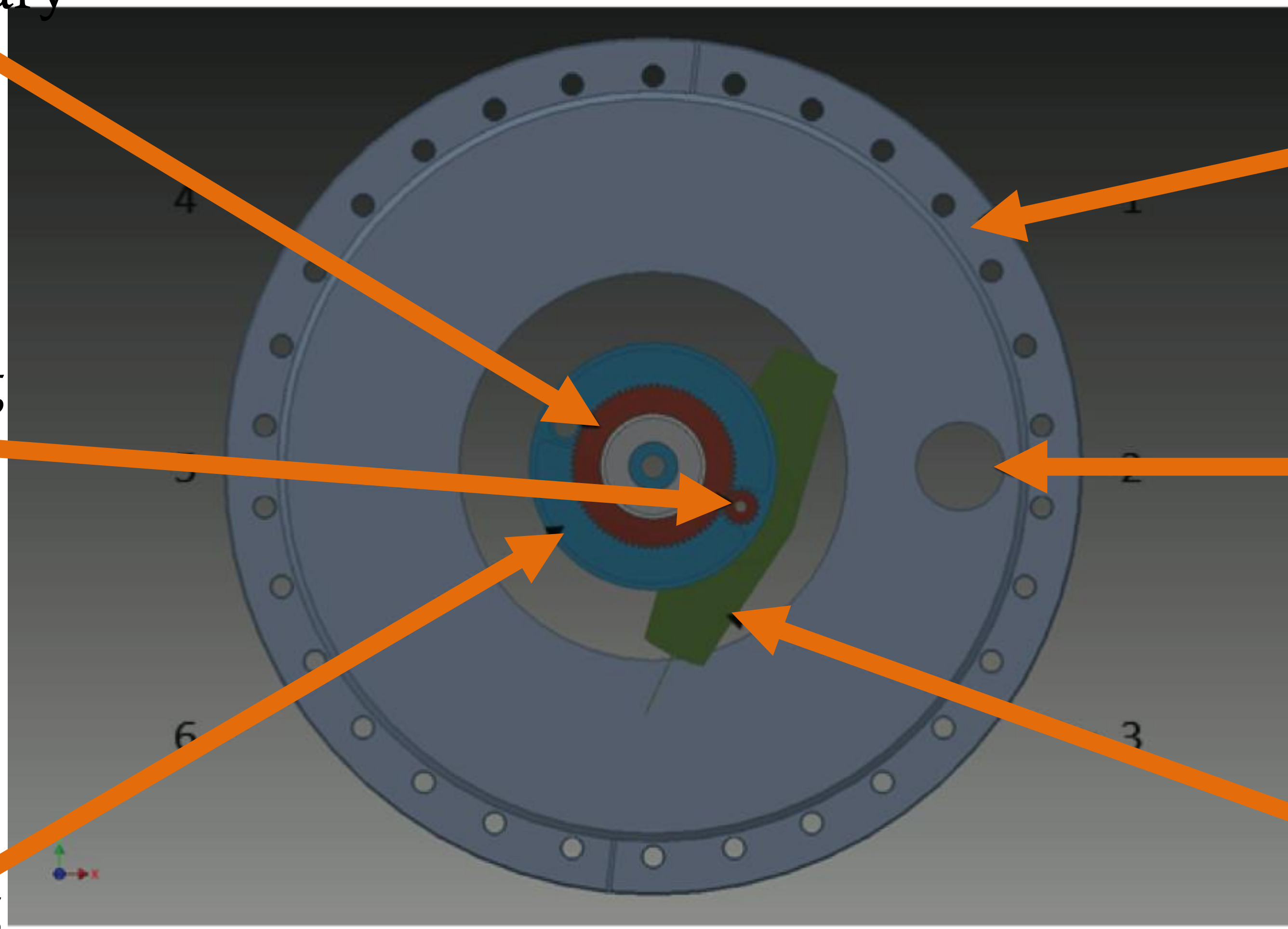


Vacuum Flange

Beam

Blade + carbon wire attached

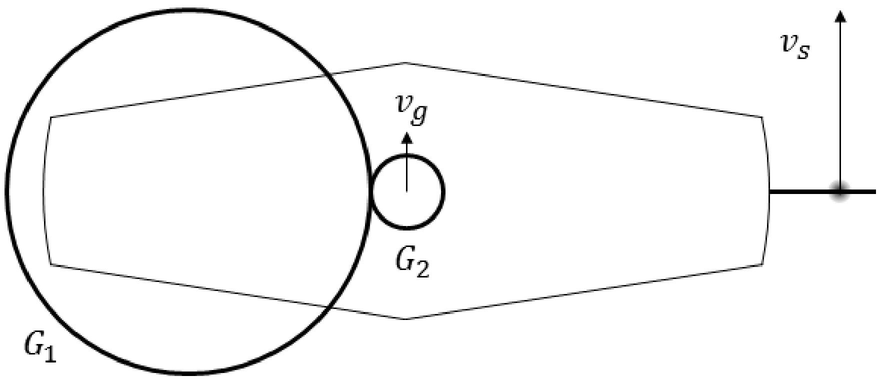
Able to be mass produced!

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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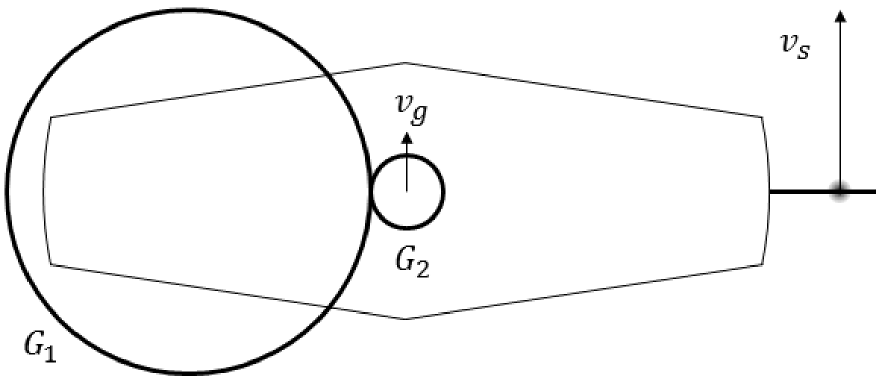

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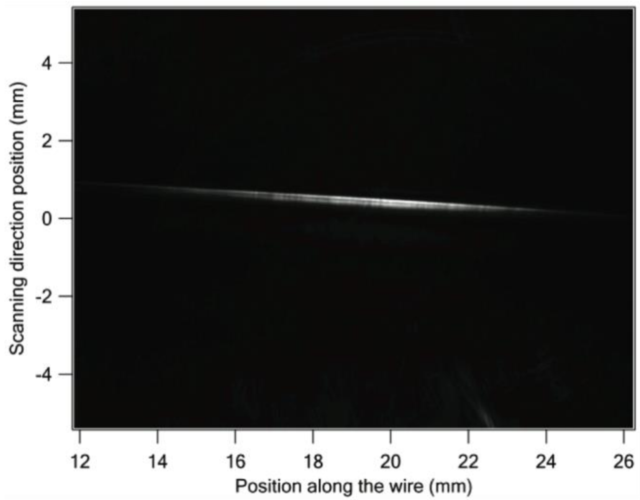
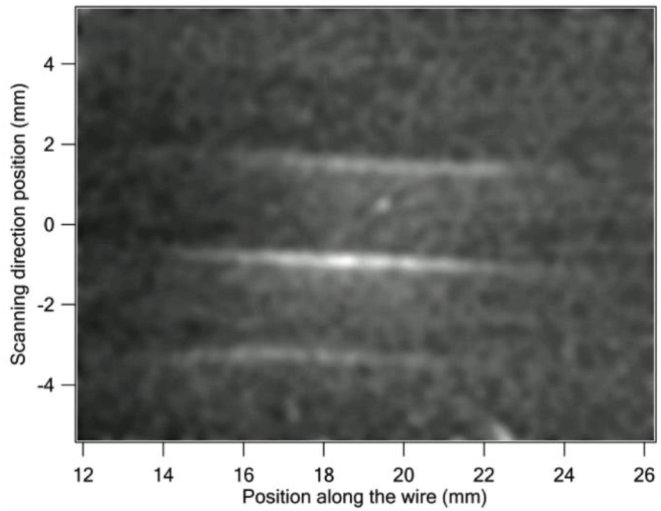
$$\mathbf{v_s \sim 6\ v_g}$$

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

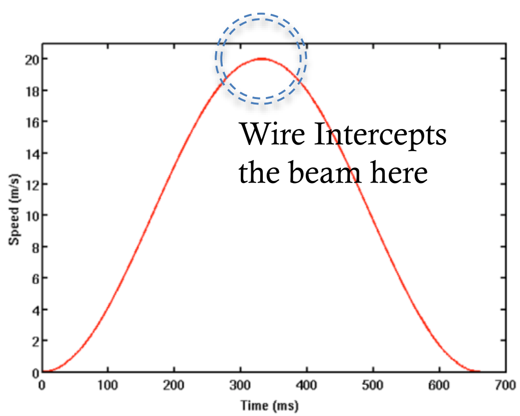
Taking pictures at 20 m/s



Stationary wire



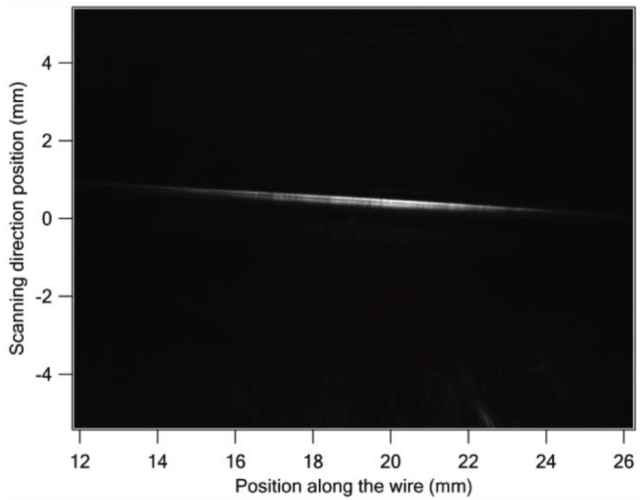
Moving wire



The wire's velocity profile

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).

Taking pictures at 20 m/s



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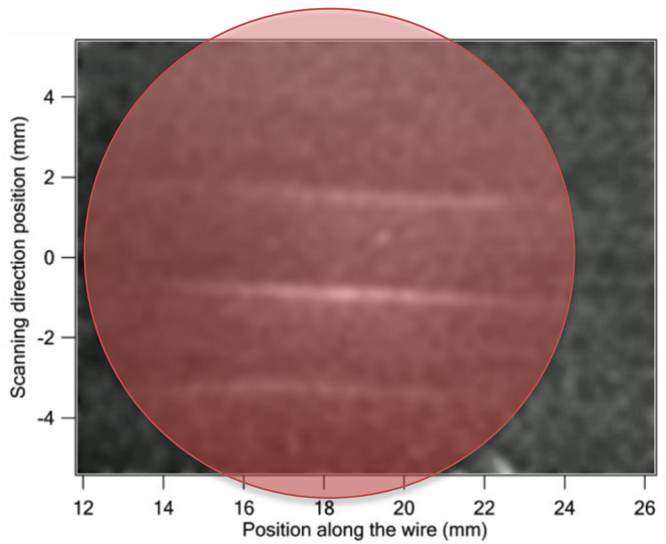

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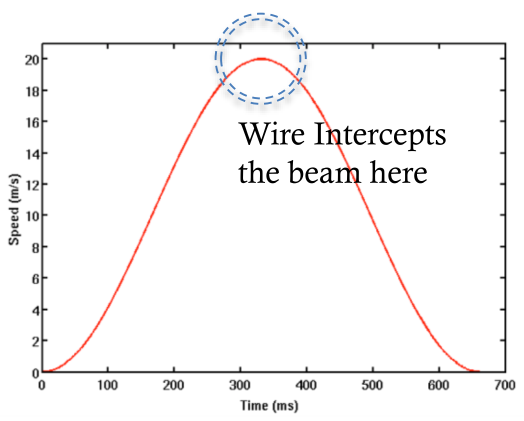

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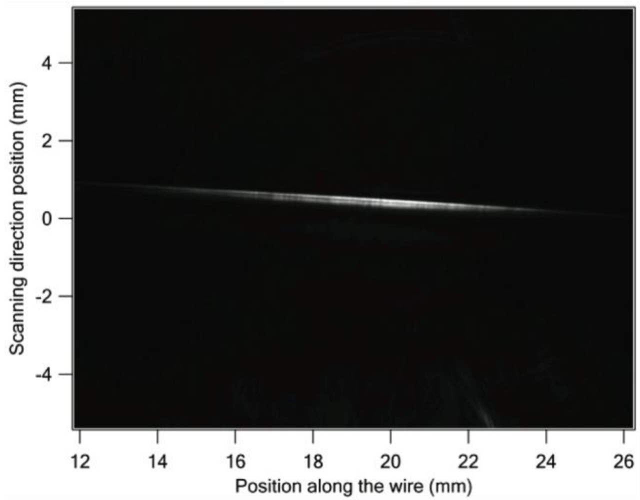

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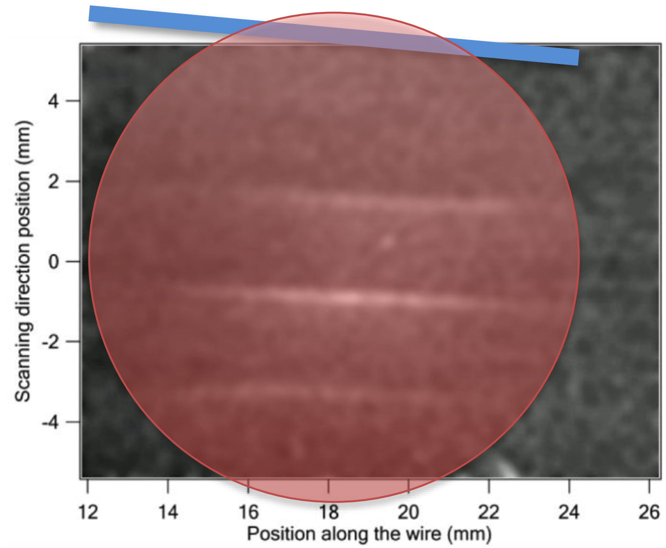

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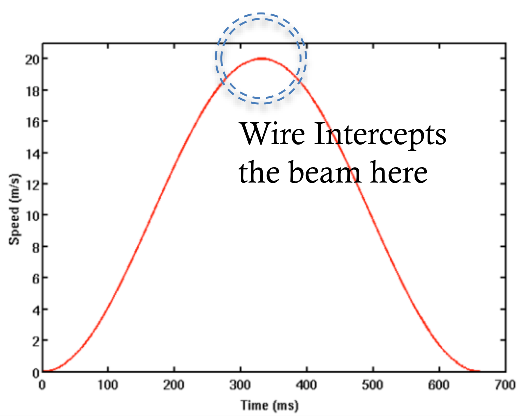

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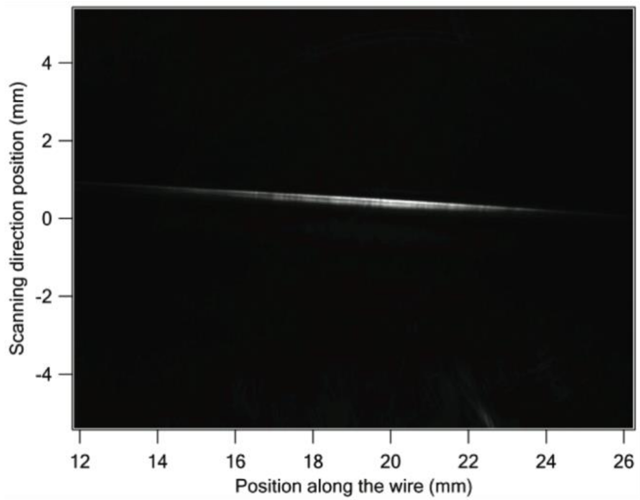

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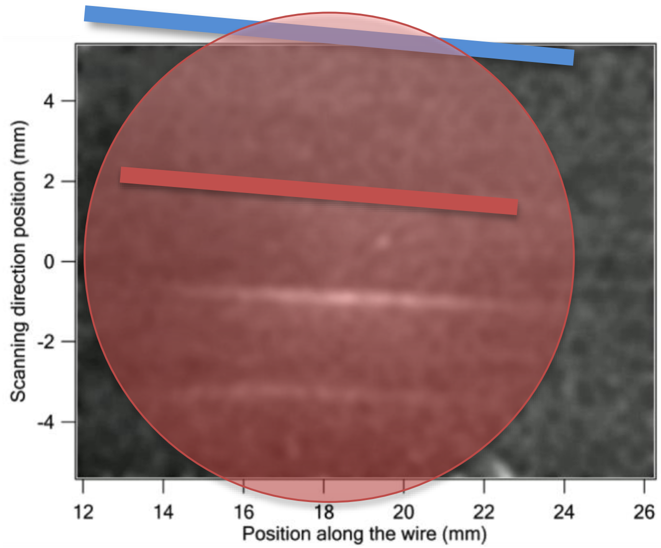

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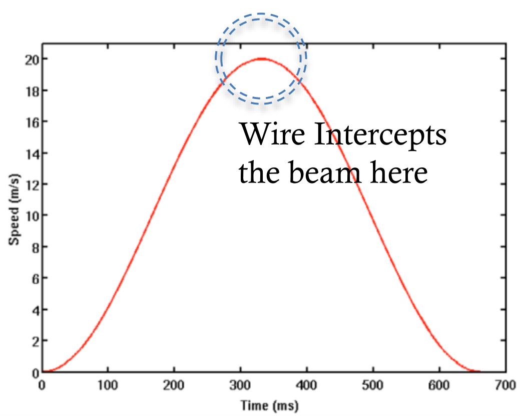

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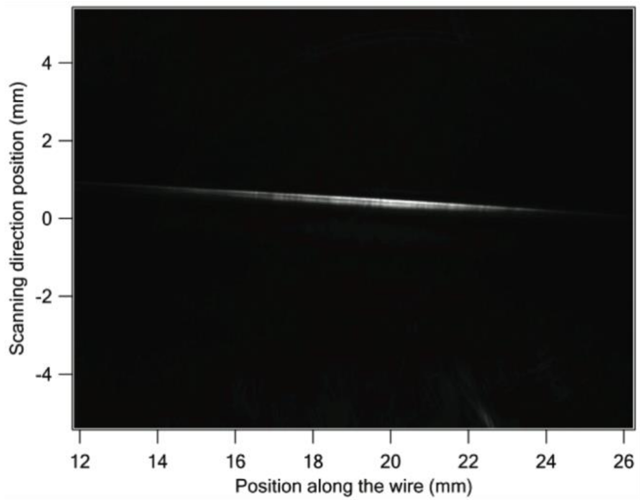

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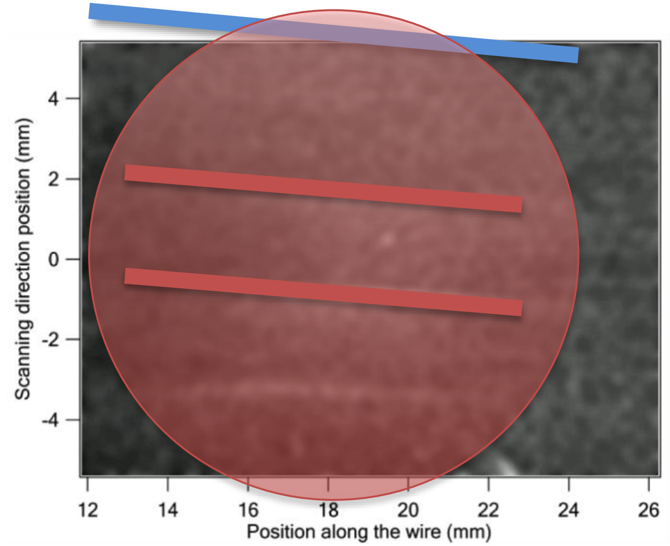

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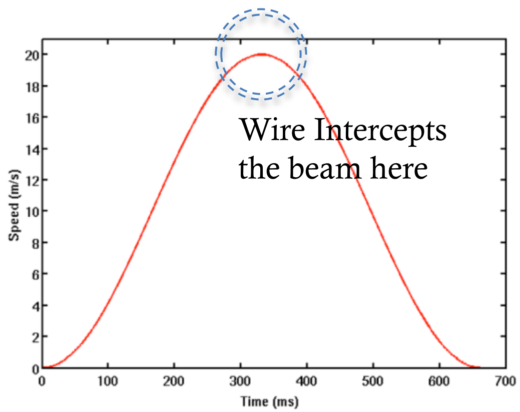

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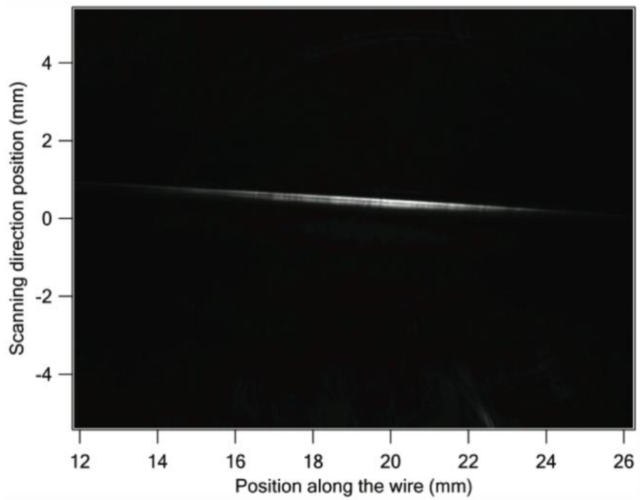

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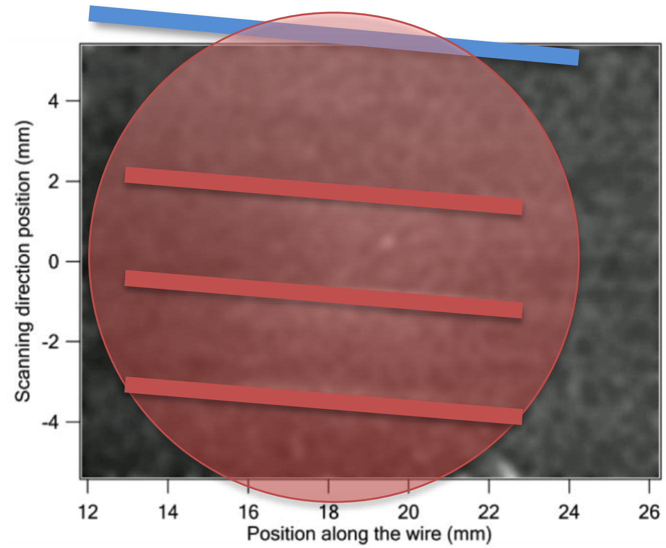

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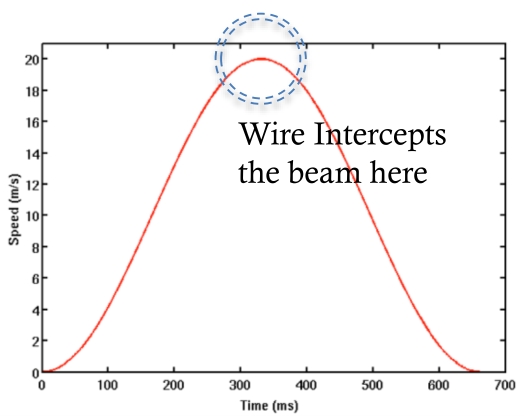

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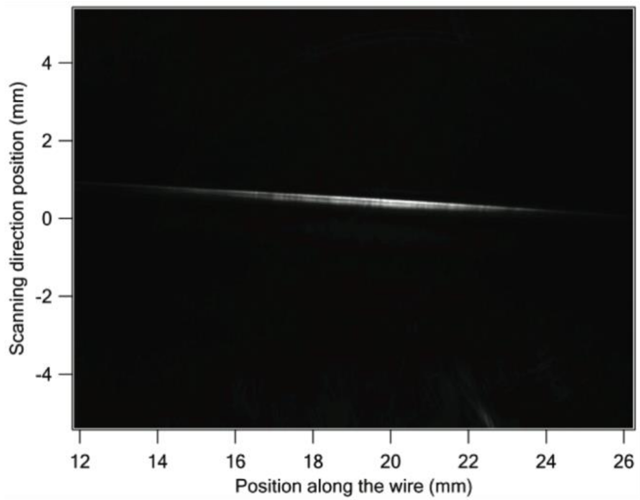

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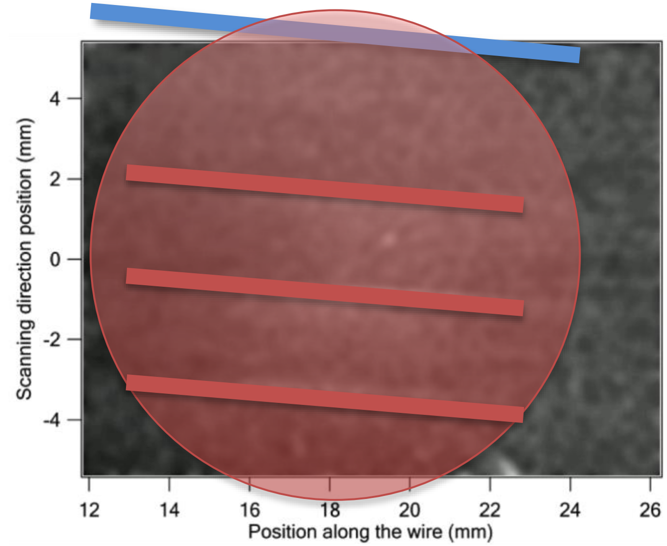
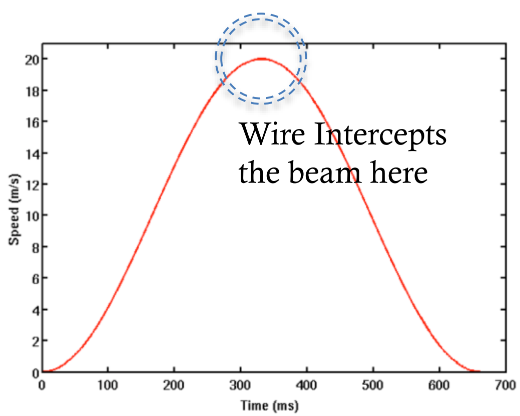


Moving wire

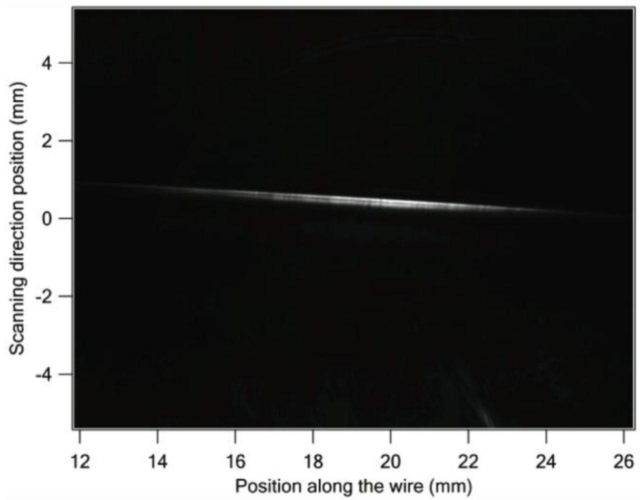


The wire's velocity profile

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



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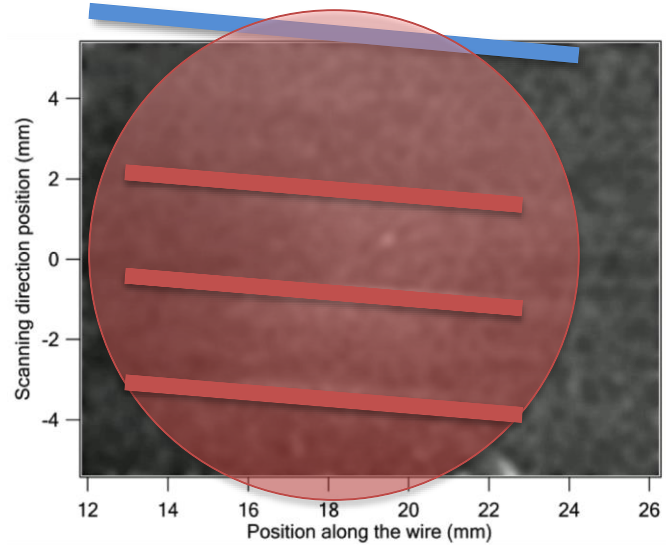

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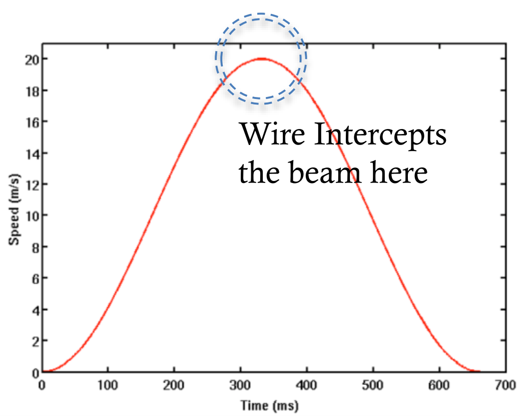

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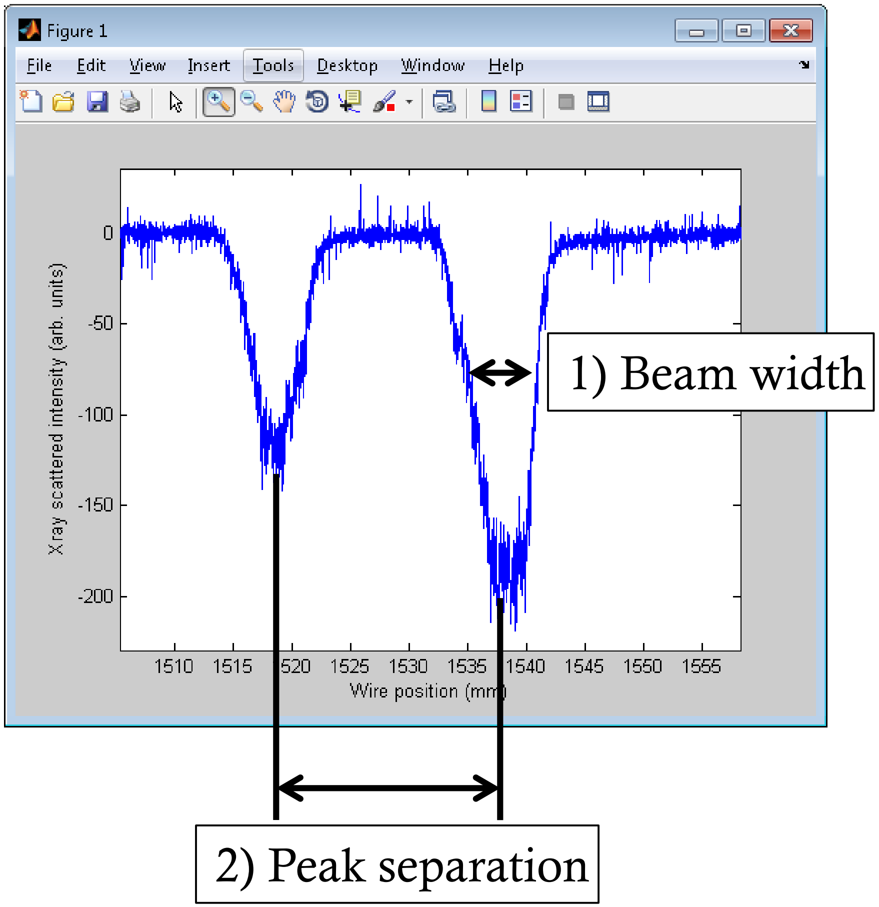
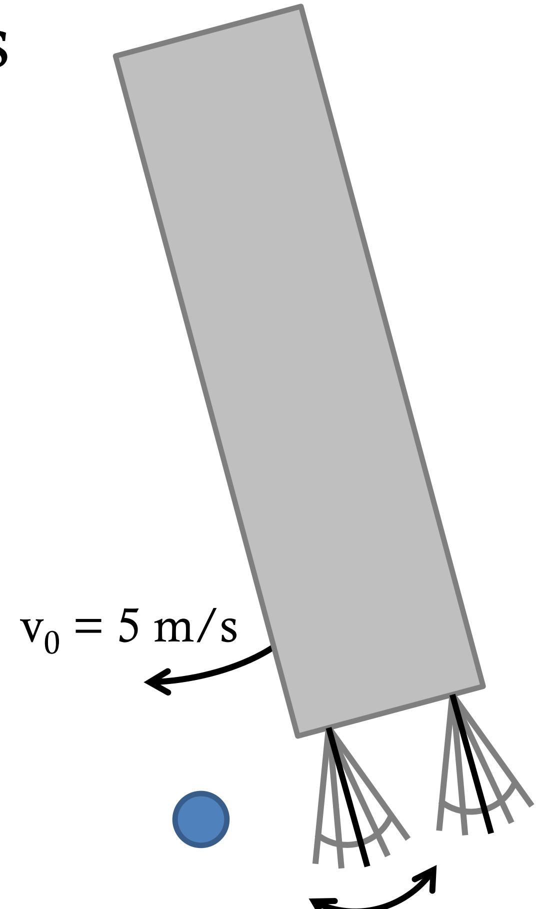
Vibration analysis using 2 wires



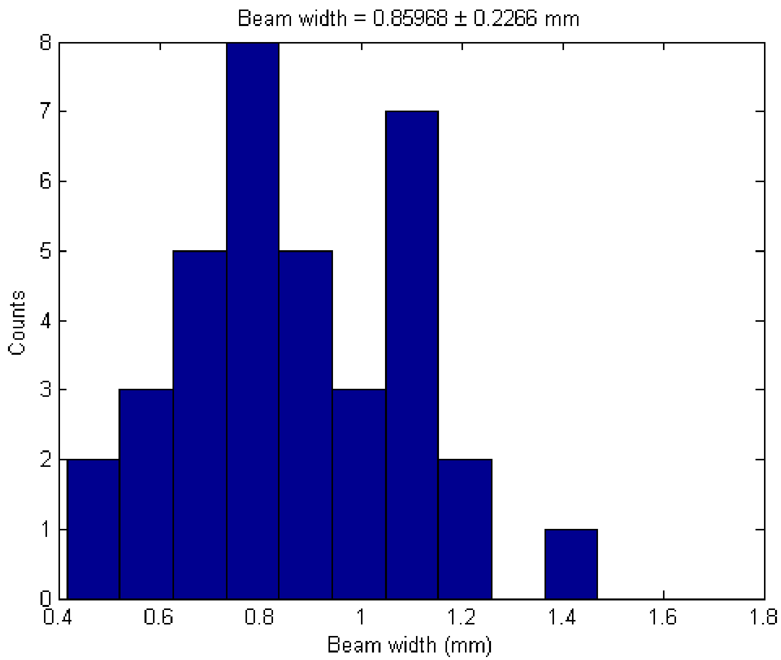


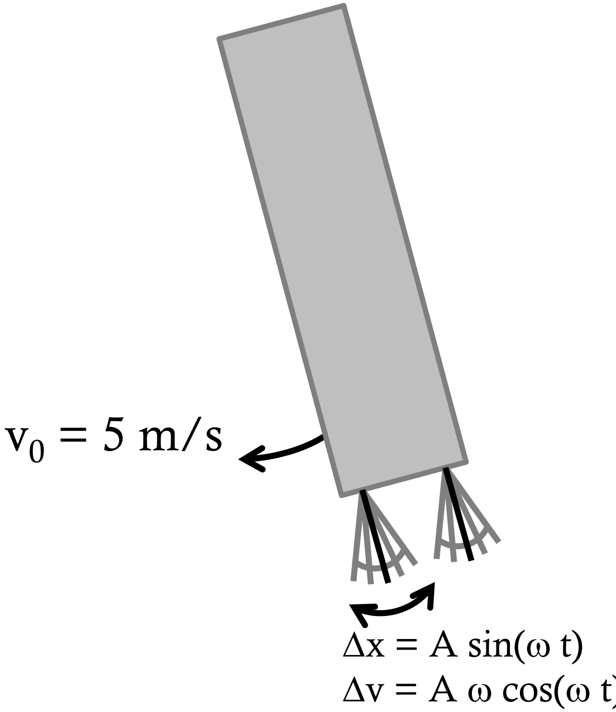
$\Delta x = A \sin(\omega t)$

$\Delta v = A \omega \cos(\omega t)$

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

Estimation of error due to wire vibrations





Viewscreen = 0.72 mm
Wire scanner = 0.86 ± 0.22 mm (25% error)
A ω = 0.25 x 5 m/s = 1.25 m/s

→ Implies A = 2.6 mm

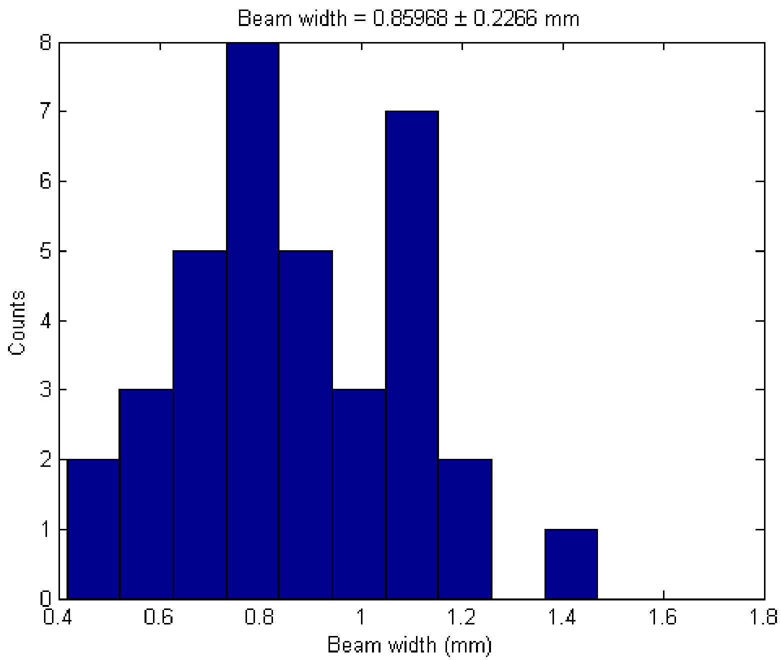
Wire separation = 11 ± 4 mm (36% error)
Separation error = 4 mm = √2 A

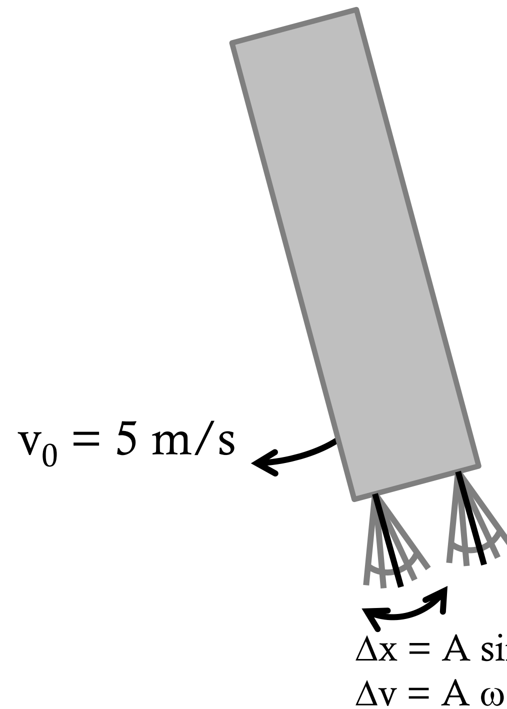
→ Implies A = 2.8 mm

f = 75 Hz (found using a modulating laser)

If the amplitude doesn't increase, at **v = 20 m/s, we expect only 6% error.**

Estimation of error due to wire vibrations





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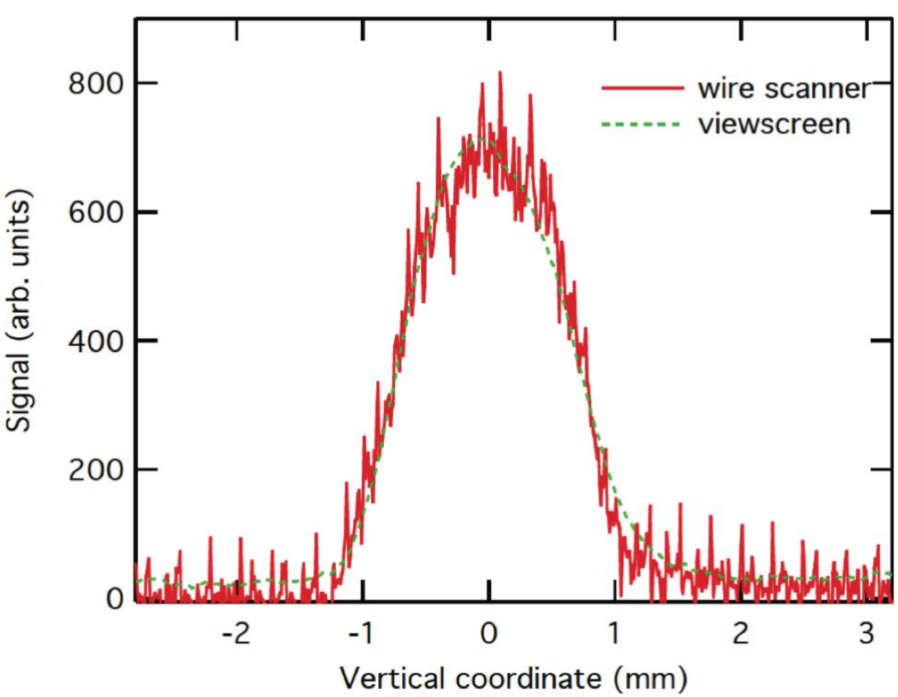
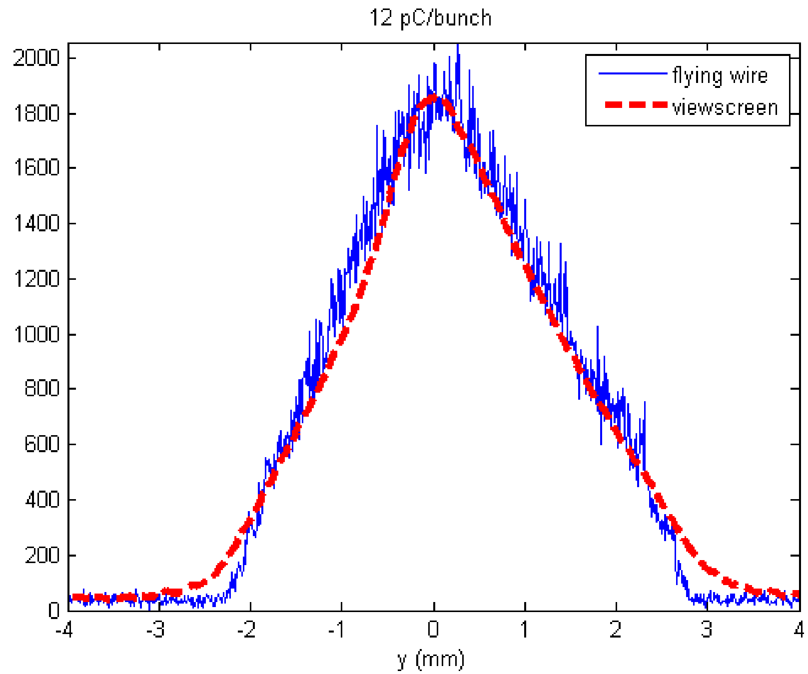
At 20 m/s it works great!

Comparisons with viewscreens at low beam current (~100 nA)





High repetition rate
Low bunch charge

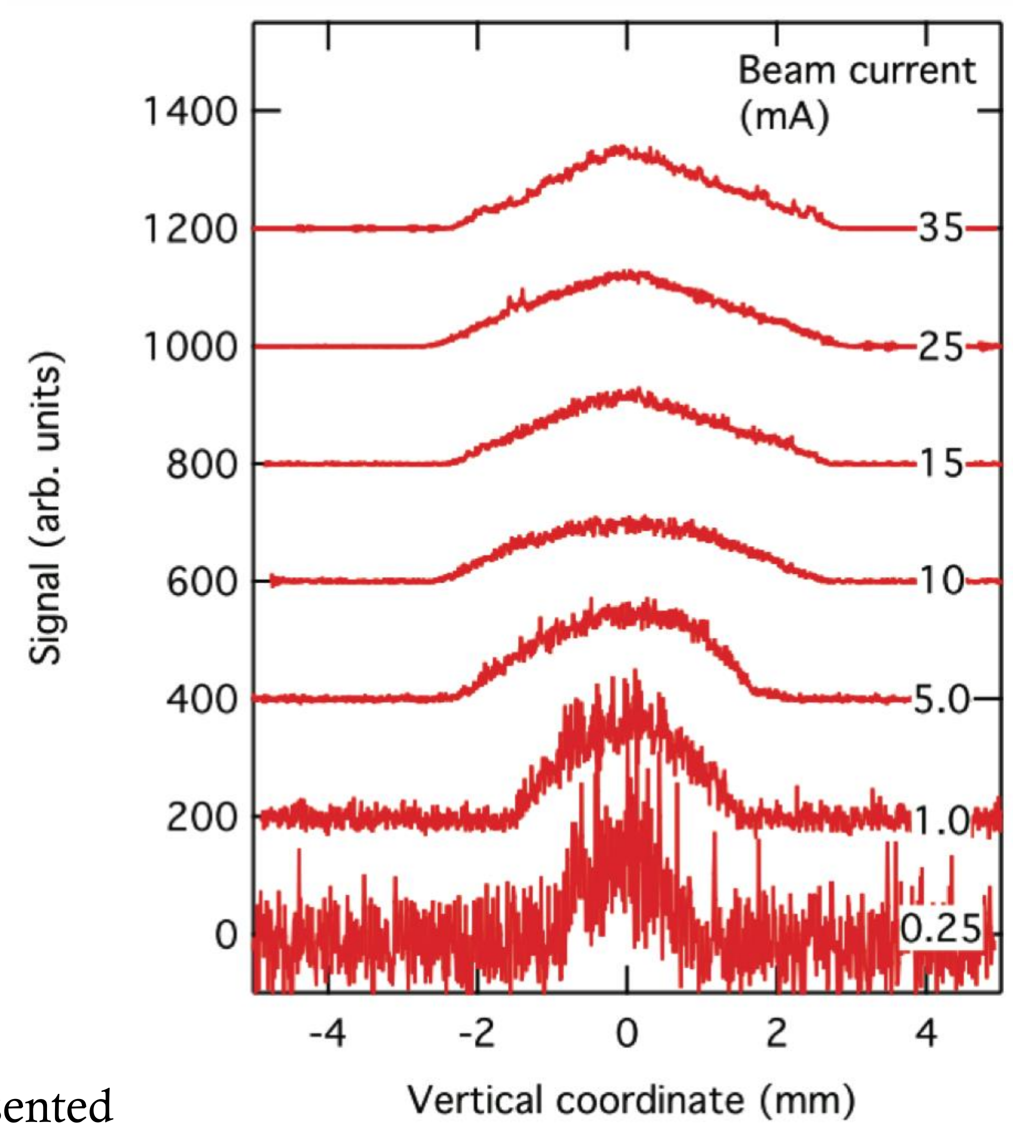
$v_0 = 20$ m/s

Low repetition rate
High bunch charge

It works!

Vertical beam profile measurements taken at Cornell's ERL Photoinjector

Parameter	Used for experiments
Beam type	Electron
Energy	4 MeV
Power	0.5 MW
Current	< 35 mA
Bunch Charge	< 27 pC
Repetition rate	1.3 GHz / 50 MHz
Emittance	0.3 µm
Trans. Beam Size	~ 3 mm



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

Take home messages

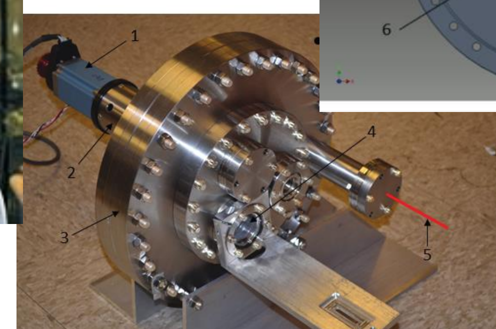
- Great option for high current/intensity beams
  - It works!
  - Compact (~40 cm)
  - Cheap (< $5000)
  - Quick to build (only 2 custom parts)

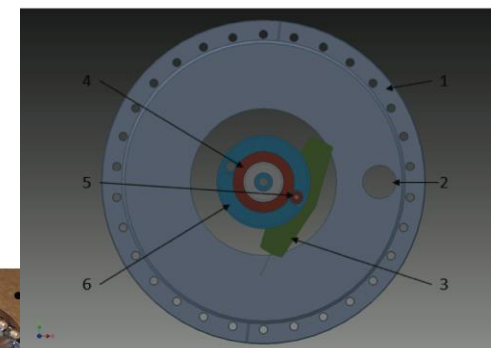
Thank you for listening!

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!

And thanks to the rest of the Cornell team:
Nick Agladze
Ivan Bazarov
Adam Bartnik
John Dobbins
Bruce Dunham
Yulin Li
Jim Savino
Karl Smolenski





Contact: Steve Full at sf345@cornell.edu
This work was supported by the financial assistance from the National Science Foundation (Grant No. DMR-0807731).