How far, how fast, and what shape?

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Continuous FSI

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Smith-Purcell Radiation

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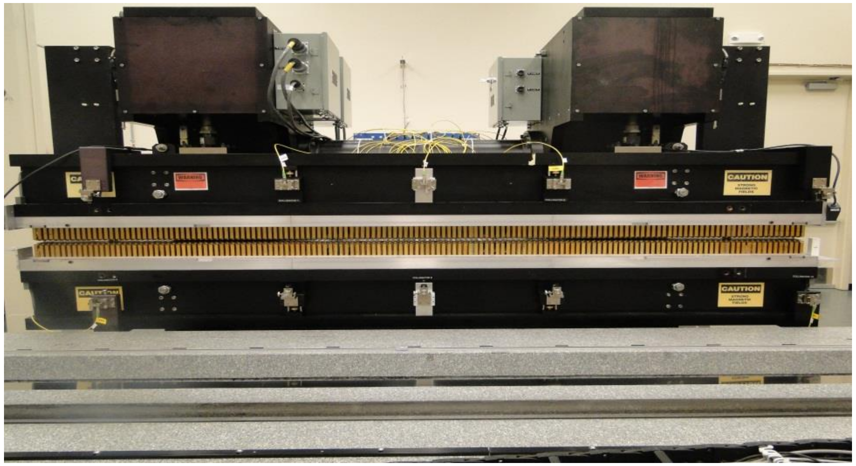
Overview

- Continuous FSI
  - Motivation.
  - Frequency Scanning Interferometry (FSI).
  - Moving targets / Dynamic FSI.
  - Continuous FSI (CFSI).
  - Enhanced CFSI.
  - Summary.
- Single-shot Smith-Purcell monitor
  - Motivation
  - Smith-Purcell radiation
  - Current system (FACET, SLAC)
  - Single-shot proposal
    - Grating layout
    - Background reduction
  - Summary

Motivation

- Absolute distance measurement.
- Contactless.
- High accuracy, high precision.
- Easily scalable.
- Many applications in HEP:
  - ATLAS.
  - LiCAS / Monalisa.
  - Undulator gap measurement.
- Industrial applications.



Picture courtesy J. Dale

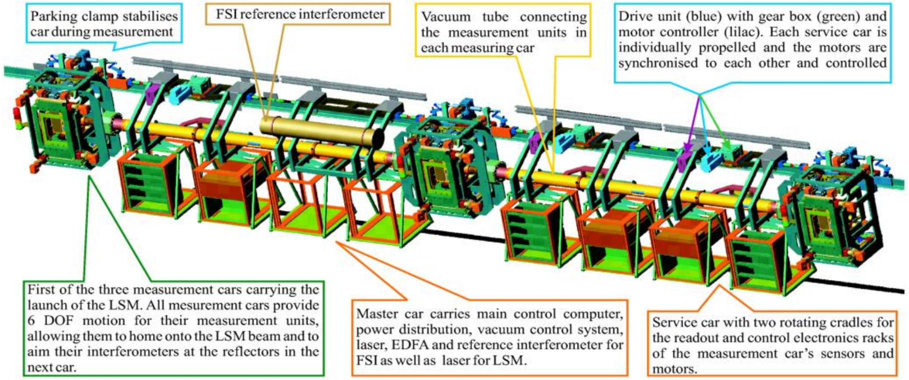
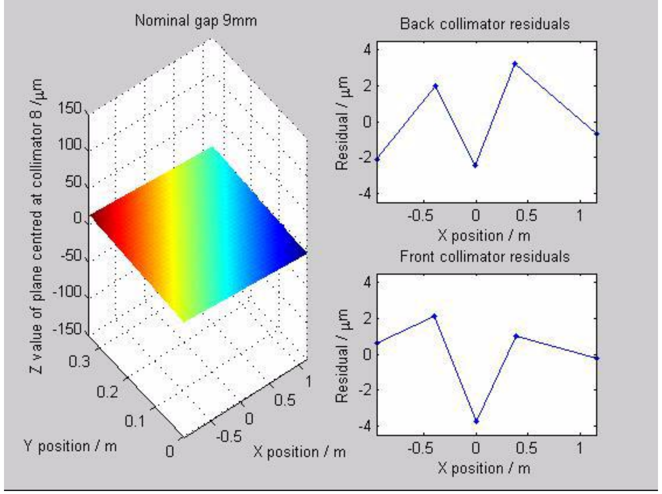
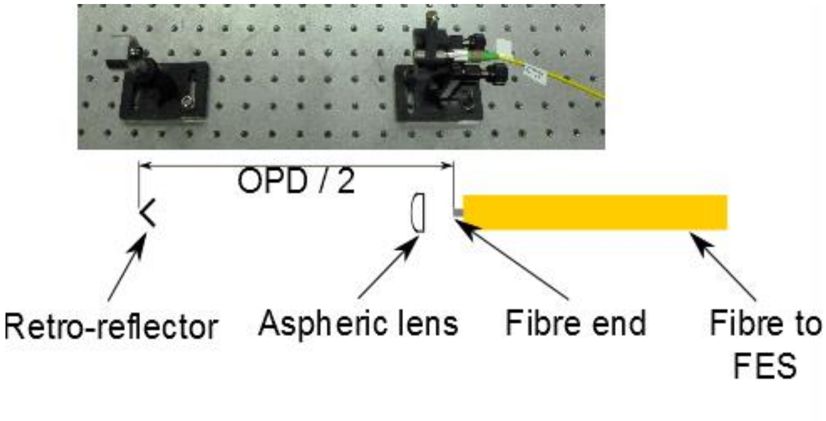


Image courtesy A. Reichold



Frequency Scanning Interferometry



$$I = I_0 cos\left(\frac{2\pi}{c}L\nu\right) \qquad \phi = \frac{2\pi}{c}L\nu$$

$$\dot{\phi} = \frac{2\pi}{c}L\dot{\nu}\,\dot{\nu} + \dot{L}\nu)$$

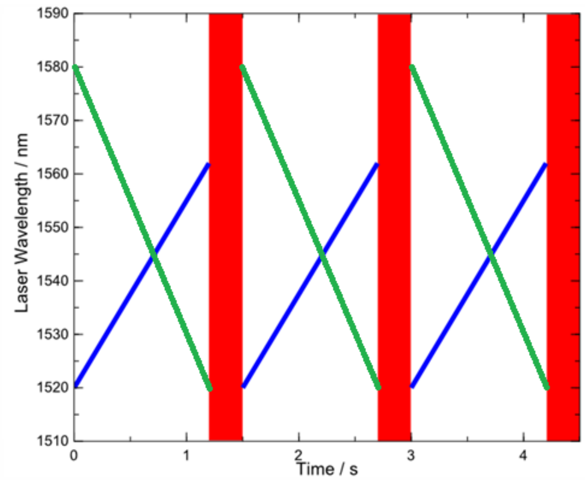
Measurement Interferometer $\Delta\phi = \frac{2\pi}{c}L\Delta\nu$

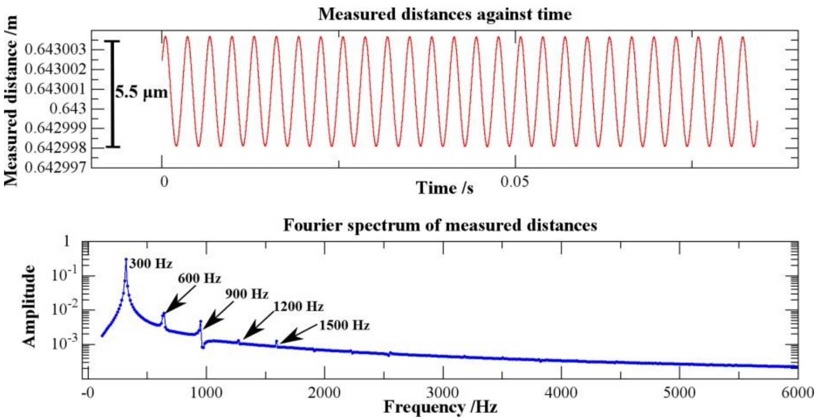
$\Delta\phi_R = \frac{2\pi}{c}L_R\Delta\nu$ Reference Interferometer

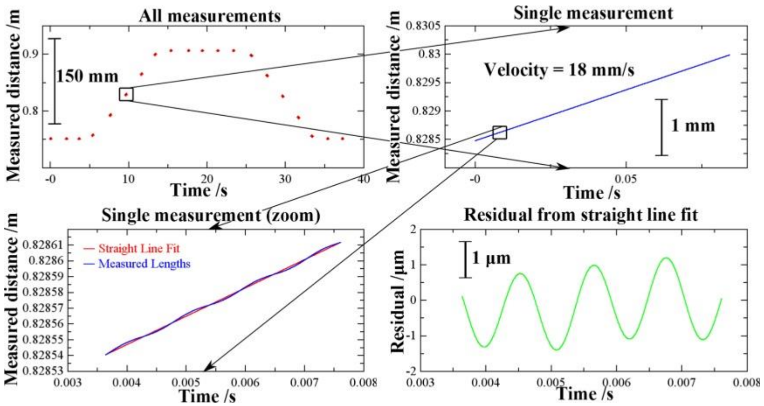
$$\frac{\Delta\phi}{\Delta\phi_R} = \frac{L}{L_R}$$

Moving targets

- Dynamic FSI:
  - Two lasers scanning simultaneously.
  - Laser frequency calculated.
  - Shot-based measurement.
  - DAQ-rate measurements within a shot.
  - <0.5x10^{-6} relative uncertainty up to 20m.



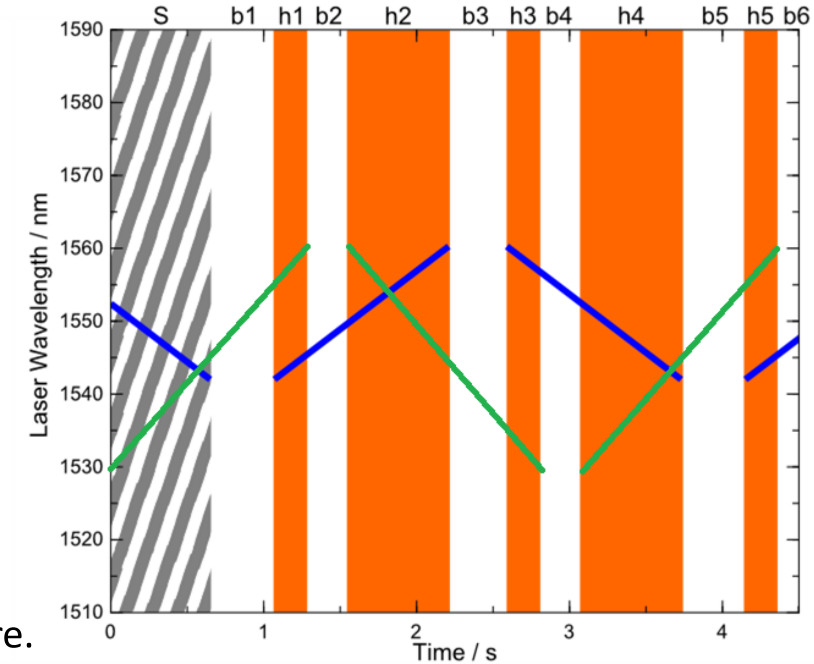




[1] J. Dale et. al., "Multi-channel absolute distance measurement system with sub ppm-accuracy and 20 m range using frequency scanning interferometry and gas absorption cells," Opt. Express **22**, 24869-24893 (2014)

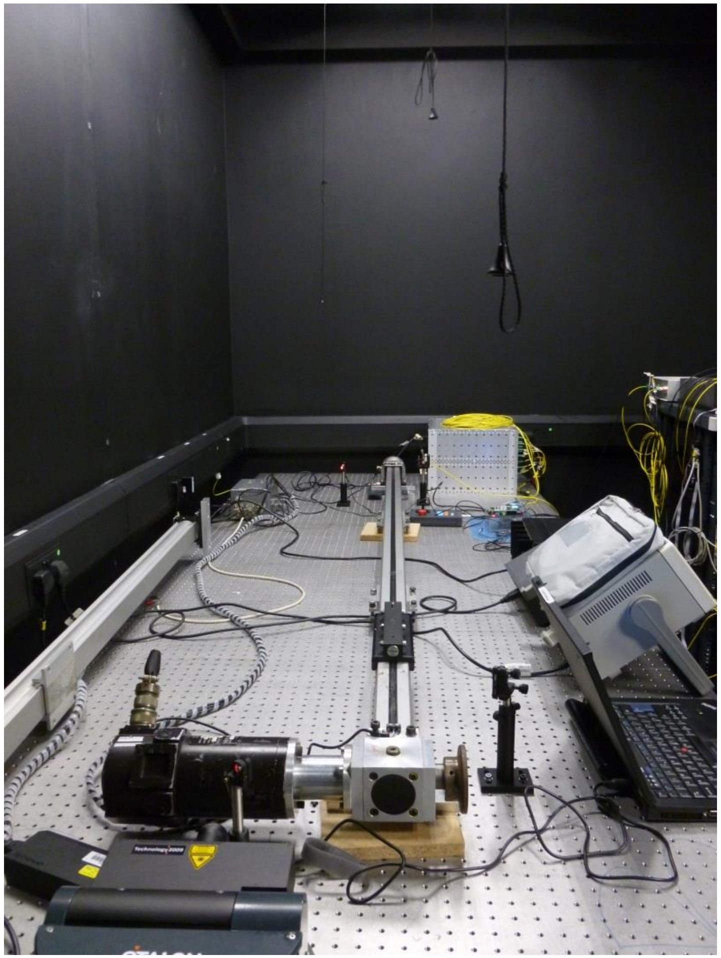
Continuous FSI

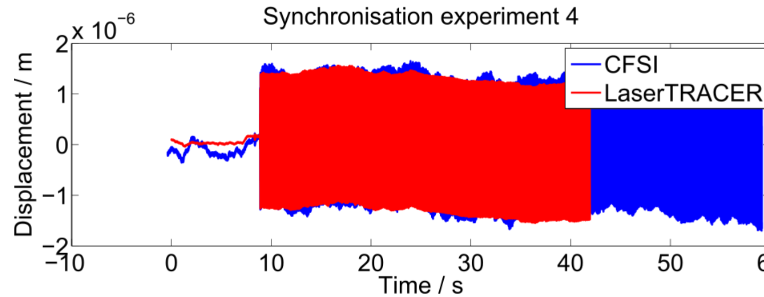
- What is needed for length calculation?
  - Measurement point
    - Known laser frequency
    - Known phase
  - Transfer point
    - Known length
    - Known laser frequency
    - Known phase
- Dynamic FSI essentially finds length.
  - Process requires two lasers.
- Once found, only one laser is required!
  - First laser can continue to scan, and so measure.
  - Second laser restarts.
  - Second laser frequency determined.
  - Length from first laser provides transfer point for second.
  - *Handover.*
  - First laser resets etc.

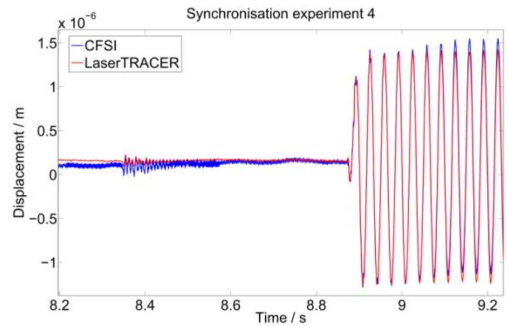


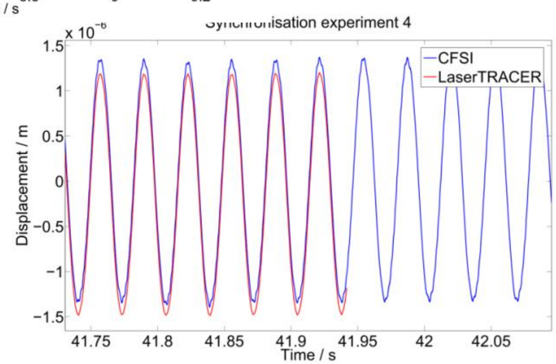
Continuous FSI

Vibration experiments





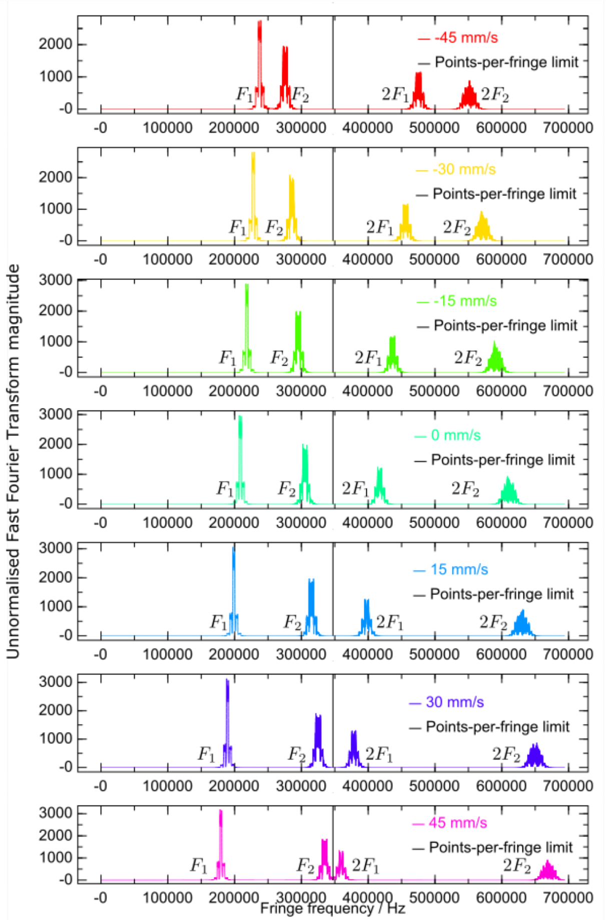




Motion Tolerance

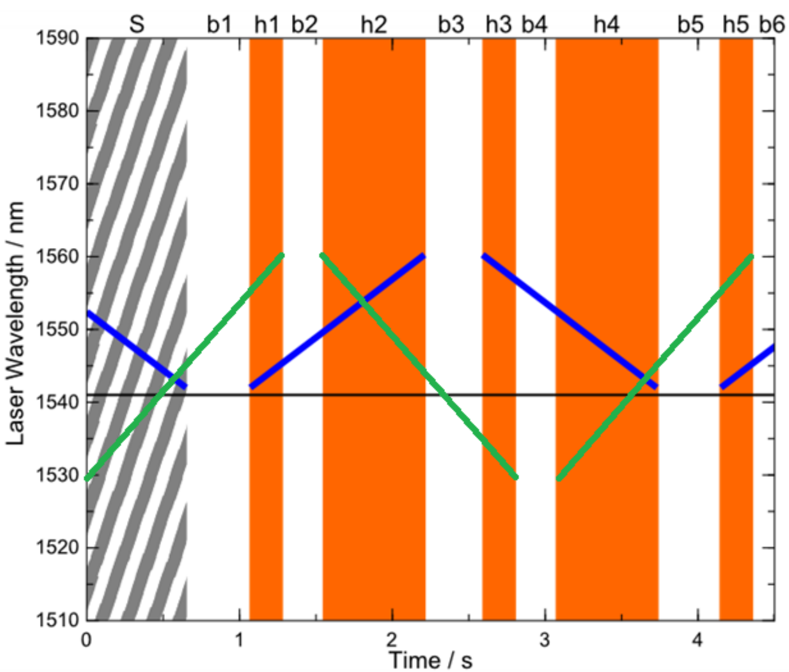
$$\dot{\phi} = \frac{2\pi}{c}\left(L\dot{\nu} + \dot{L}\nu\right)$$

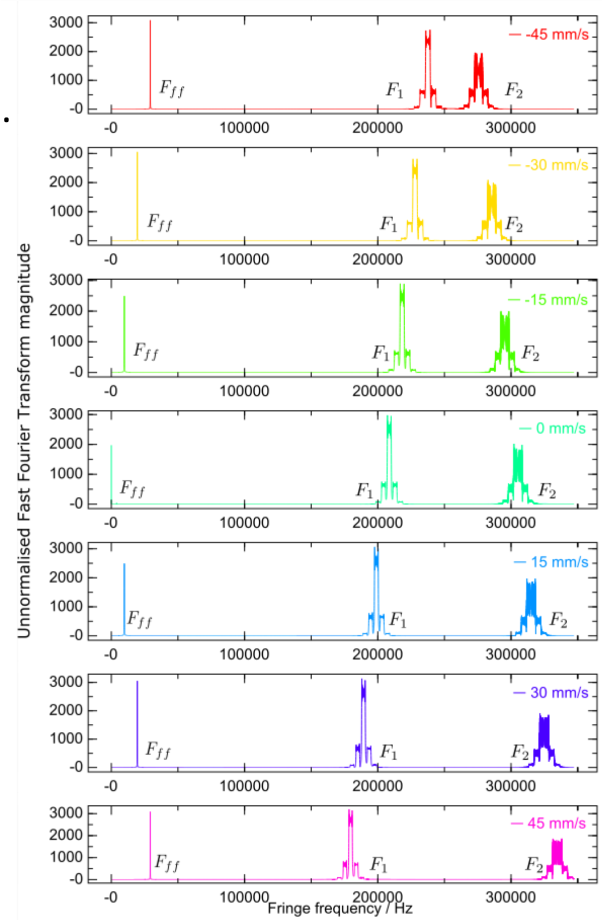
- Limits on phase extraction:
  - Minimum 8 points per fringe.
  - Non-zero fringe rate.
  - Different fringe rates.
- Leads to limits on target motion.
- Exacerbated by lack of directionality.
- Reduces applicability of the technique.



Enhanced CFSI

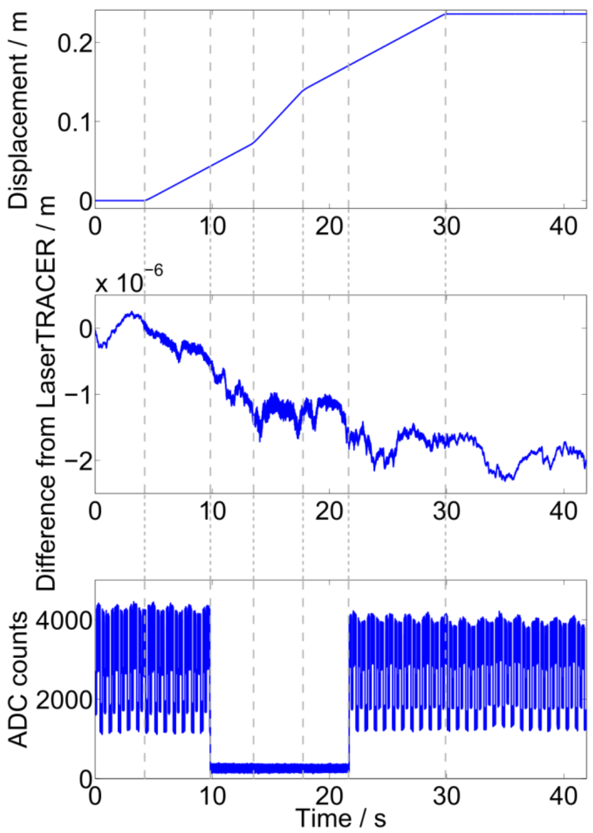
- Solution: add a fixed-frequency laser!
  - Scanning lasers blocked with fast target motion.
  - Target speed limited by DAQ rate.
  - Adds a subtle acceleration limit.





Enhanced CFSI

Turnoff experiments



Summary

- (Enhanced) Continuous FSI demonstrated as a feasible technique.
  - Measurements of vibration and stage motion compared against reference system.
  - Handovers to fixed frequency laser demonstrated.
  - Scanning lasers removed from measurement interferometer without disruption.
- Several developments required:
  - Investigation into drift discrepancy.
  - Accuracy improvements.
  - Analysis speed increase.

We acknowledge support via STFC CASE studentship ST/I000526/1 and EPSRC grant EP/H018220/1, both in conjunction with NPL.

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  - Motivation
  - Smith-Purcell radiation
  - Current system (FACET, SLAC)
  - Single-shot proposal
    - Grating layout
    - Background reduction
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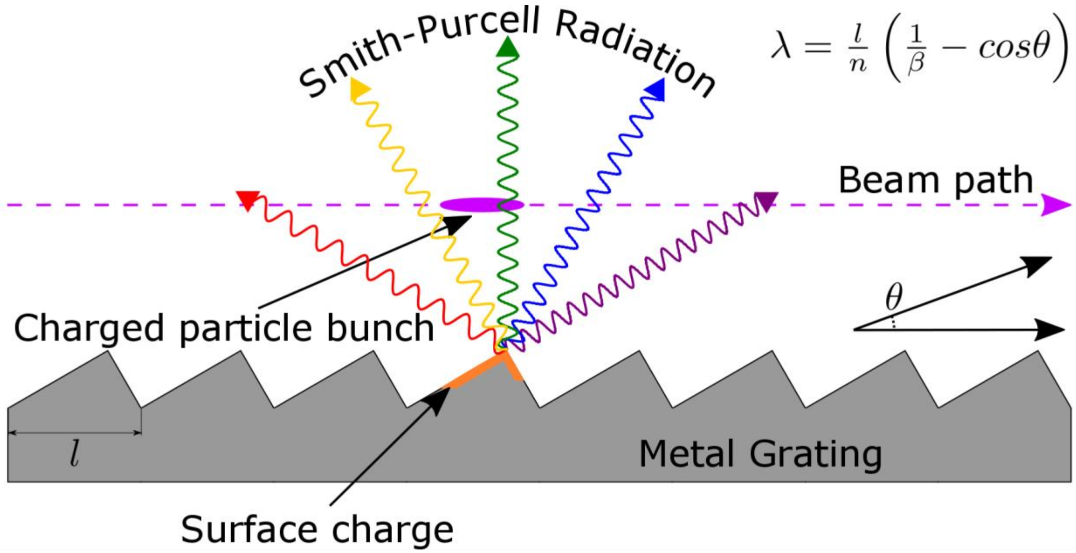
Motivation

- Many applications require (or provide) short bunch lengths:
  - Particle colliders.
  - Plasma wakefield acceleration.
  - Free-electron lasers.
- Bunch profile can vary on a shot-by-shot basis.
- Complex interactions can be difficult to model.
- Better to simply measure the beam!
  - Needs to be non-destructive.

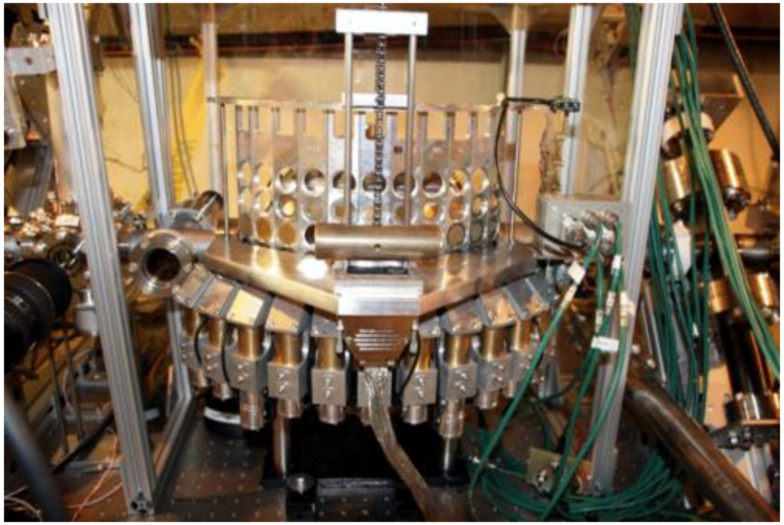
Smith-Purcell Radiation



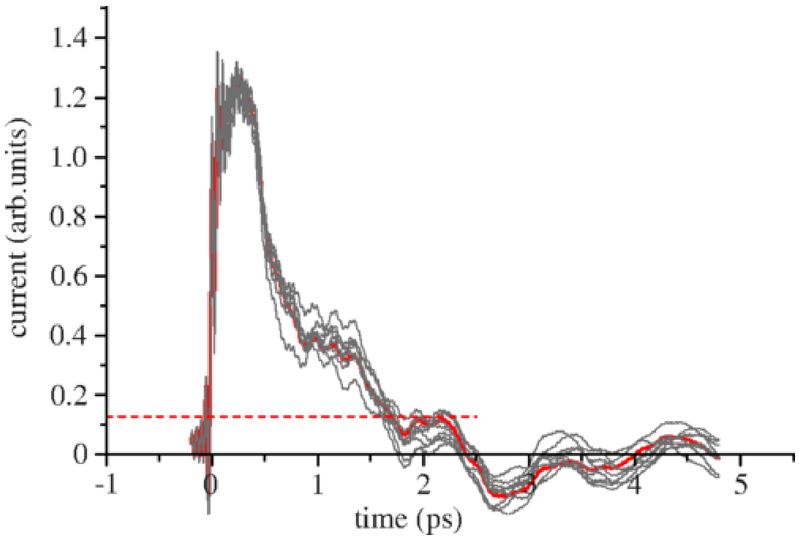
- Charged particle bunch passes above a metal grating.
- A surface current is induced.
- The grating forces changes in current direction – leads to emission of radiation.
- Length profile of the bunch encoded within the SPR intensity distribution.

Current system

- Experiments performed at FACET [2].
- ≈20 GeV electrons.
- 0.5 - 2.0 x 10^{10} electrons per bunch.
- Normalized emittance 60 mm-mrad.
- Bunches at 10 Hz.

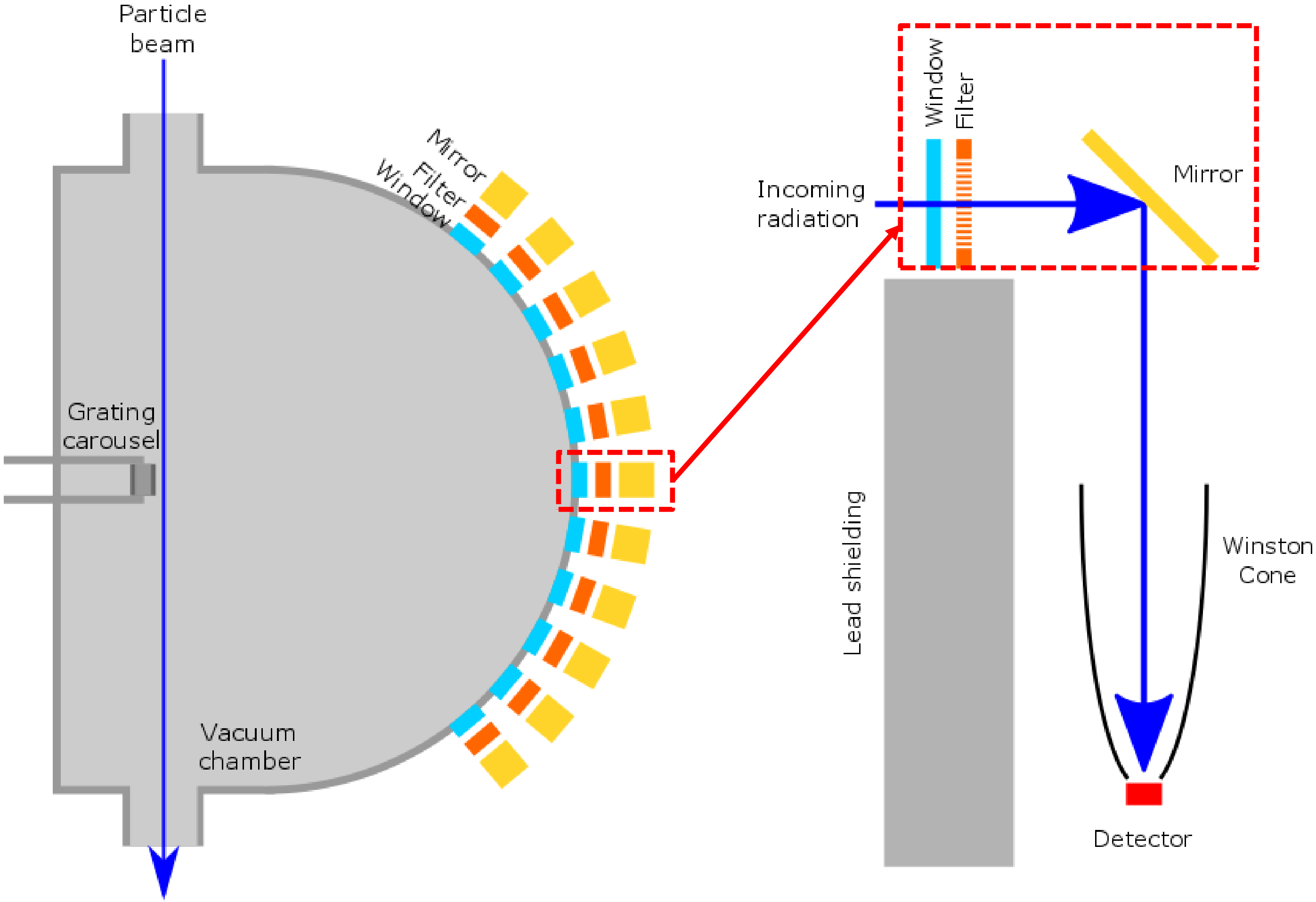


- Measurement of sub-ps bunch profiles.
- SPR properties also studied.

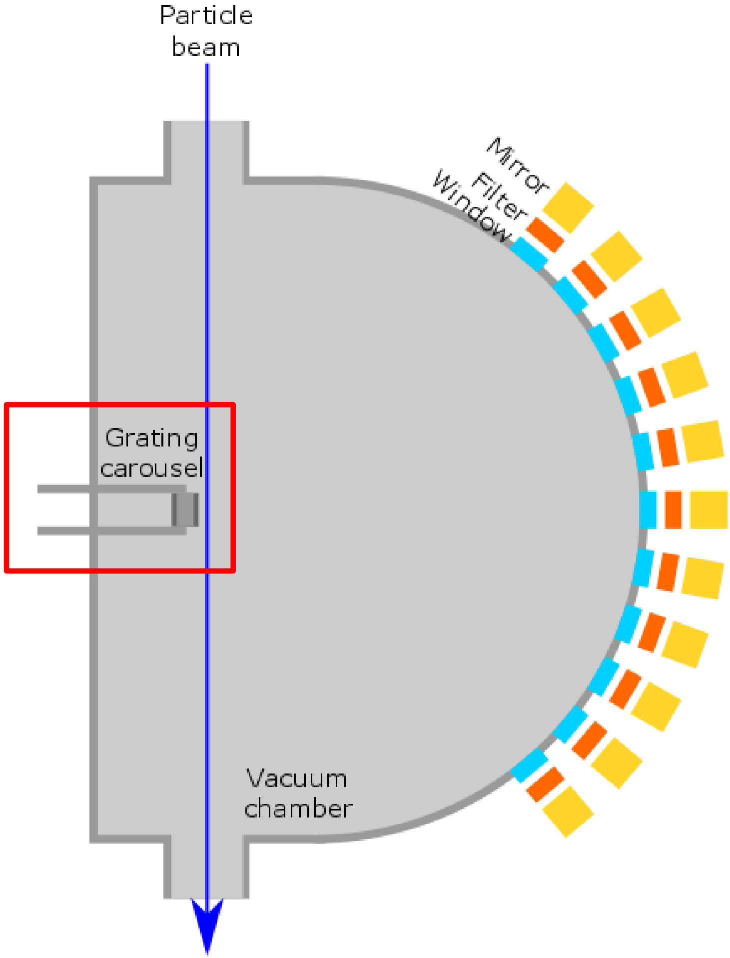


[2] H.L. Andrews et. al., "Reconstruction of the time profile of 20.35 GeV, subpicosecond long electron bunches by means of coherent Smith-Purcell radiation," Phys. Rev. ST Accel. Beams, **17**, 052802, 2014.

Schematic layout

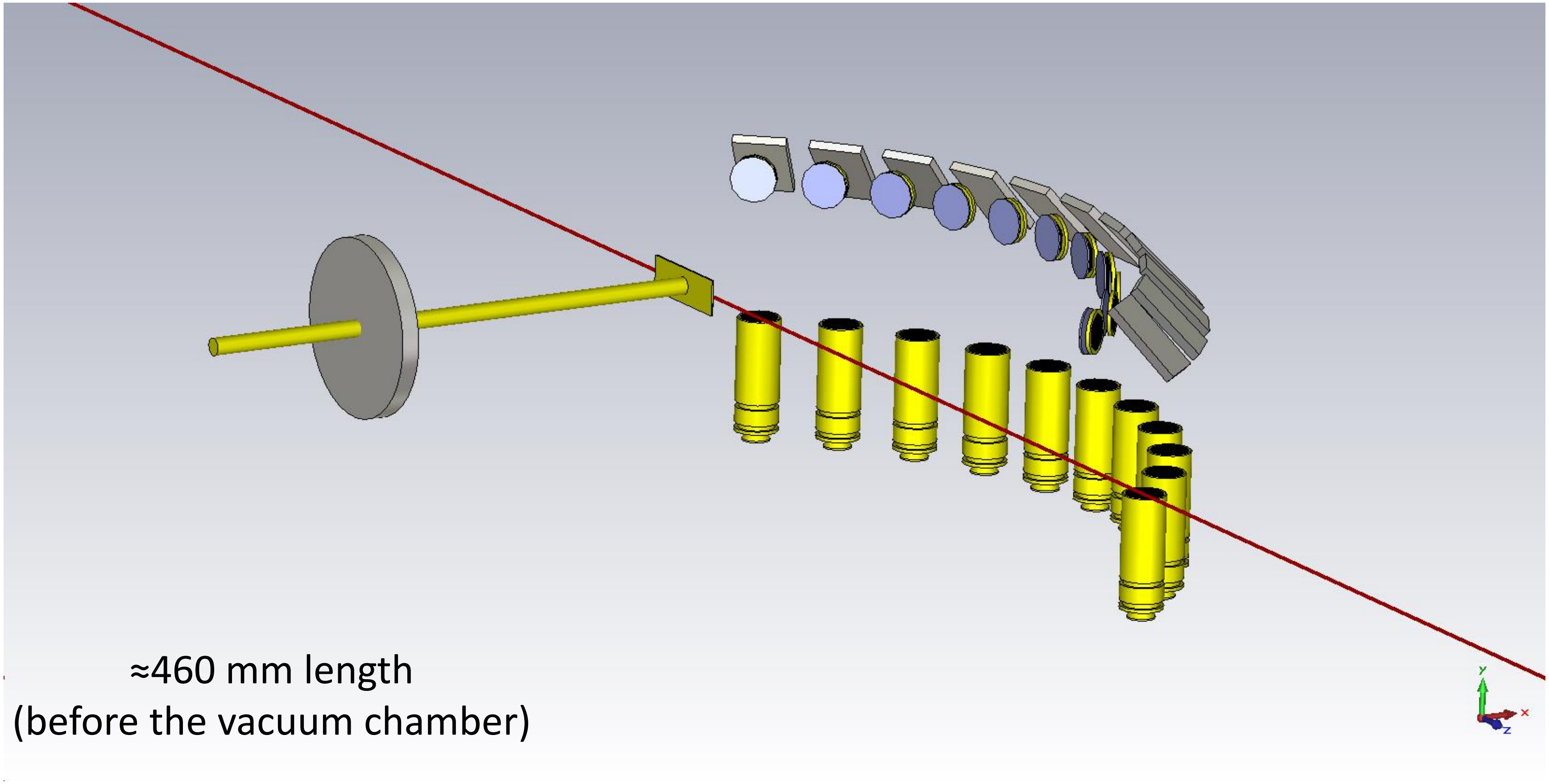


Limitations



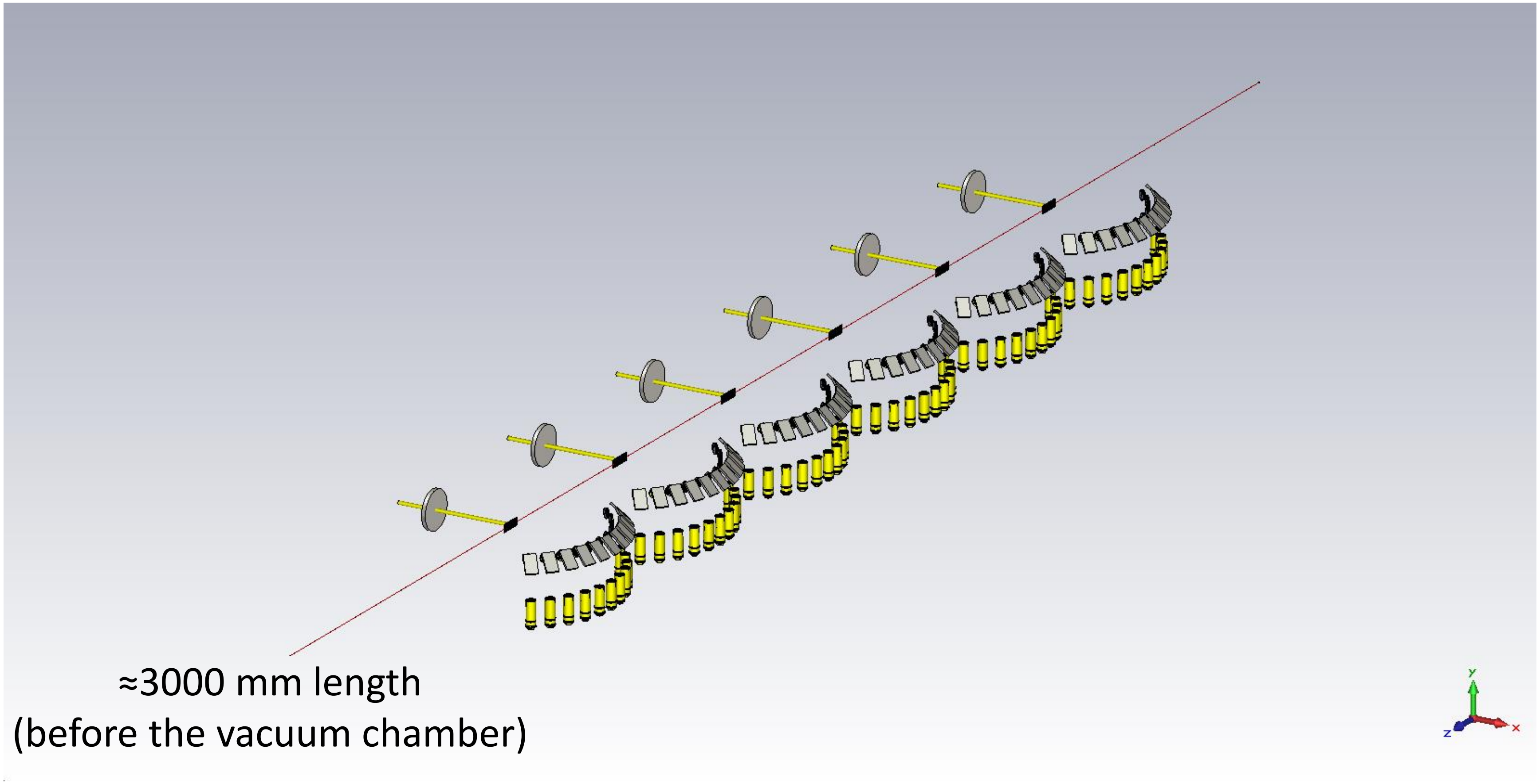
- High background, low signal.
  - Requires significant averaging.
- Requires 6 sets of measurements:
  - Three different gratings on carousel.
  - One "blank" measurement for each.
- Mechanically complex:
  - Carousel rotation.
  - Carousel translation.
  - Changing filters.
- Components must be λ-independent.
- Geometry changes required.

3D geometry



≈460 mm length
(before the vacuum chamber)

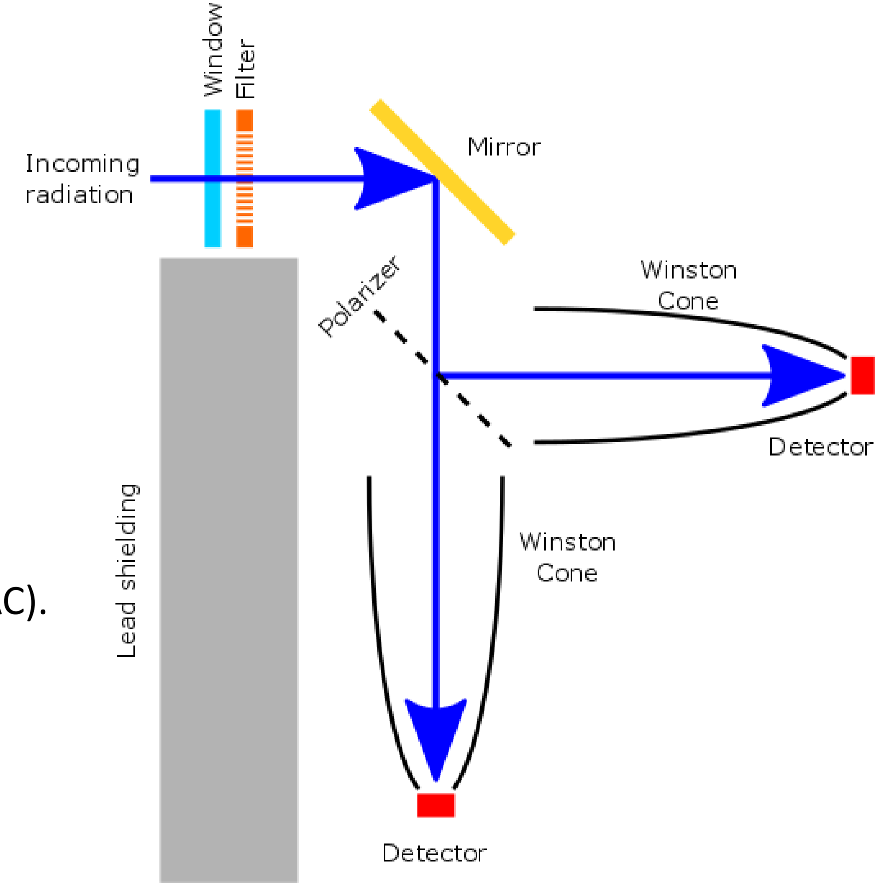
Multi-grating layout



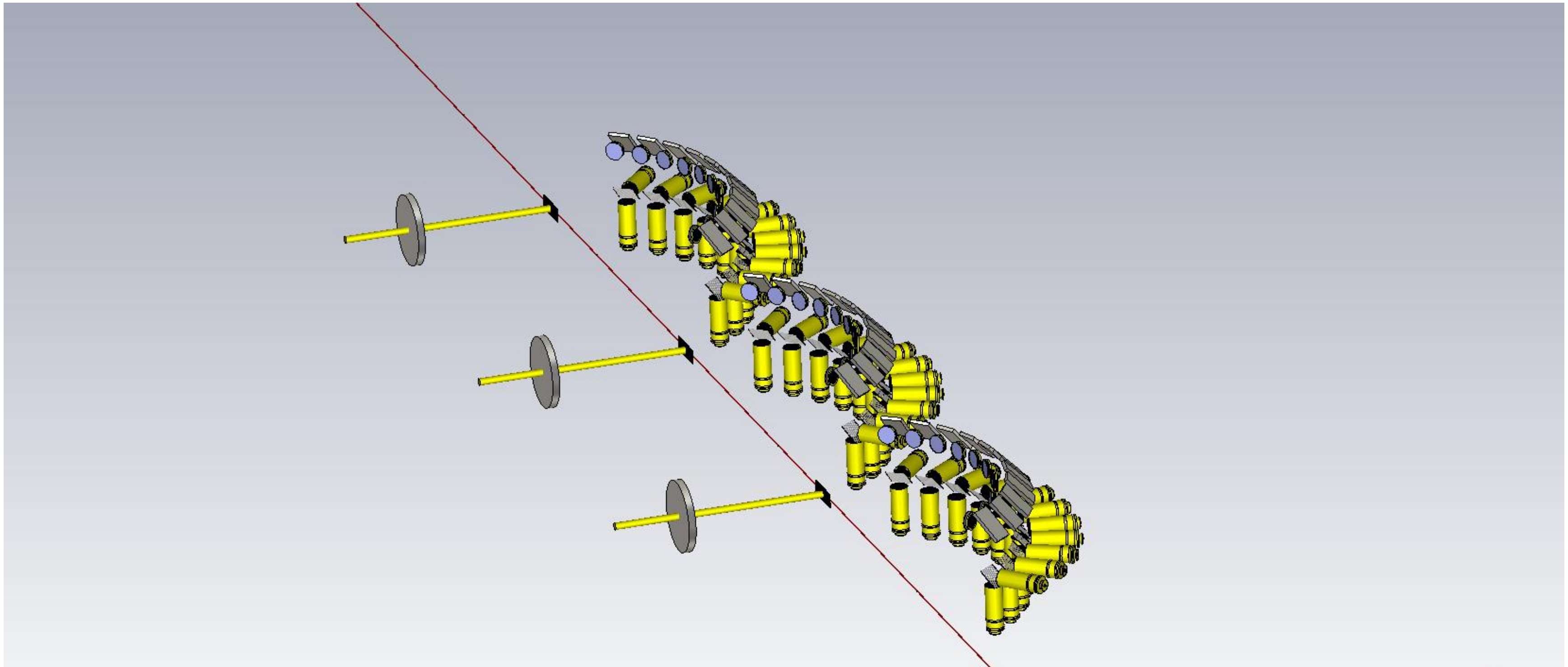
≈3000 mm length
(before the vacuum chamber)

Background signal

- Low signal-to-noise ratio expected.
  - Current system uses blank measurements.
  - Provides background estimate.
- New system would require 3 blanks.
  - Extra detection system for each.
  - Different environment to grating.
  - Increases system length.
  - Difficult for a single shot system.
- Proposed solution – polarization.
  - Preliminary results show SPR polarized (SLAC).
    - Repeat measurements at LUCX (KEK).
  - Seen in both simulation and experiment.
  - Background unpolarized (at FACET).

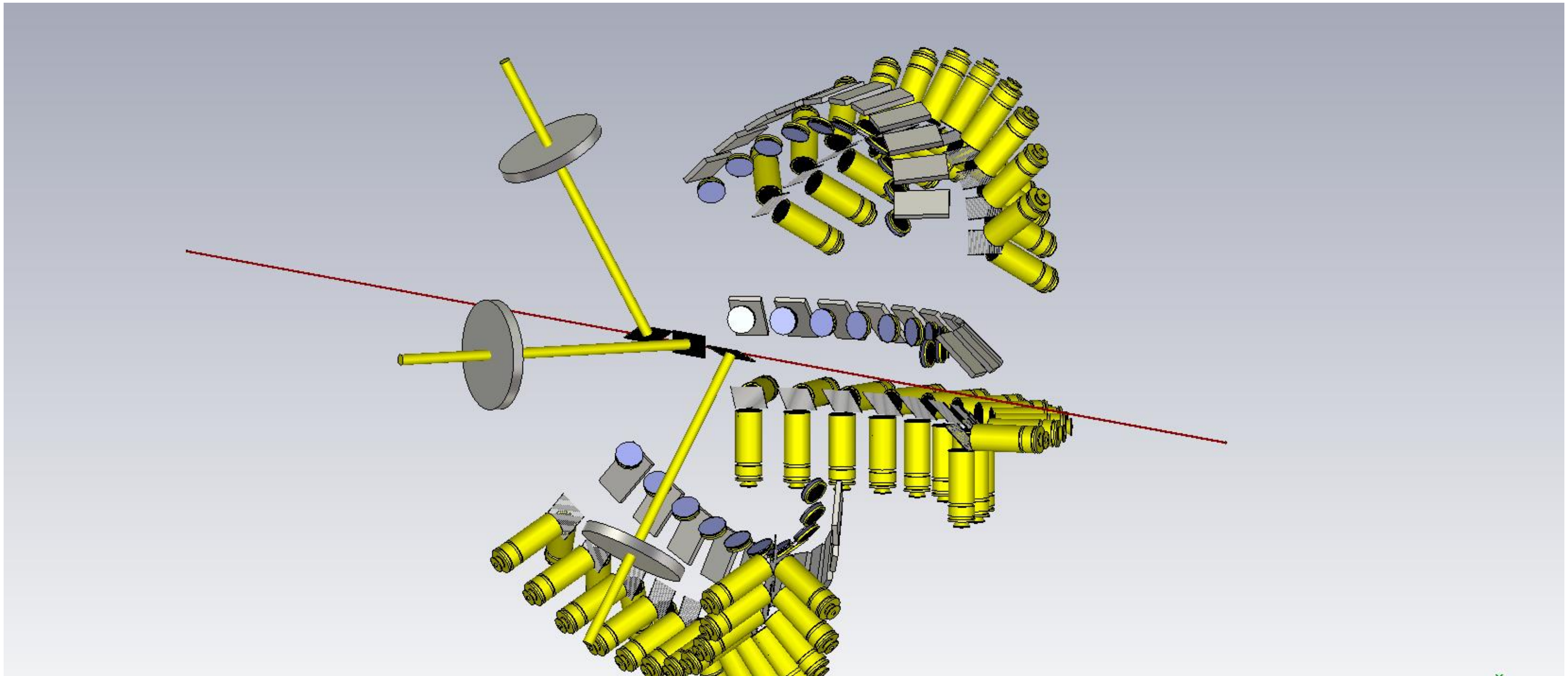


Polarization layout



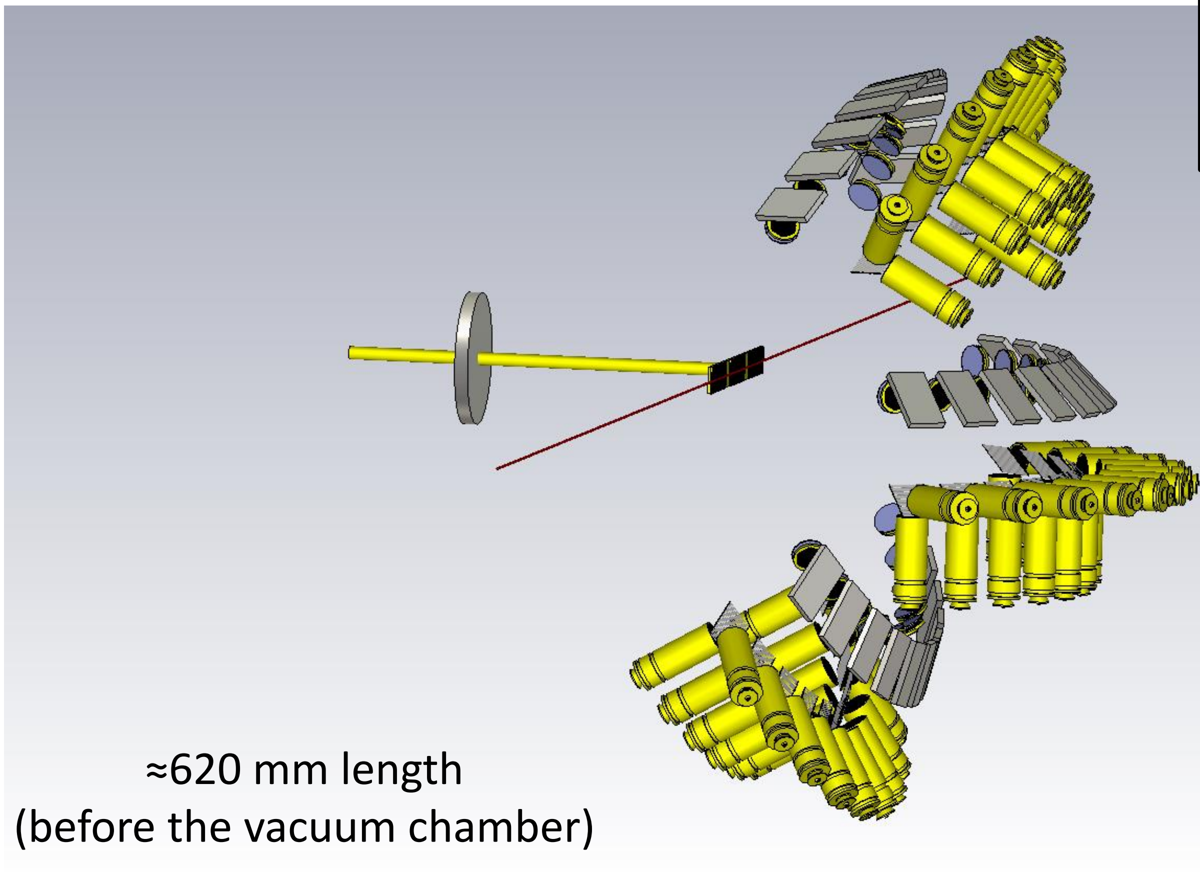
≈1750 mm length
(before the vacuum chamber)

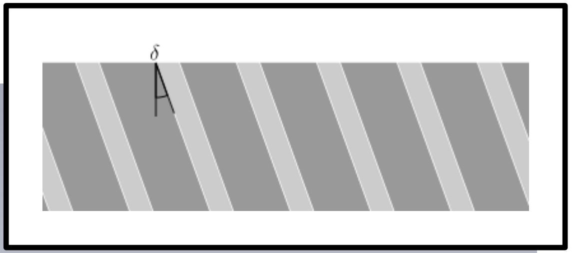
Hexagonal layout



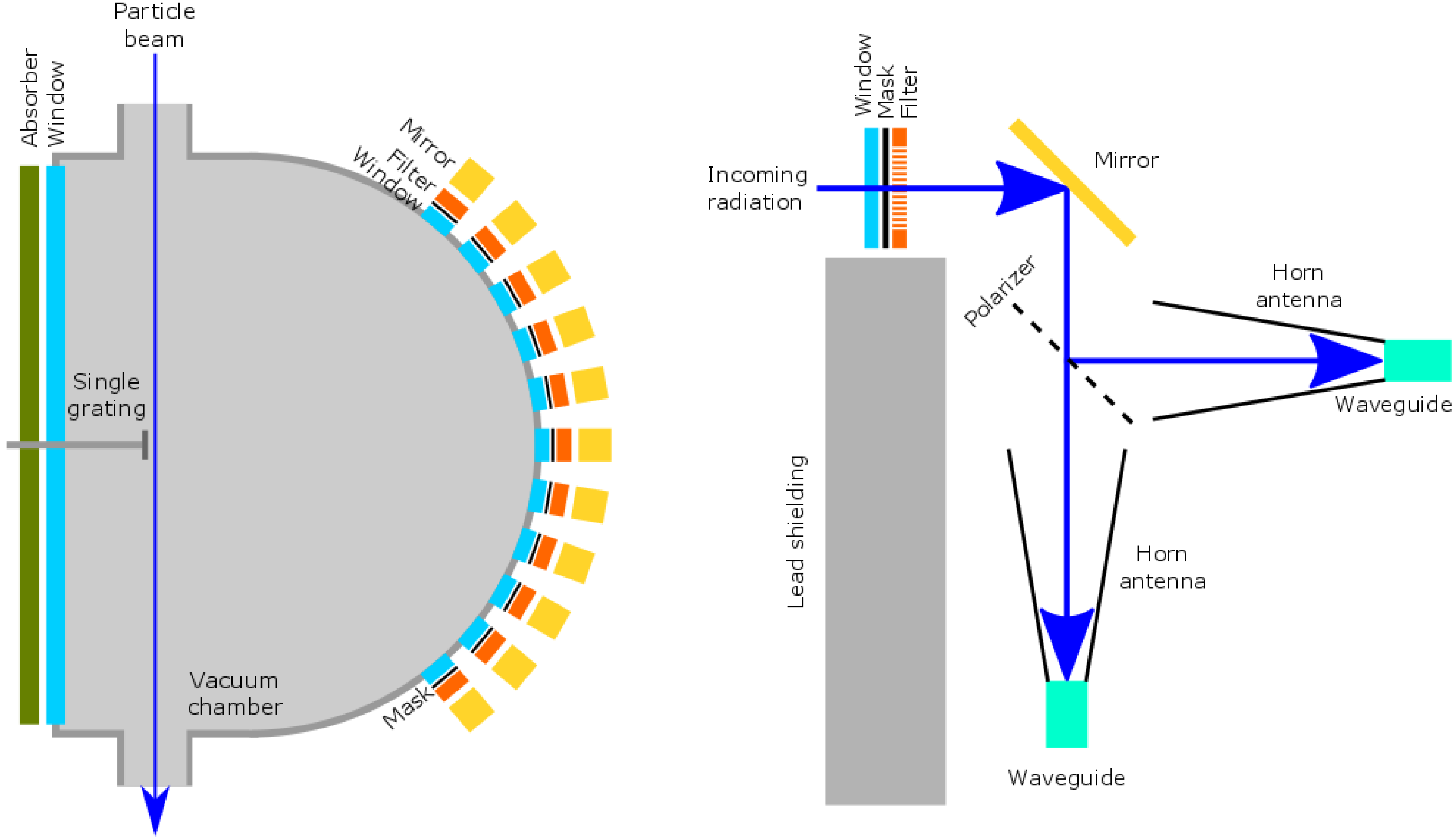
≈620 mm length
(before the vacuum chamber)

Tilted layout





"Final" geometry



Summary

- Outline of a single-shot SPR beam profile monitor.
- Revision of almost all subsystems of the current experiment.
- Aim to have a conceptual design by January 2017.

This work was supported (in parts) by the: UK Science and Technology Facilities Council (STFC UK) through grant ST/M003590/1 and The Leverhulme Trust through the International Network Grant (IN – 2015 – 012). F. Bakkali Taheri would like to thank STFC UK and H. Harrison to thank STFC UK and JAI University of Oxford for supporting their DPhil projects.

3D diagrams produced using CST Studio Suite 2015.

Any questions?

Backup slides

Continuous FSI

$$L_{i,M} = \frac{1}{\nu_{i,1}}\left(\frac{c}{2\pi}\Delta\phi_{i,1} + \nu_{t,1}L_{t,M}\right)$$

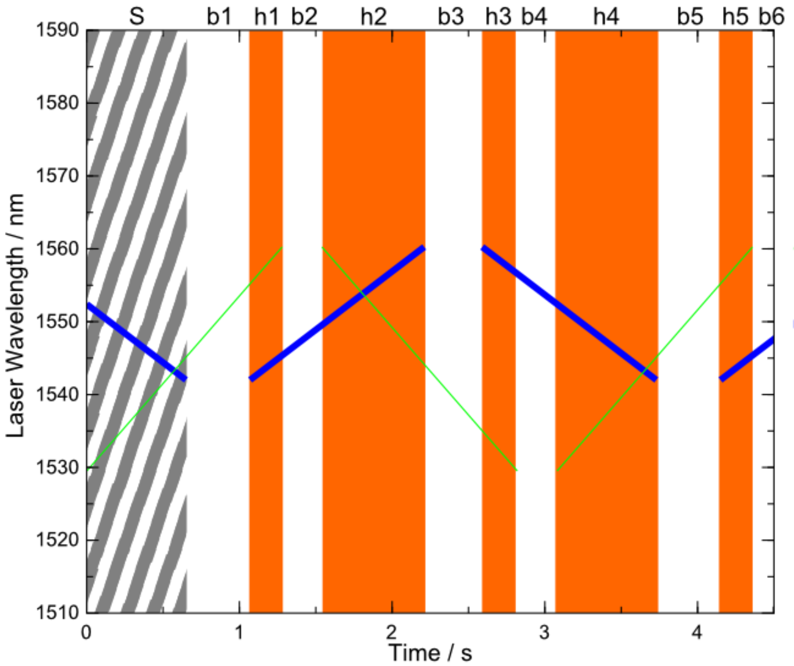
$$L_{i,M} = \frac{1}{\nu_{i,2}}\left(\frac{c}{2\pi}\Delta\phi_{i,2} + \nu_{t,2}L_{t,M}\right)$$

$$L_{t,M} = \frac{\frac{\nu_{i,1}}{\nu_{i,2}}\Delta\phi_{i,2} - \Delta\phi_{i,1}}{\frac{2\pi}{c}\left(\nu_{t,1} - \frac{\nu_{i,1}}{\nu_{i,2}}\nu_{t,2}\right)}$$

$$\nu_{i,1} = \left(\left(\frac{c}{2\pi L_R}\right)(\phi_{i,1,R} - \phi_{p,1,R})\right) + \nu_{p,1}$$

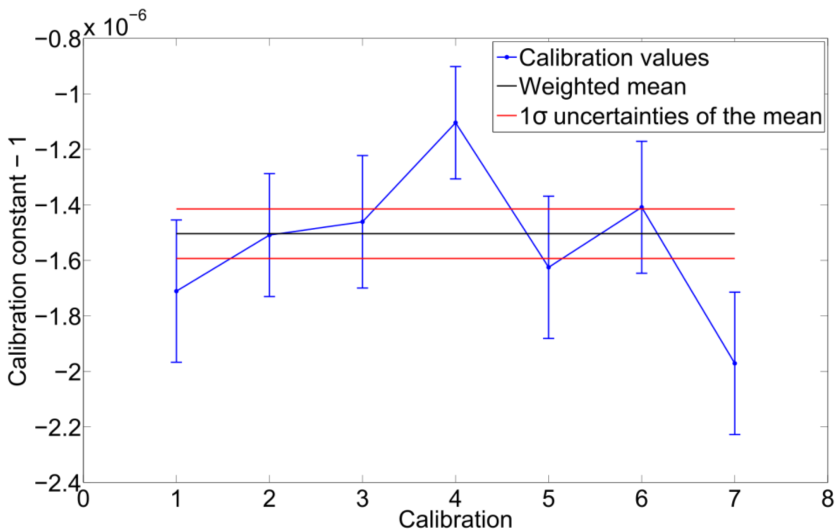
$$\nu_{i,2} = \left(\left(\frac{c}{2\pi L_R}\right)(\phi_{i,2,R} - \phi_{q,2,R})\right) + \nu_{q,2}$$

- After setup only one laser required.
- Shift the scanning pattern.
- No time with no laser present.
- Handover after a laser restarts.
- No measurement interruptions.
- Same time resolution as dynamic FSI.

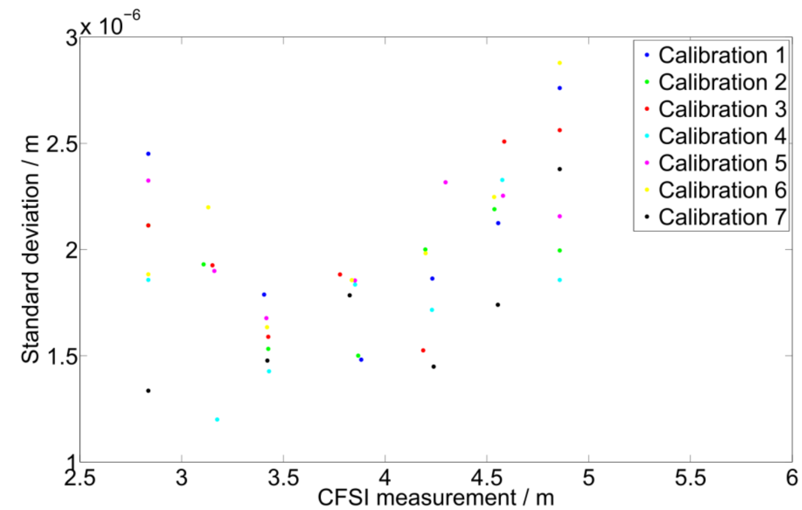


Continuous FSI

Absolute Calibration

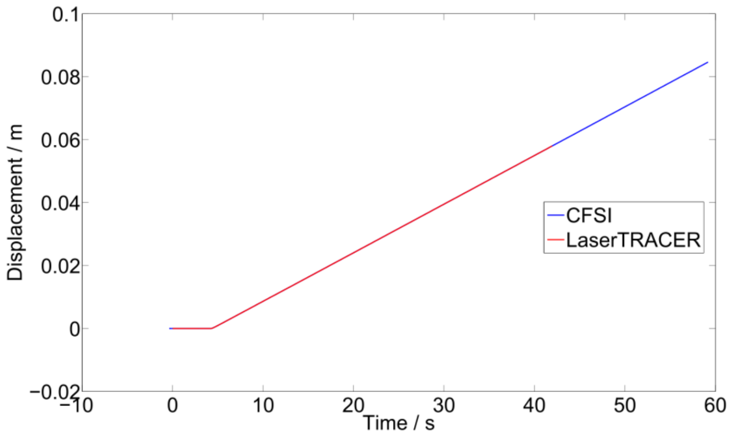


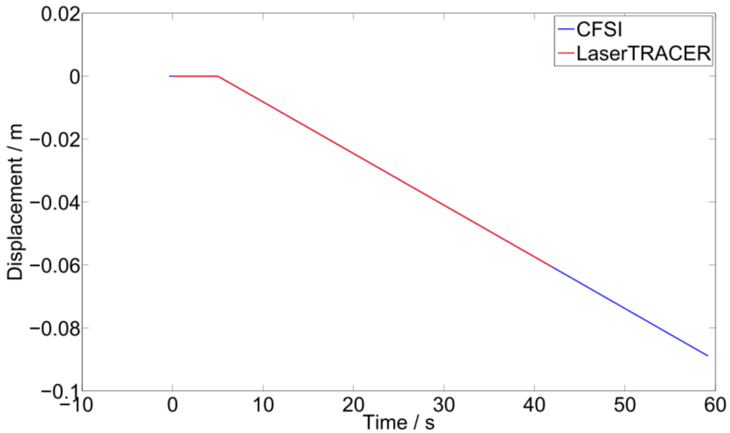
Measurement consistency

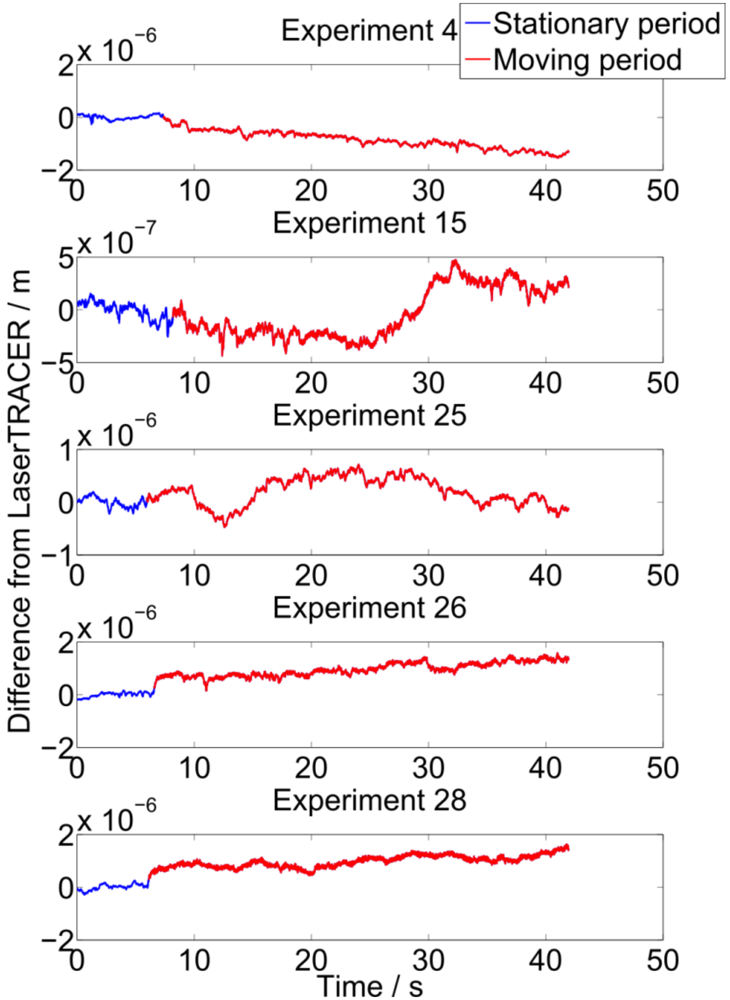


Continuous FSI

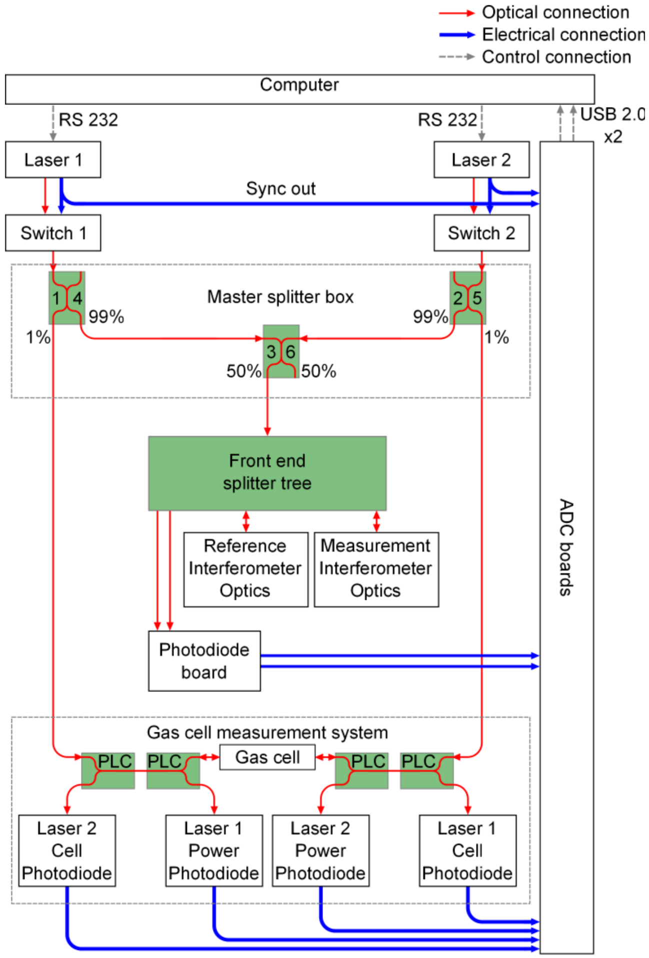
Motion experiments



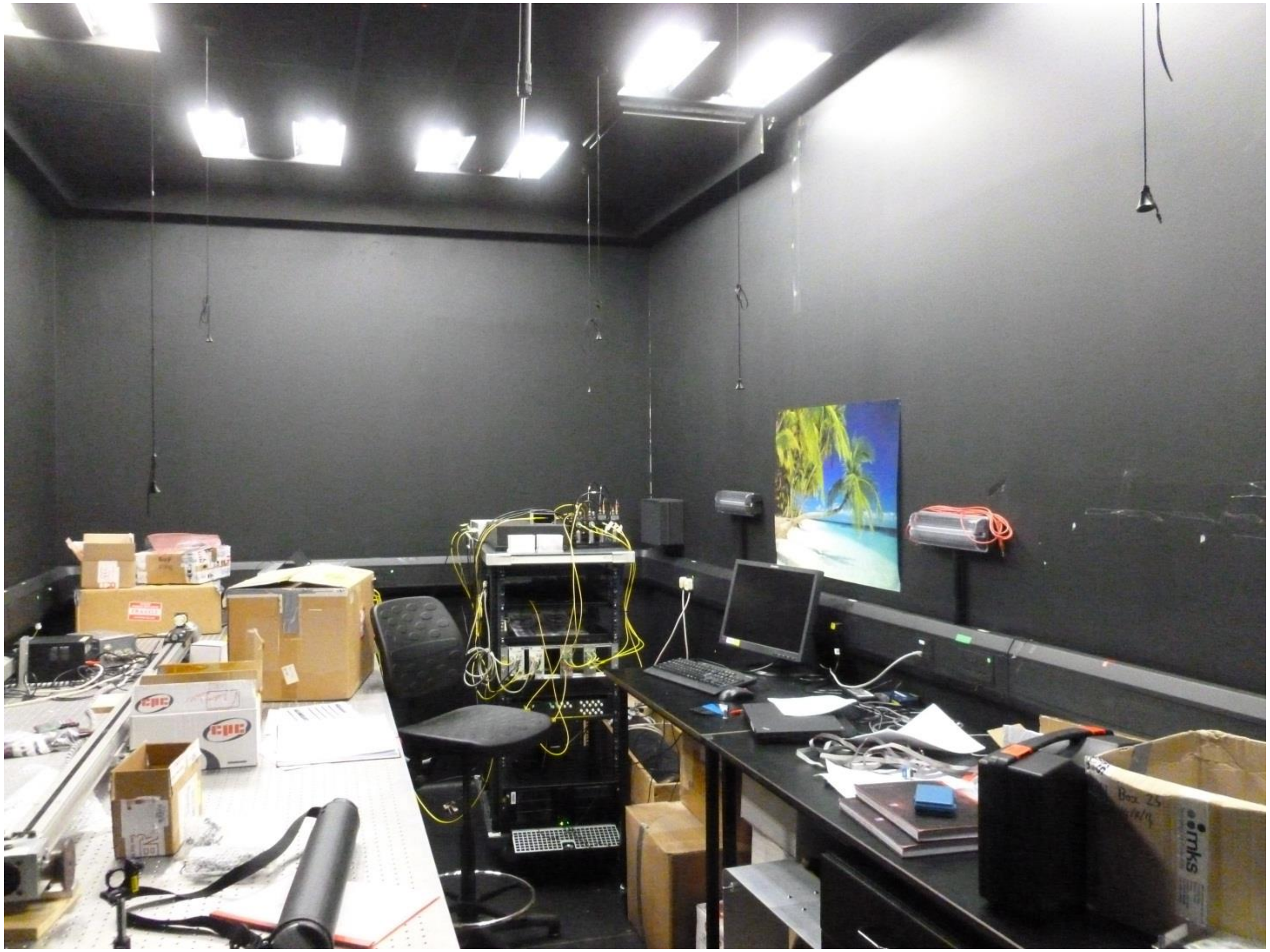




Continuous FSI

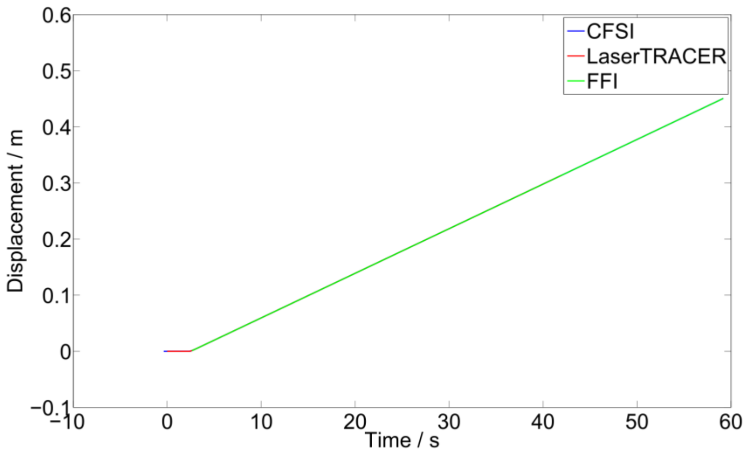


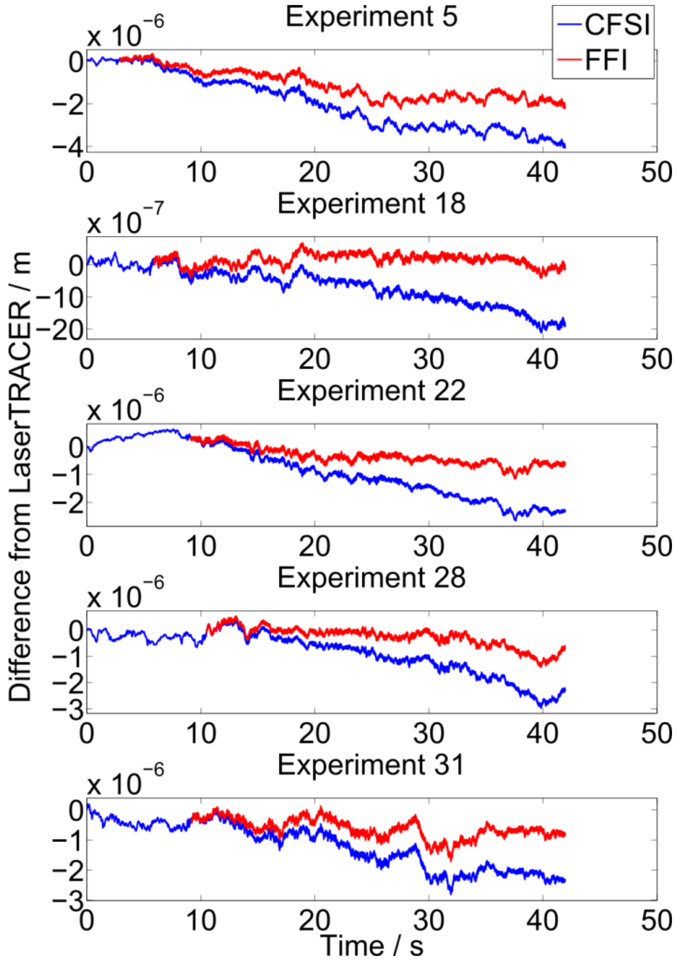
Continuous FSI



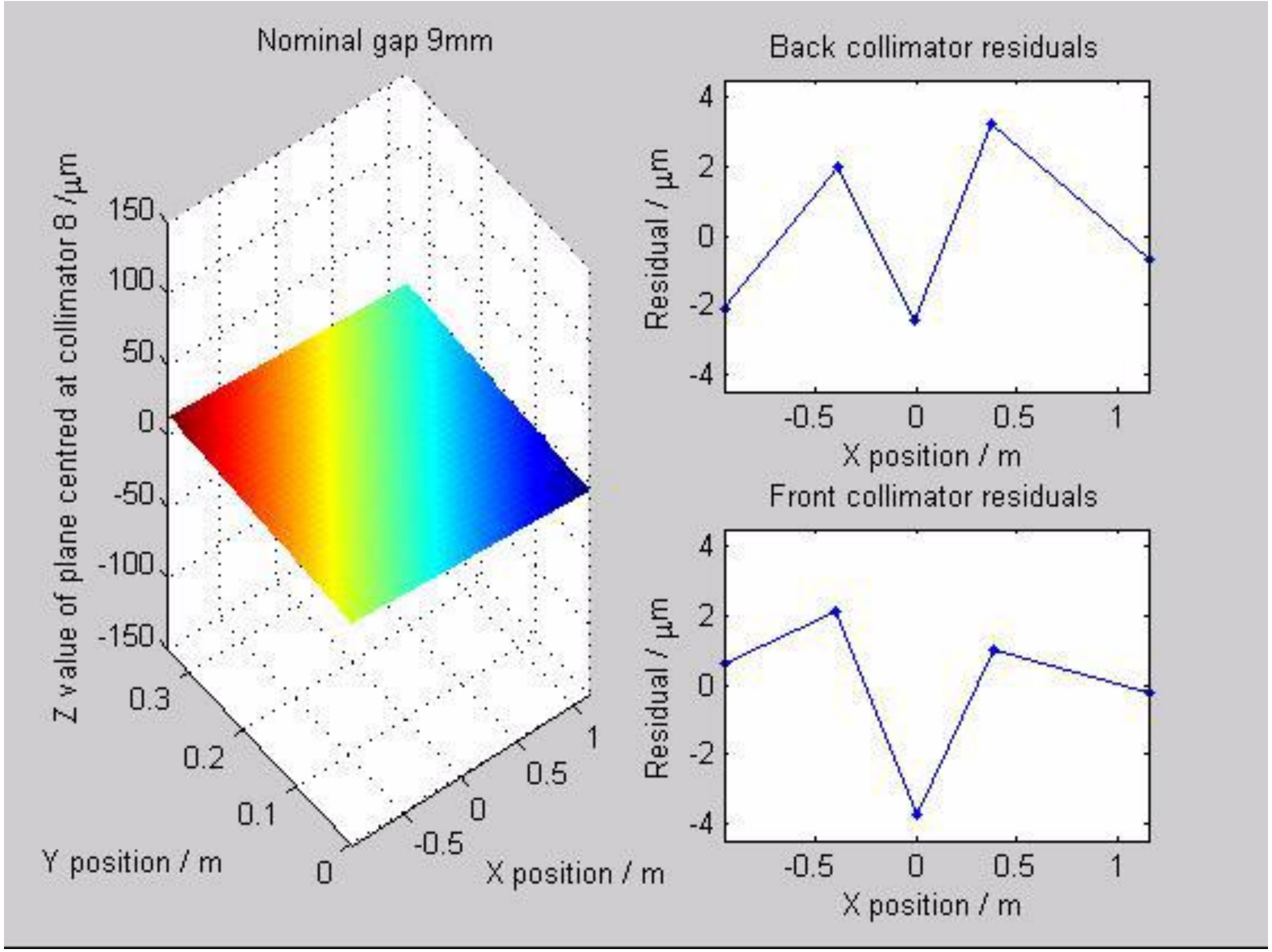
Enhanced CFSI

Motion experiments



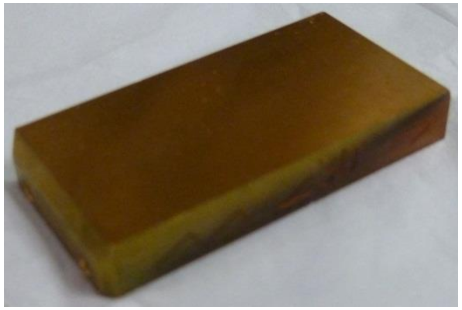


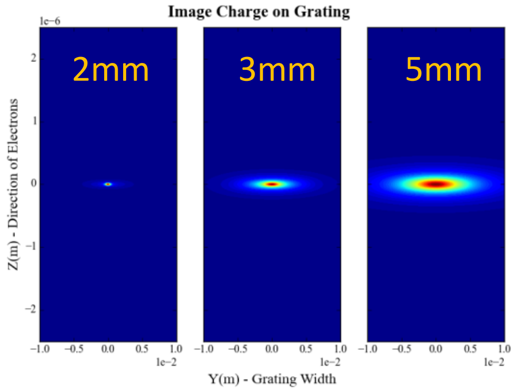
Magnet tilt

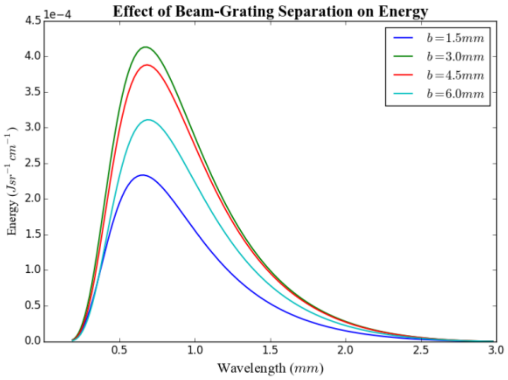

Nominal gap 9mm
Z value of plane centred at collimator 8 /µm
150
100
50
0
-50
-100
-150
0.3
0.2
0.1
0
Y position / m
-0.5
0
0.5
1
X position / m
Back collimator residuals
Residual / µm
4
2
0
-2
-4
-0.5
0
0.5
1
X position / m
Front collimator residuals
Residual / µm
4
2
0
-2
-4
-0.5
0
0.5
1
X position / m

Grating development

- How many gratings do we need?
- Grating size?
- Grating shape?
- Distance from the beam?
- How good is our surface-current model?

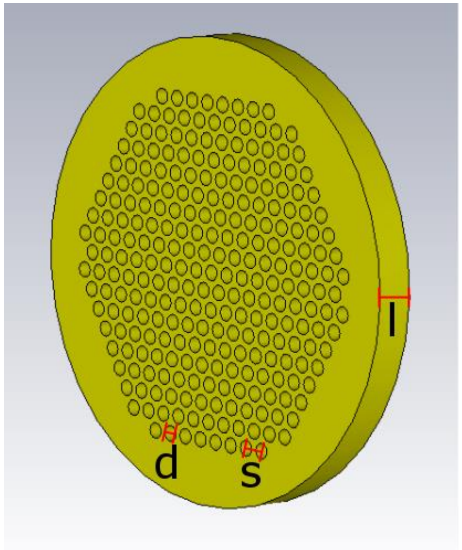


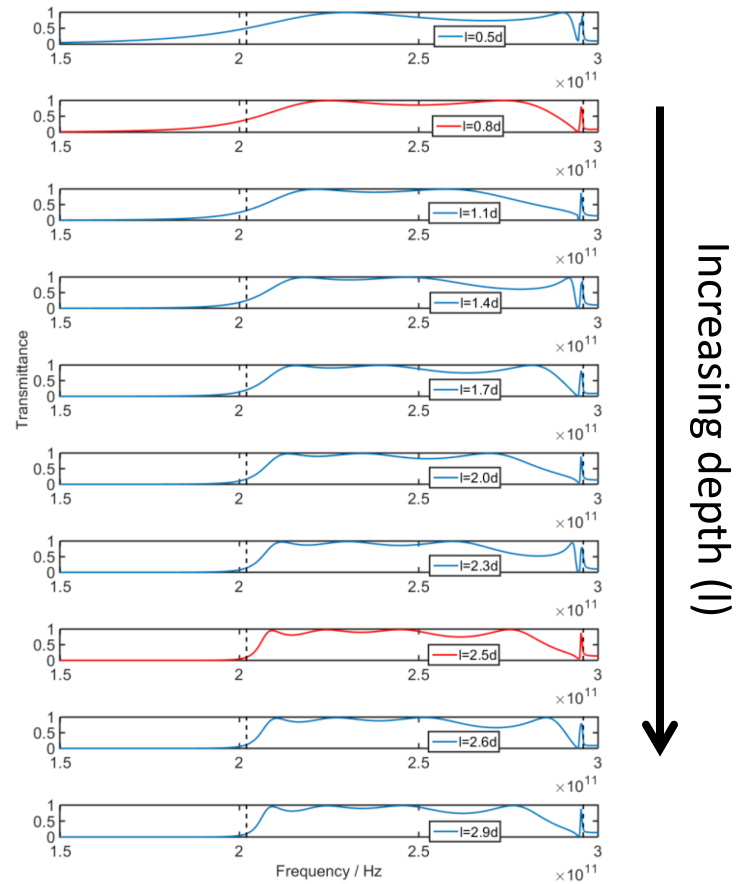




Simulation work by H. Harrison

Filters

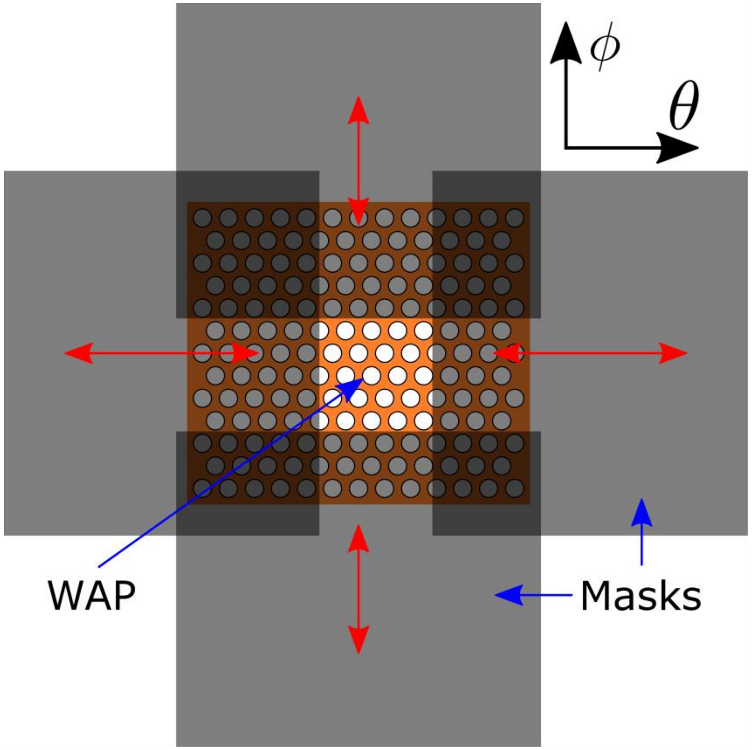




- Use waveguide array plate filters (WAPs).
  - Well understood (e.g. Winnewisser [3]).
  - Predictable geometry defined pass-band limits.
  - Polarization independent.
- Simulations in CST Microwave studio
  - Angular dependence.
  - Depth studies etc.
- Not expecting to change filter style.

[3] C. Winnewisser, F. Lewen and H. Helm, “Transmission characteristics of dichroic filters measured by THz time-domain spectroscopy,” Appl. Phys. A, **66**, 593-598, 1998.

Proposed update



- Larger filters.
- Square layout.
- Add adjustable masks.
  - Similar slit used at SLAC.
- Two main benefits:
  - Selection of angular acceptance.
  - Allows study of SPR distribution.
- Adds mechanical complexity.
- "Wish list" feature.
  - Nice but not essential.

Winston cones

- Non-imaging concentrators [4].
- Wavelength independent.
  - Important for multi-grating system.
  - Not necessary for single-shot layout.
- Looking at horn antennae.
  - Waveguide coupled collection.
- Two benefits:
  - Transmission away from accelerator.
  - Possibility of additional filtering.

[4] A. Rabl and R. Winston, "Ideal concentrators for finite sources and restricted exit angles," Appl. Opt. **15**, 2880-2883, 1976.