Design of the RUEDI ultrafast electron diffraction beamline at Daresbury Laboratory

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FUSE Workshop

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Summary

- What is RUEDI?
- What do we want from a UED facility?
- UED beamline options
- The RUEDI diffraction beamline
  - Electron source
  - Magnetic compressor
  - Diffraction optics
- Conclusions

The RUEDI (Relativistic Ultrafast Electron Diffraction & Imaging) Project

- A future UK National User Facility for time-resolved UED & UEM pump-probe experiments.
- Full project approval announced £124.4 million from ~2026 subject to full business case approval
- The facility will be located at Daresbury Laboratory in the North West of England.

UKRI project through EPSRC

UK Research and Innovation

Engineering and Physical Sciences Research Council

Main partners:

Science Case: University of Liverpool

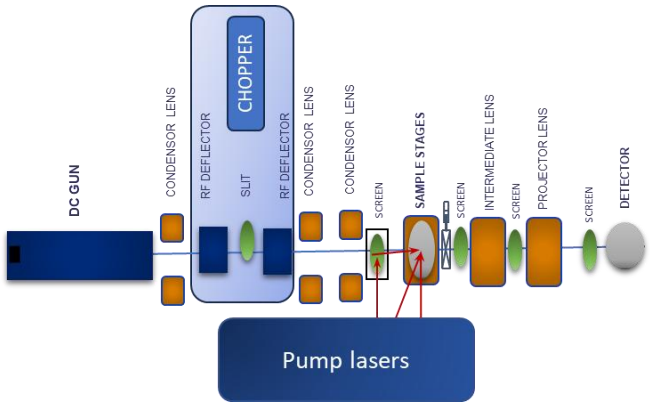
Imaging line: The Rosalind Franklin Institute

Diffraction line: Science and Technology Facilities Council, Daresbury Laboratory

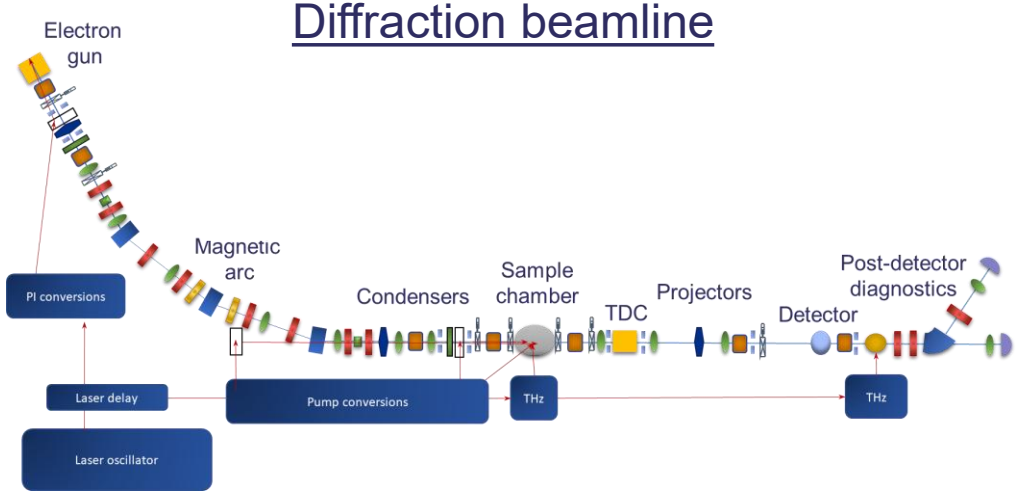
- 2020 - Funding bid
- 2022 - Design stage
- 2025 - Business Case
- 2026 - Construction
- 2032 - User facility

The RUEDI (Relativistic Ultrafast Electron Diffraction & Imaging) Project

Imaging beamline



Diffraction beamline



- RUEDI has two beamlines:
  - UEM - Ultrafast electron microscopy
  - **UED - Ultrafast electron diffraction**

What do we want from a UED facility?

Coherence length

$$L_c = \frac{\lambda}{2\pi\sigma_{x'}} = \frac{\lambda\sigma_x}{2\pi\varepsilon} \approx \frac{1}{\Delta Q}$$

Related to Q resolution

Temporal resolution

$$\Delta t = \sqrt{\Delta t^2_{Bunch\ length} + \Delta t^2_{jitter} + \Delta t^2_{Laser\ pulse\ length} + \Delta t^2_{velocity\ mismatch}}$$

The RUEDI diffraction line's design focus is < 10 fs temporal resolution

- 1 kHz repetition rate
- Flexible focusing onto the sample
- Single shot and stroboscopic modes
- Wide range of sample environments & pumps
- Low dark current
- Ease of operations and set up

Target beam parameters at sample	
Bunch charge	1.6 – 160 fC
FW beam size	30 – 400 um
Emittance	2 – 40 nm rad
Bunch length	< 10 – 100s fs
Time of arrival jitter	< 10 fs

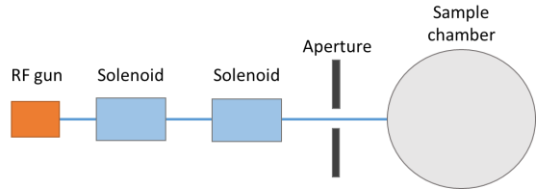
UED beamline options

- We looked at several different designs:
  - Just an electron gun
  - RF buncher – uses velocity differences to compress
  - Many magnetic compressors – use path length differences to compress
- Other options not considered
  - e.g. THz compression.

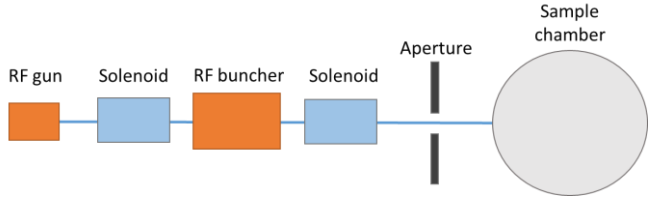
	Just gun	RF buncher	Magnetic
Coherence length	High	Medium	Medium-low
Bunch length	Long	Short	Short
Timing jitter	Medium	High	Low
Complexity	Low	Medium	High

- Timing resolution was our design priority so we selected a magnetic compressor.

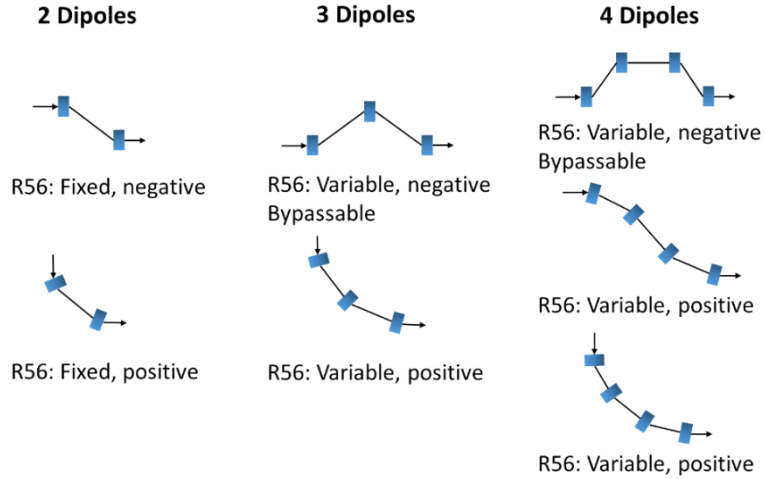
No compression – just an electron gun



RF buncher



Magnetic compressor topologies



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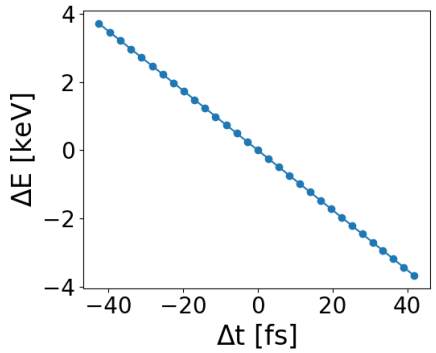
Jitter suppression

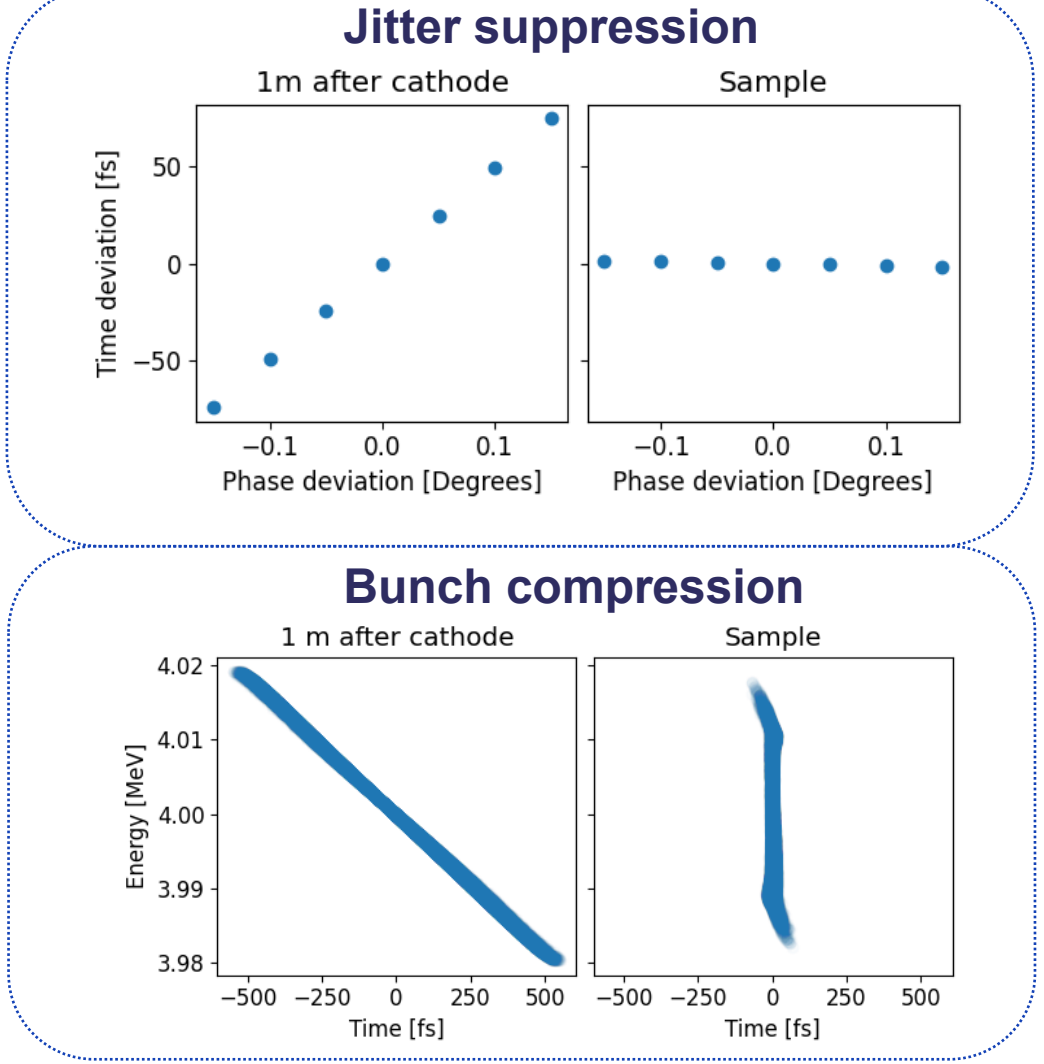
- Gun jitters have a correlated $\frac{\Delta E}{\Delta t}$



- Set magnetic R56 to the opposite of the gun jitter $\frac{\Delta E}{\Delta t}$ to cancel it

$$\Delta t = R_{56}\Delta E$$

- Set electron beam chirp *(using space charge)* to enable simultaneous compression and jitter cancellation
- Experimentally proven

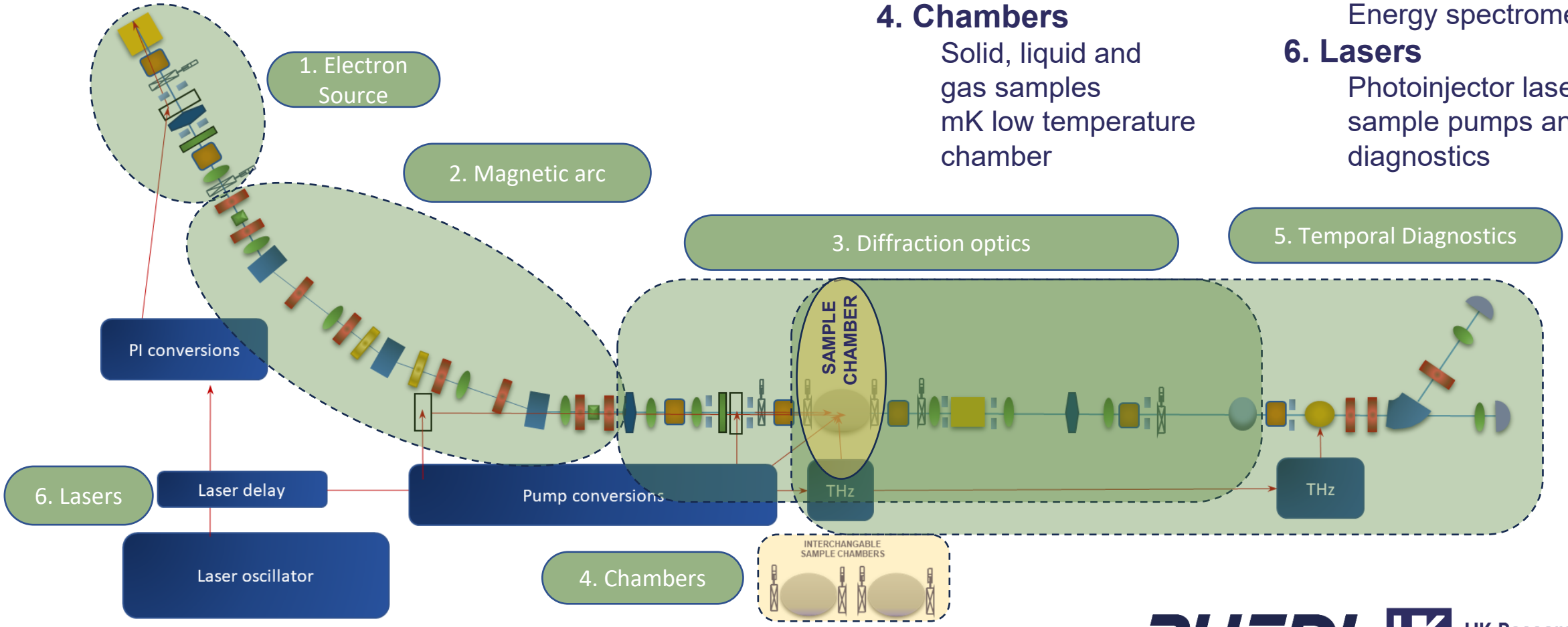


H.W. Kim et al, "Towards jitter-free ultrafast electron diffraction technology", Nature Photonics, Vol. 14, Pages 245–249, 2020.

Qi, Fengfeng, et al. "Breaking 50 femtosecond resolution barrier in MeV ultrafast electron diffraction with a double bend achromat compressor." Physical review letters 124.13 (2020): 134803.

RUEDI diffraction line layout

1. **Electron source**
   S-band RF photoinjector
   Creates high brightness, short pulse beams
2. **Magnetic arc**
   Simultaneously compresses bunch length and reduces jitter for overall time resolution <**10fs**
3. **Diffraction optics**
   Variable magnification + camera length
   Direct electron detector
4. **Chambers**
   Solid, liquid and gas samples
   mK low temperature chamber
5. **Temporal diagnostics**
   Time of arrival
   RF and THz streaking for bunch length
   Energy spectrometer
6. **Lasers**
   Photoinjector laser, sample pumps and THz diagnostics



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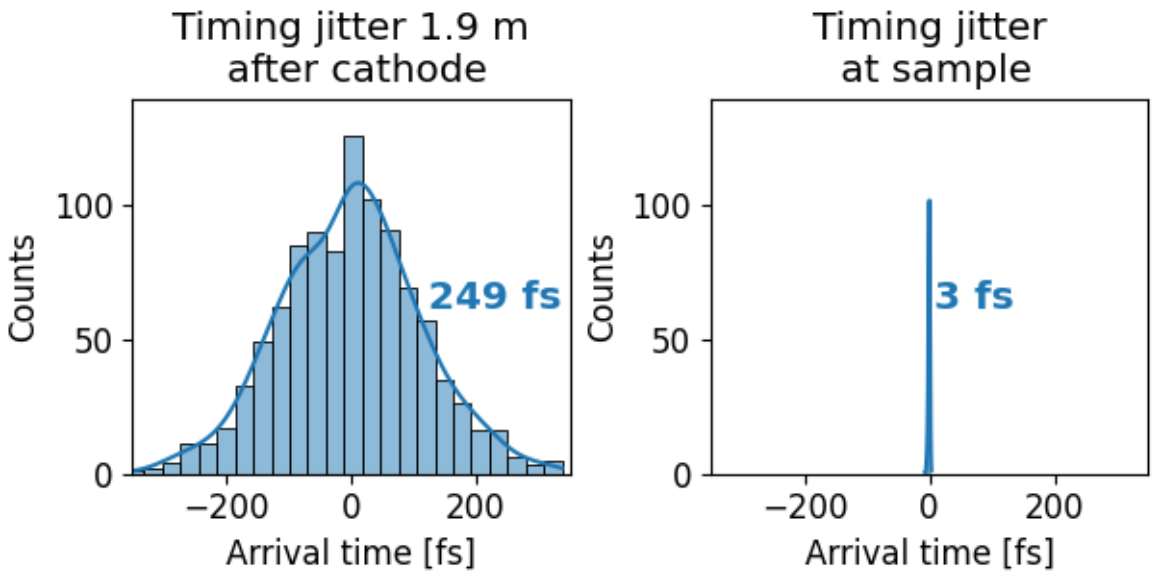
Some general design details

- The machine operates at 4 MeV.
- A magnetic arc is used for simultaneous bunch compression and jitter suppression.
- The arc is kept as constant a possible during operations and the mode adjusted downstream.
- A large charge (400 fC) is emitted from the gun in all modes then collimated to 1.6-160 fC later.
  - Have enough charge for BAM (Beam Arrival Monitor) signals.



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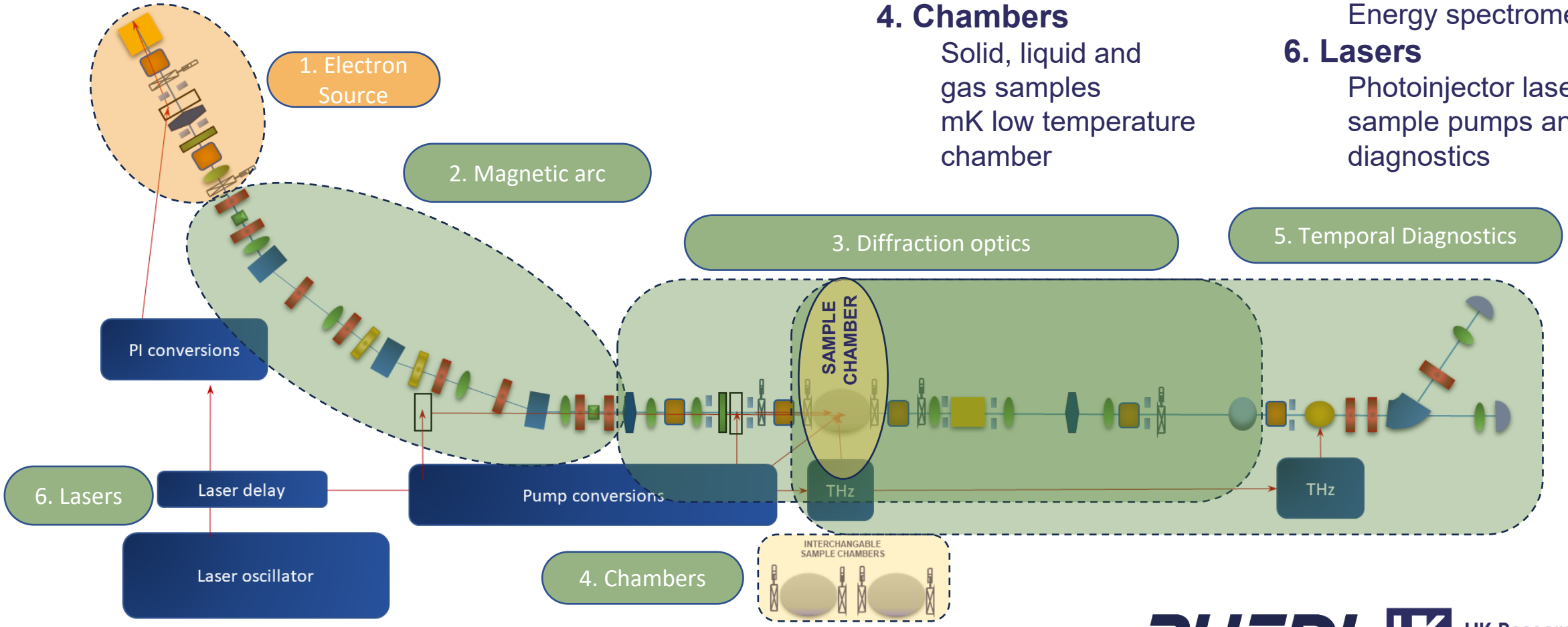

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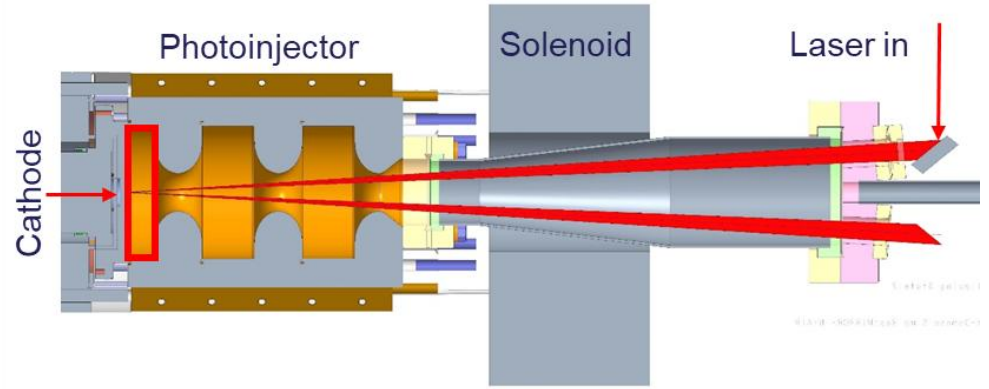
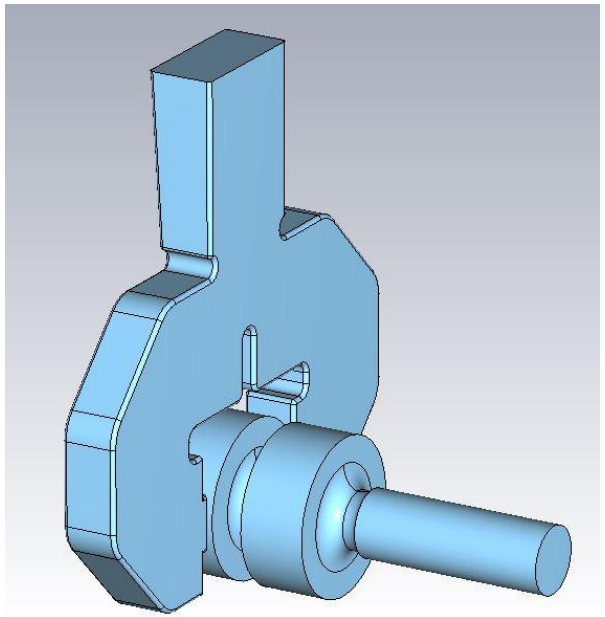
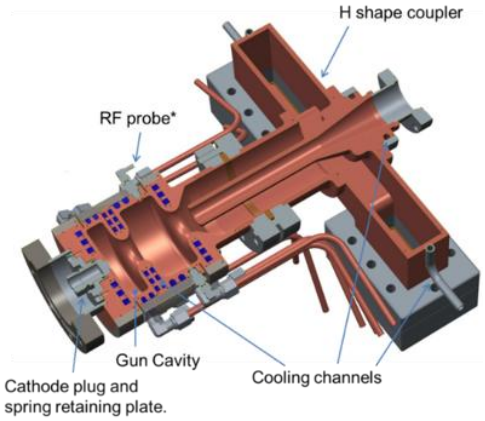
Electron gun overview

- Normal conducting S-band RF gun
- Designed to be paired with a magnetic compressor.
- 1 kHz repetition rate
- 2.X cells
  - Lower fields therefore:
    - Less heating
    - Less dark current
- Cooling similar to CLARA 400 Hz gun
- Copper cathode – backwall of electron gun
- Side coupled RF
- Photoinjector laser
  - Front laser injection with out of vacuum final mirror
  - Blow-out regime – short: ~60 fs pulse duration





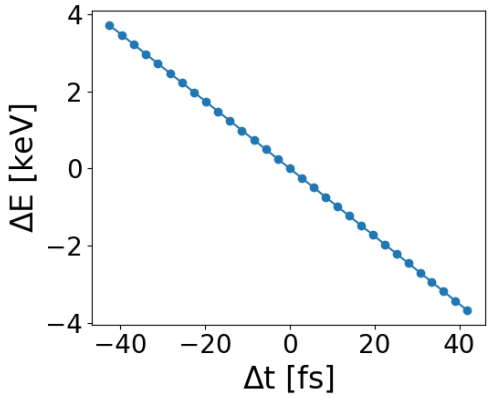
CLARA gun 400 image with cooling channels

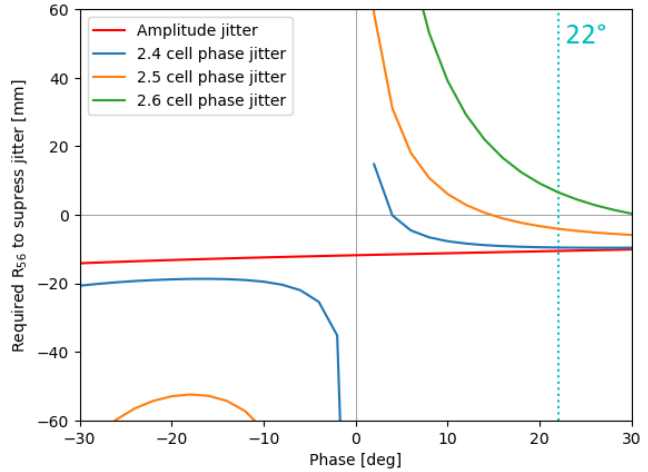


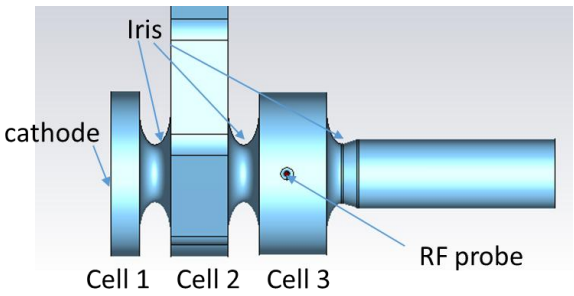
Optimising the gun for jitter suppression

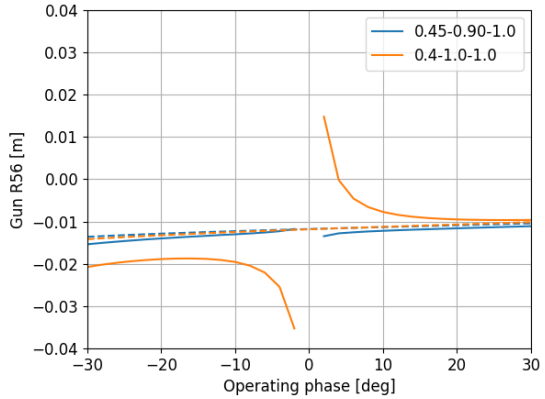
$$\Delta t = R_{56}\Delta E$$

- Phase & amplitude jitters need different R56 to suppress.
- Depends on:
  - Exit beam energy
  - Gun phase
  - Gun geometry
- Optimise to make phase and amplitude jitter suppression conditions as close as possible.
- Chosen cell lengths: **0.45-0.9-1.0**



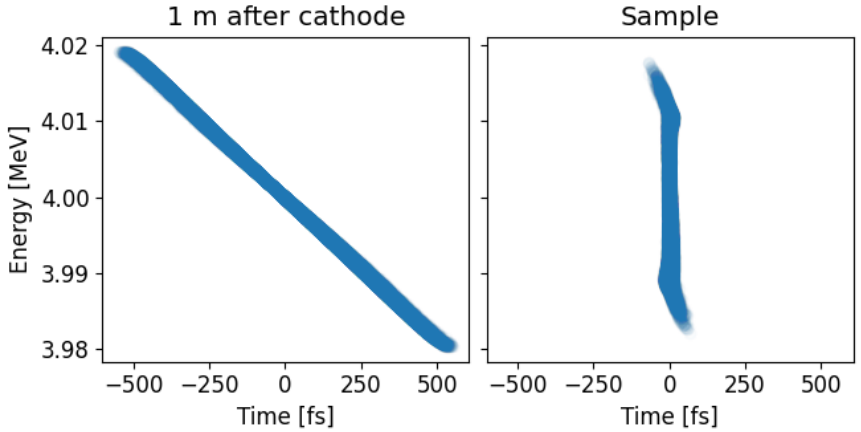


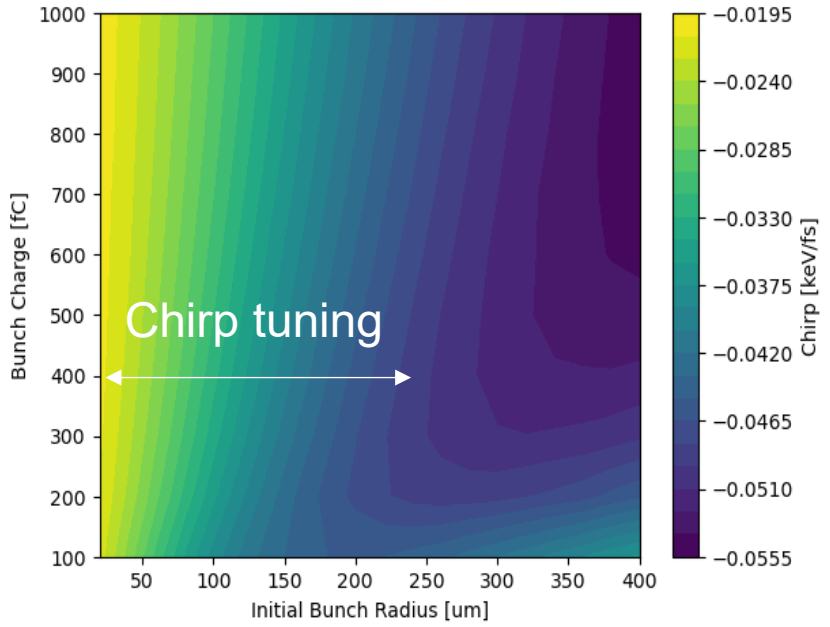




Laser parameters

- Operate in the blowout regime
  - ~60 fs FWHM laser
- Very linear longitudinal phase spaces = very short bunches at the sample
- Chirp depends strongly on laser spot size at the cathode.
  - Use laser spot size as longitudinal focus tuning knob
- Trade-off: Relatively large transverse laser spots (few hundred um) on the cathodes leads to worse transverse emittance.





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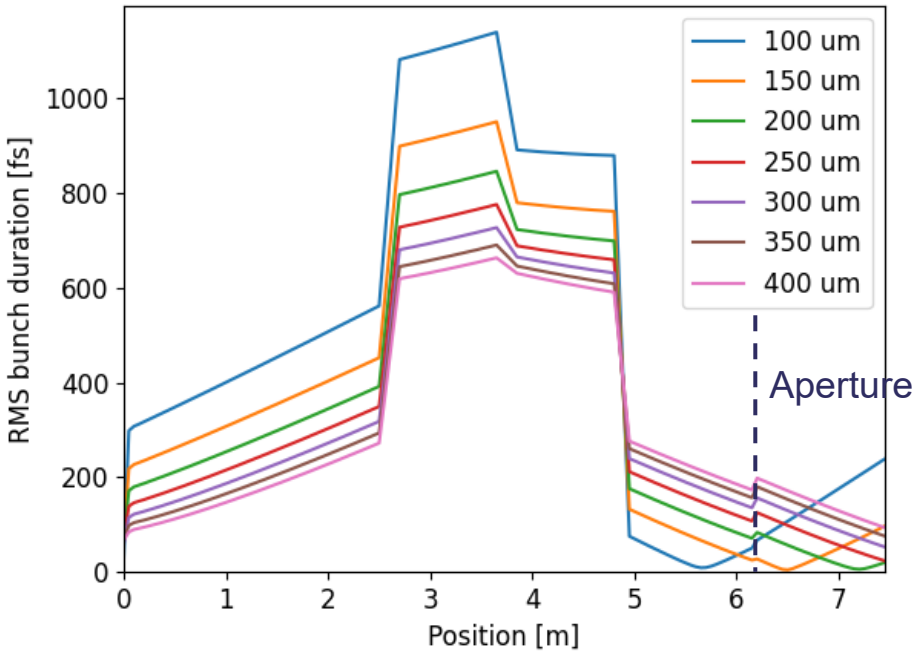
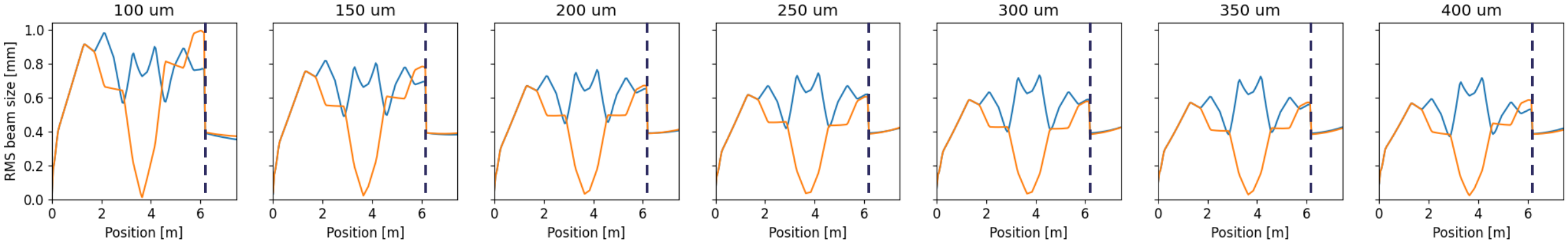
Tuning bunch length

- For photoinjectors in the blowout regime the chirp depends strongly on the laser spot size
- This means that we can use the laser spot size to tune the compression
- Change bunch length & hence temporal resolution at the sample by moving the longitudinal focus
- Transverse optics well preserved

Note: Plots up to sample position





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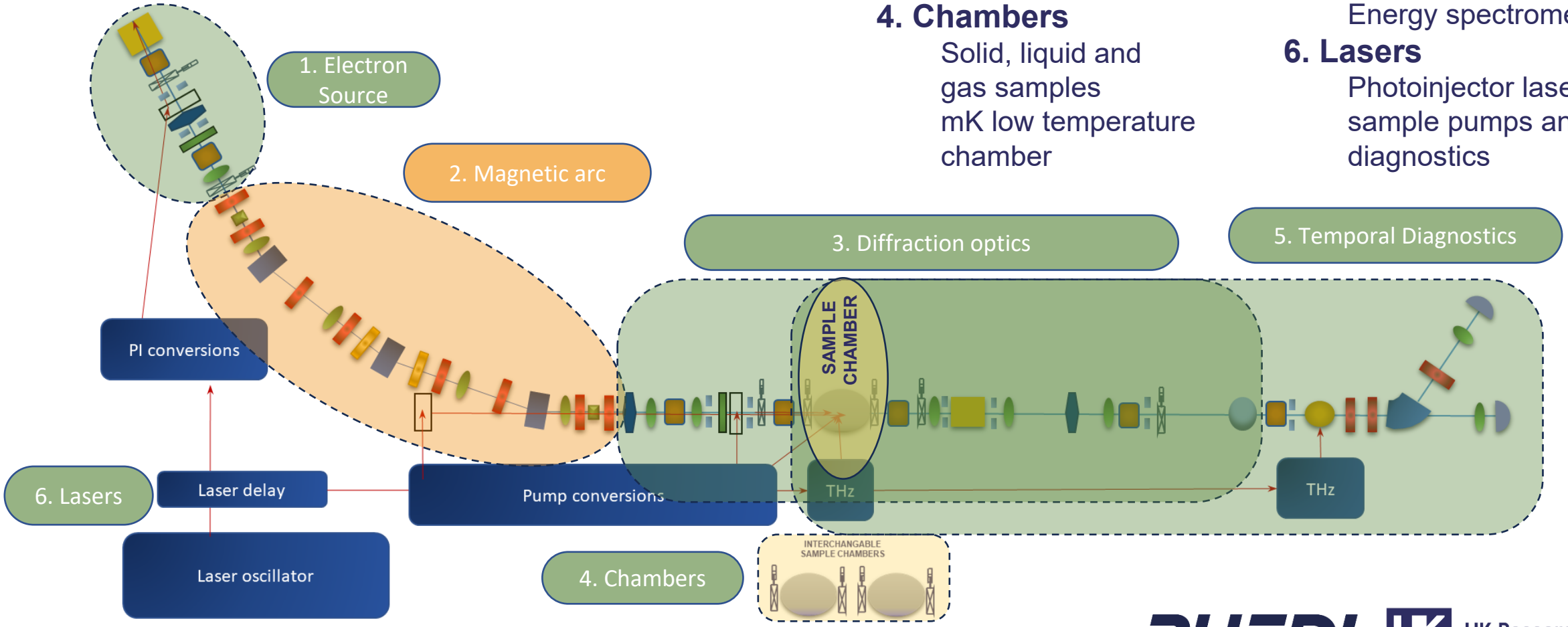

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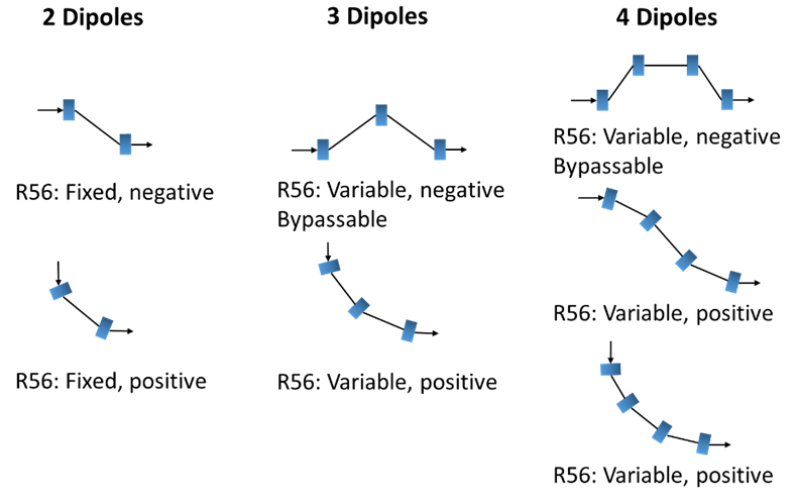
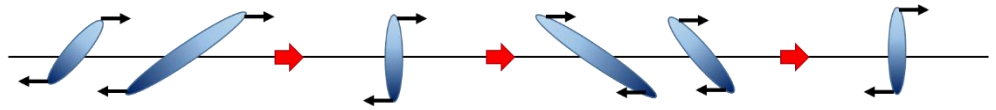
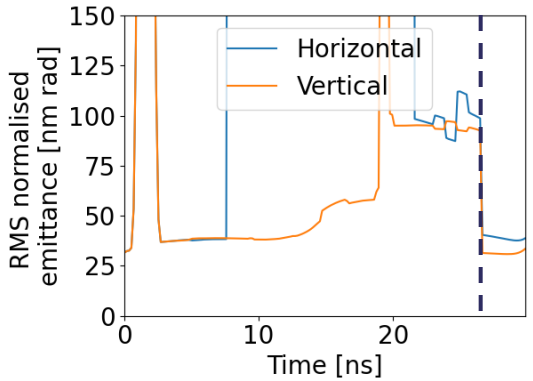
Compressor topology choice

- Need positive (arc-like) R56
  - Space charge chirp
  - Jitter suppression condition
- Variable R56 beneficial
- At low energy all compressors are hybrids of magnetic & ballistic
  - The drift has a negative R56
- Need at least one over-compression.
- Over-compression = strong space charge
  - Favour single over-compression designs
- TBA meets requirements

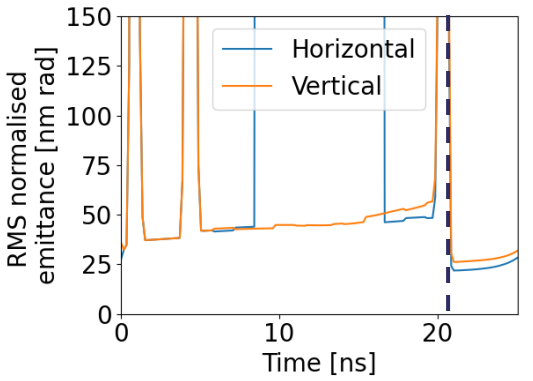




Four dipole arc-like
3 over-compressions

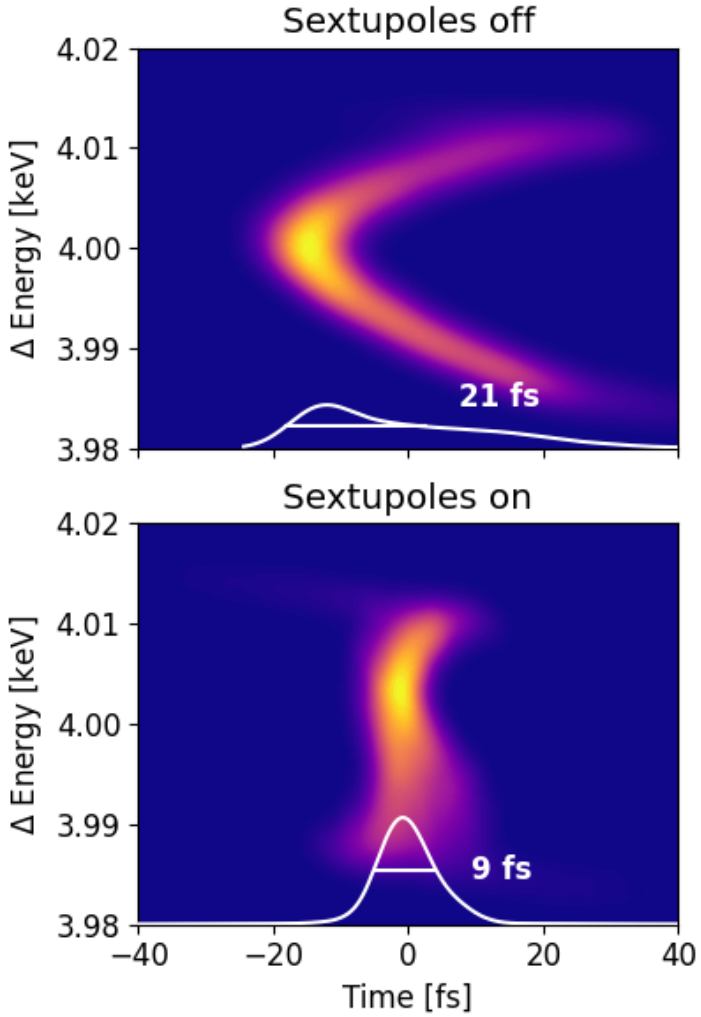


Triple bend achromat
1 over-compression



Correcting longitudinal non-linearities with sextupoles.

- The arc is set up so the 1st order longitudinal dispersion (R56) cancels the gun jitter.
- The 2nd order longitudinal dispersion (T566) also matters and increases both the bunch length and the TOA jitter.
- T566 can be corrected with a sextupole pair.
- The 3rd order (U5666) is not significant so octupoles are unnecessary.



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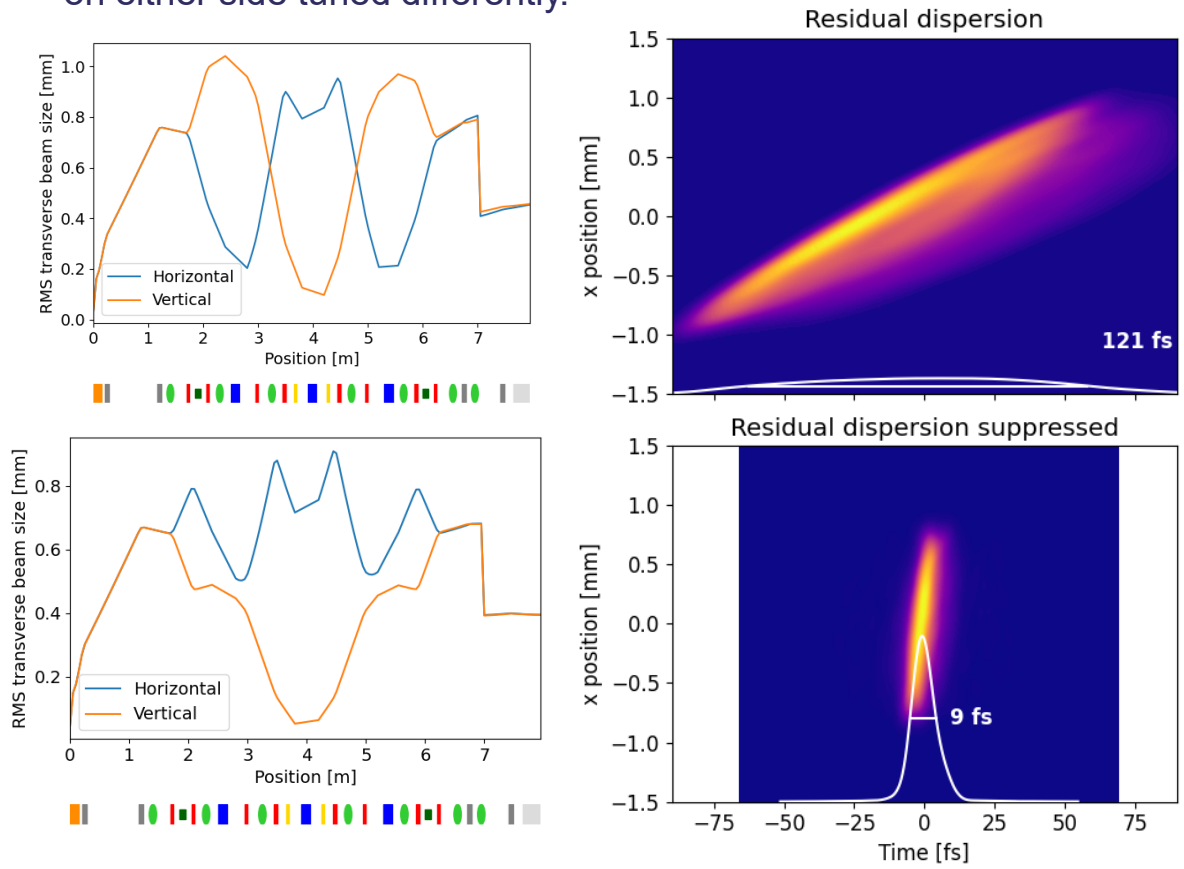
Suppressing space charge induced residual dispersion

- Longitudinal space charge chirps the bunch as it moves through the TBA.
- Particles have different energy in different dipoles.
- Leads to residual dispersion.
  - Bend plane emittance growth
  - Bunch length growth
- Suppress this effect by minimising beta x in the central dipole
  - Based off CSR kick minimisation method.
- Easier to set this up in TBA than other compressor topologies.

These plots depict the same TBA but with the matching quads on either side tuned differently.



Note: This is an extreme example smaller tilts with no residual dispersion suppression are possible.

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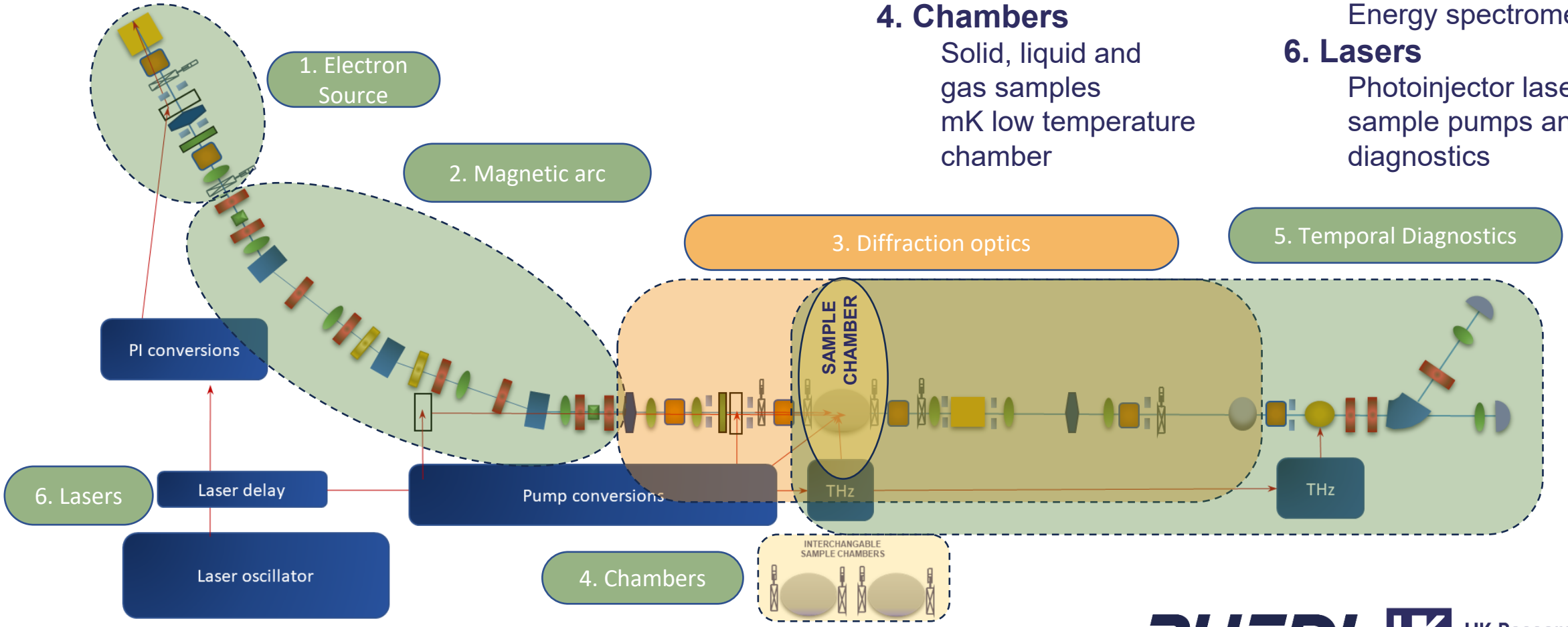

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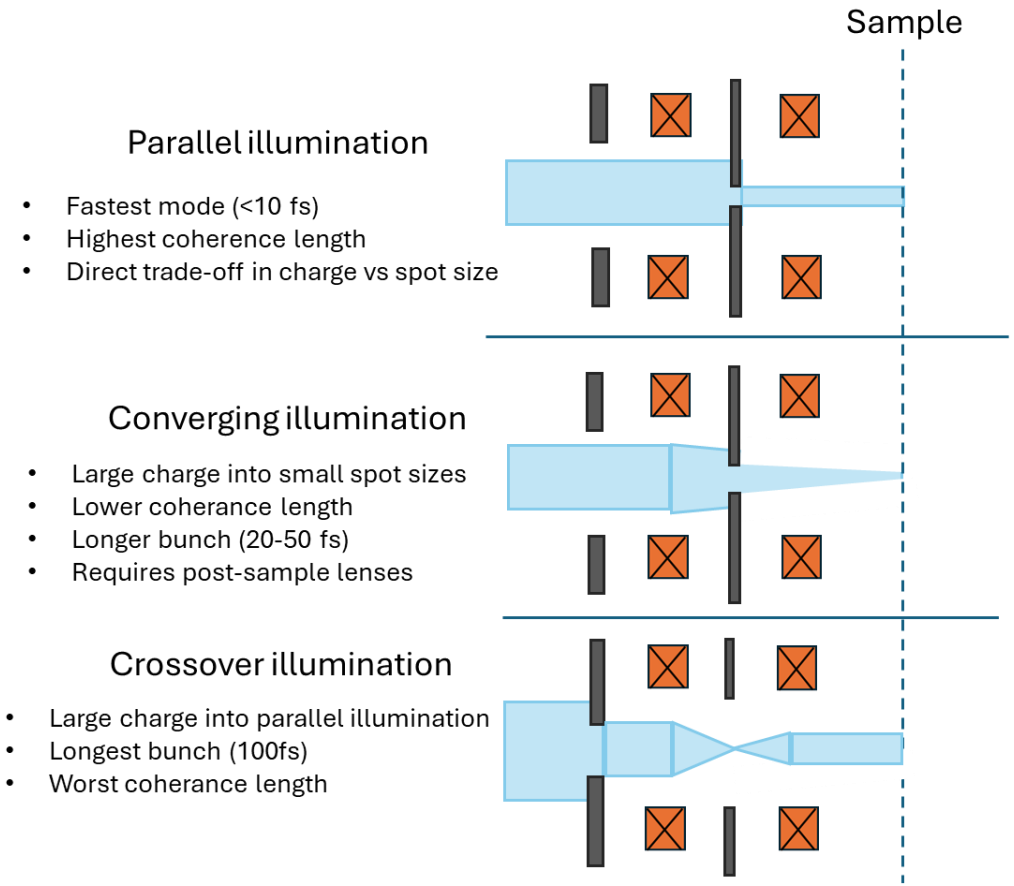
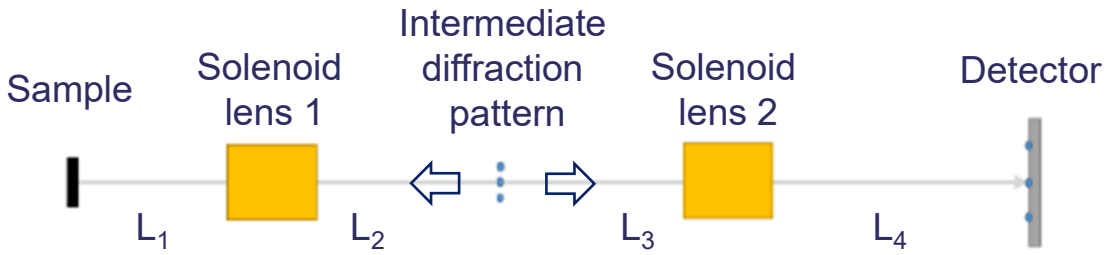
Initial charge, condenser optics & changing modes

- The arc is kept constant with 400 fC emitted from the gun.
- Single shot and stroboscopic modes are achieved by collimating after the arc.
- Focusing onto the sample can be adjusted with a pair of solenoids.
  - Affects: coherence length & bunch length.
- Benefits:
  - The arc set-up is the same for all modes – less need to adjust it in operations.
  - More charge and therefore signal in arc diagnostics



$$L_c = \frac{\lambda \sigma_x}{2\pi\varepsilon}$$

Magnification lenses

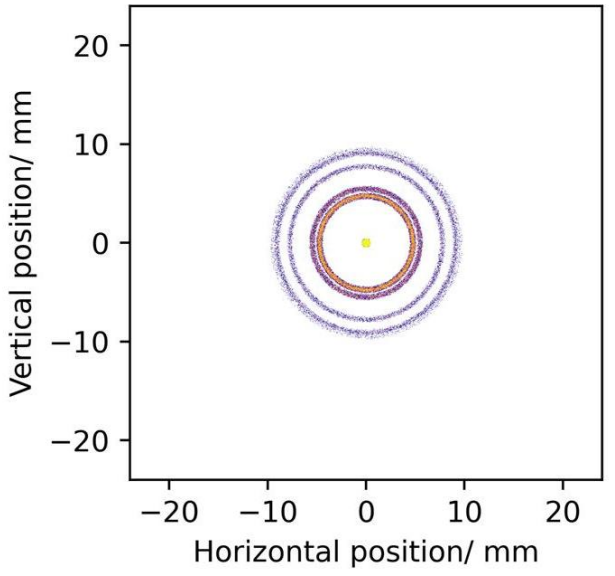


To adjust the camera length tune the solenoid lenses to move the intermediate diffraction pattern

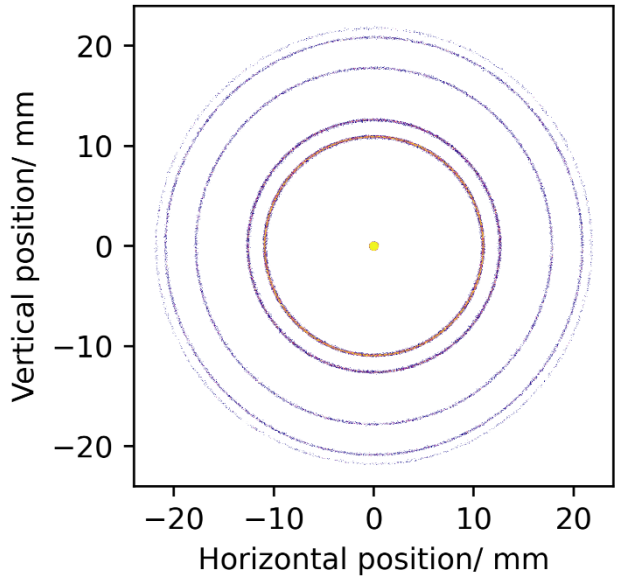
$$C_L = \frac{L_2 L_4}{L_3}$$

- Problem: Detector resolution limits Q resolution.
- Solution: Magnify diffraction patterns.
- Two EM solenoid lens system for magnification.
  - Lens 1: Forms intermediate diffraction pattern.
  - Lens 2: Image intermediate diffraction pattern onto the detector.
- EM solenoids allow tuneable camera length.

4 m camera length
no lenses

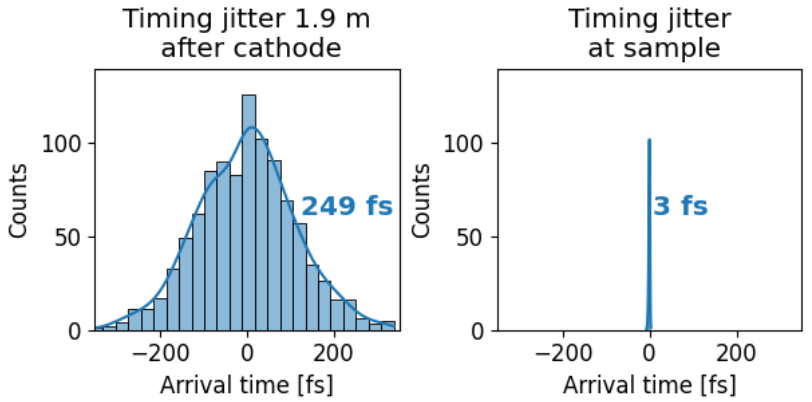


9.35 m camera length
with lenses

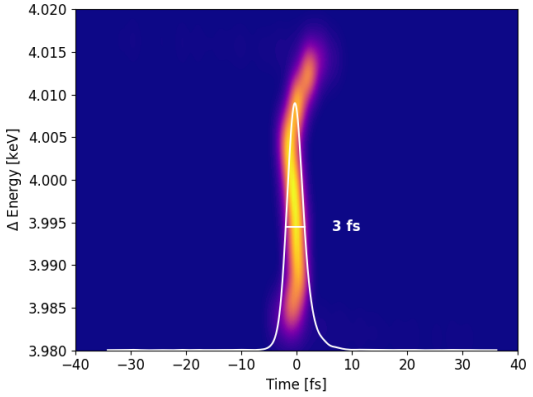


RUEDI UED performance

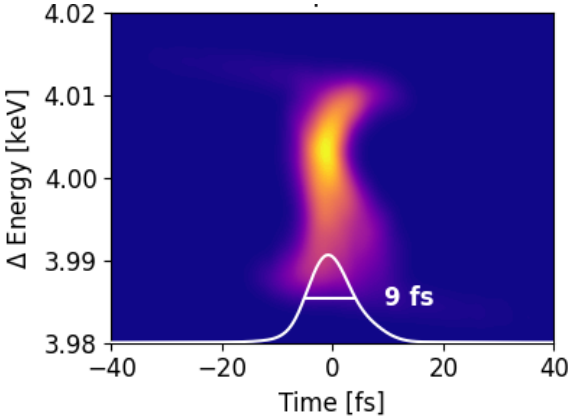
- The RUEDI diffraction line uses a TBA based magnetic compressor and provides a flexible range of modes.
- It offers a range of capabilities:
  - < 10 – 100s fs timing resolution
  - < 7.7 nm coherence length
  - Flexible sample illumination
  - 1 kHz
- The stroboscopic parallel illumination mode is the fastest and highest Q resolution mode.



Stroboscopic



Single shot



Beam property	Stroboscopic	Single shot	Tuning ranges
Number of electrons	~ 10^4	~ 10^6	10^4 - 10^6
FW transverse beam size [um]	~ 200	~ 1600	30 – 1600
Coherence length x/y [nm]	7.7 / 8.1	5.7 / 5.1	< 7.7
4D brightness [e-/(nm rad)^2]	2430	1230	< 2430
Bunch length RMS/FWHM [fs]	3.2 / 3.0	4.7 / 9	3 – 100s

Conclusions

- RUEDI is a planned UK national user facility for time resolved electron diffraction and imaging.
- It has two beamlines: one for imaging and one for diffraction.
- The diffraction beamline uses a magnetic compressor to simultaneously compress the bunch and suppress the time of arrival jitter.
- To achieve very short bunches a number of design features are used:
  - A PI laser operated in the blowout regime.
  - A compressor topology with only one longitudinal crossover.
  - Sextupoles to correct the longitudinal non-linearity.
  - Optics tuned to suppress the space charge induced residual dispersion.

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