Beam dynamics of the RUEDI ultrafast electron diffraction beamline

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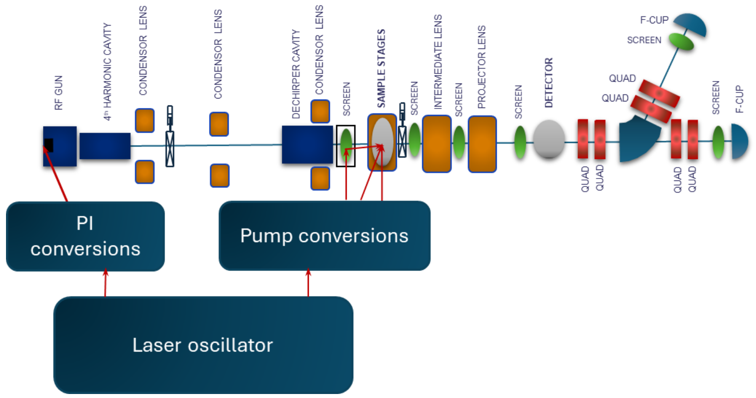
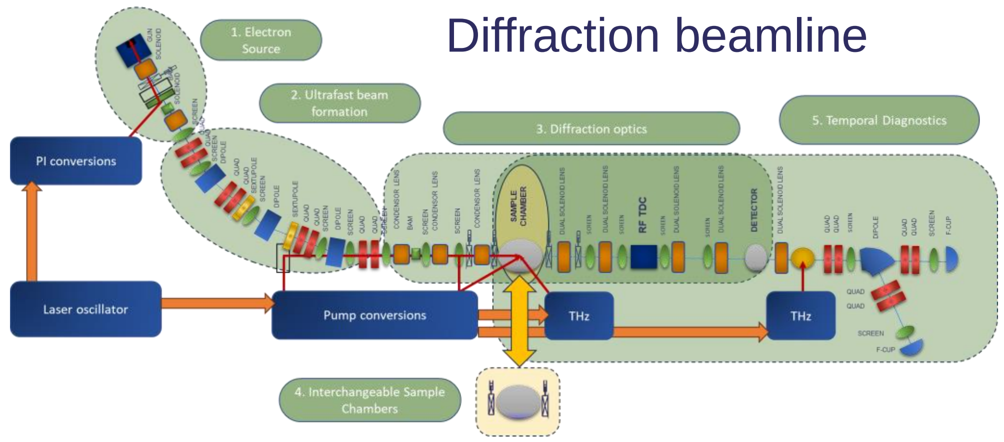
RUEDI (Relativistic Ultrafast Electron Diffraction and Imaging)

Imaging beamline



Diffraction beamline

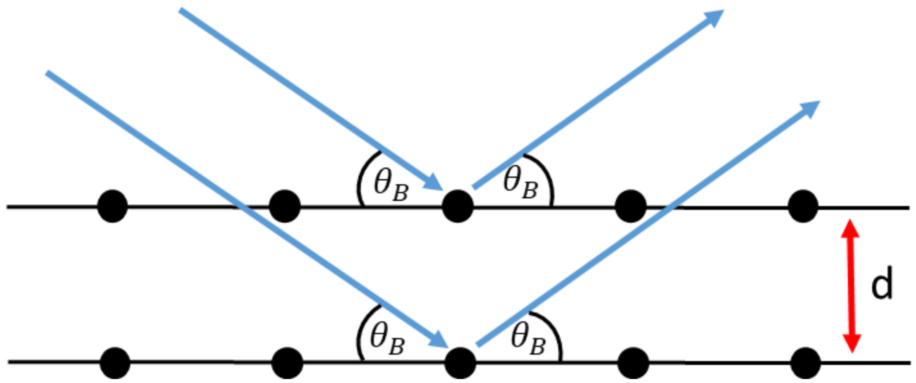


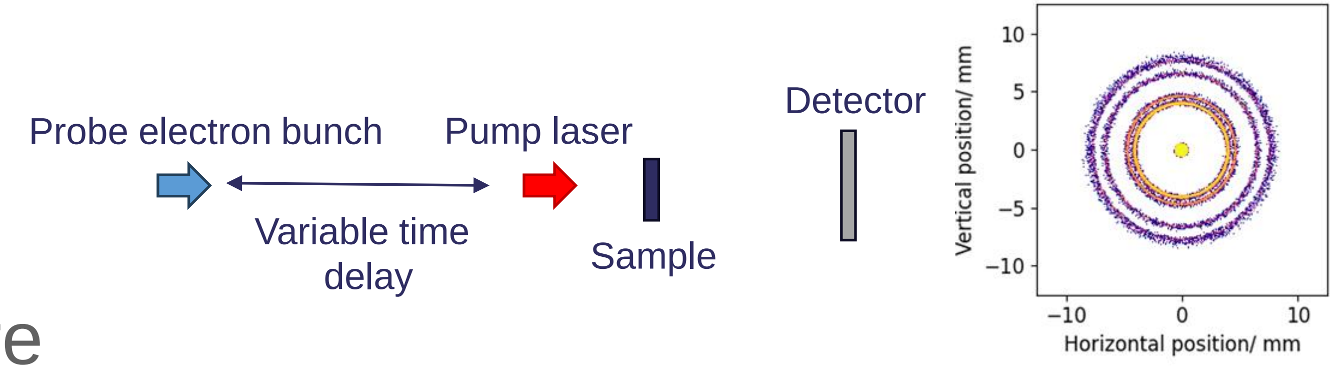
- RUEDI is an MeV time resolved electron diffraction and imaging user facility which will be built at Daresbury laboratory.
- It has two beamlines:
  - An imaging beamline
  - **A diffraction beamline.**

How does a UED experiment work?

- The RUEDI diffraction beamline is a machine for measuring changes in the structure of materials.
- At 4 MeV the wavelength of an electron is 0.277 pm.
- Electrons diffract and the pattern provides information about the sample.
- Pump-probe experiments are used to measure changes.

$$\lambda = \frac{h}{p}$$





Measuring diffraction patterns

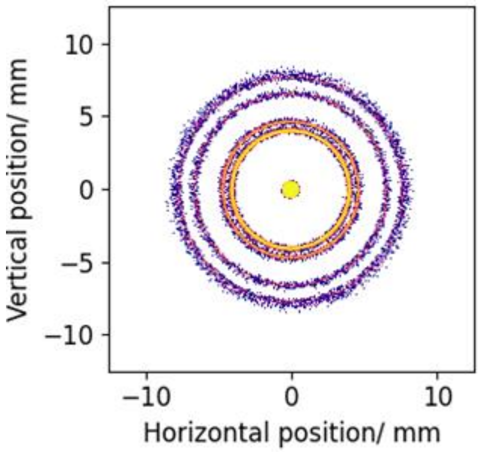
- Diffraction patterns are measured by observing the positions that electrons hit the detector.
- This can be converted to a momentum transfer or Q in $Å^{-1}$.
- The distance between lattice planes, d is

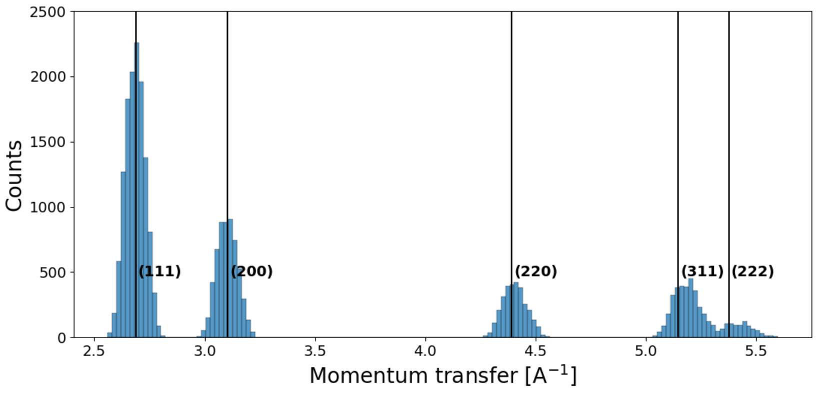
$$d = \frac{2\pi}{Q}$$

- The electron beam quality figure of merit is coherence length, L_c

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

- An alternative figure of merit is Q resolution $\Delta Q = 1/\ L_c$





	Single shot	Stroboscopic
Emittance	< 50 nm rad	< 5 nm rad
Number of electrons	10^6	10^4
Bunch charge	160 fC	1.6 fC

Measuring ultrafast processes

- Temporal resolution is given by:

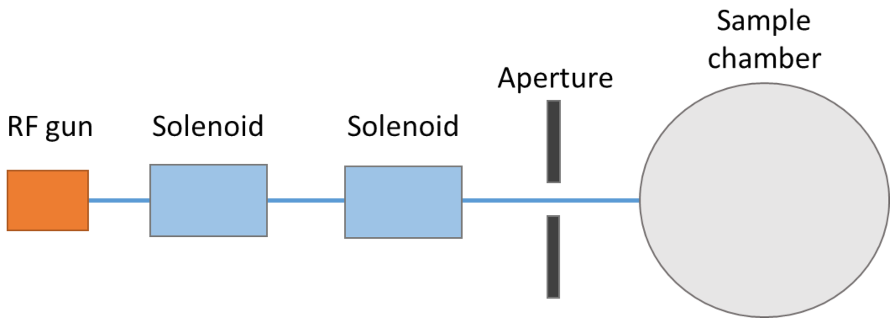
$$\Delta t = \sqrt{\Delta t_{Bunch\ length}^2 + \Delta t_{Jitter}^2 + \Delta t_{Laser\ pulse\ length}^2 + \Delta t_{velocity\ mismatch}^2}$$

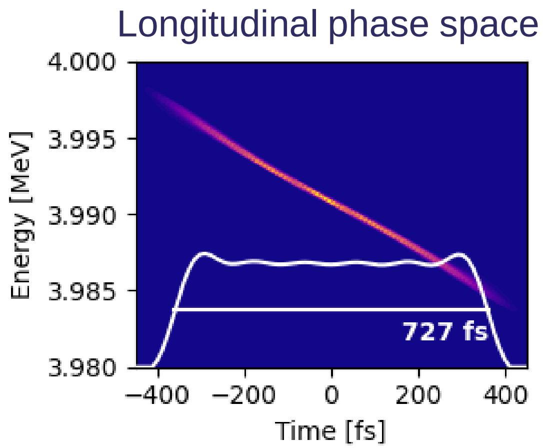
- Temporal resolution depends on
  - **Probe electron bunch length**
  - **Time of arrival jitter**
  - Pump laser pulse length
  - Velocity mismatch
- RUEDI is aiming for a temporal resolution of **<10 fs**

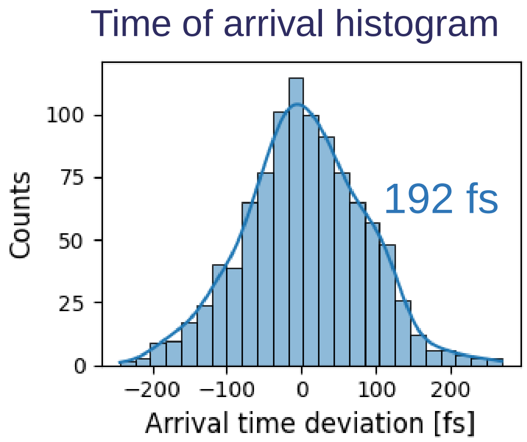
$$\Delta t = \sqrt{\Delta t^2_{Bunch\ length} + \Delta t^2_{Jitter}}$$

Simplest scheme: RF gun

- The simplest scheme is an RF gun + focusing solenoids + sample chamber.
- Space charge forces lead to an increase in the bunch length.
- The RF gun produces long bunches with large time of arrival jitter.
- Ways to improve the scheme
  - Reduce bunch charge.
  - Shorten the distance from gun to sample.
  - Compress using the gun phase.
- However to achieve < 10 fs a different approach is needed.



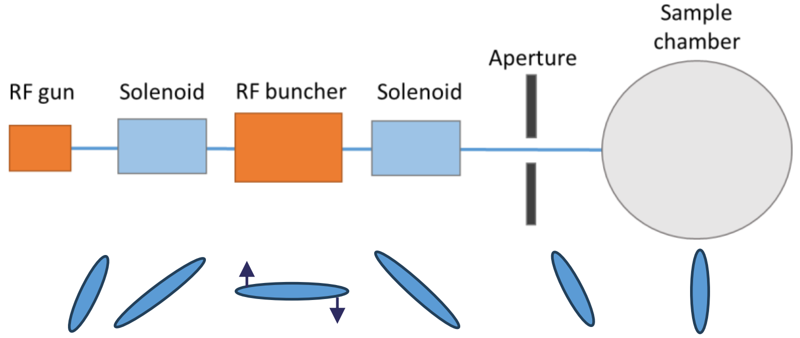


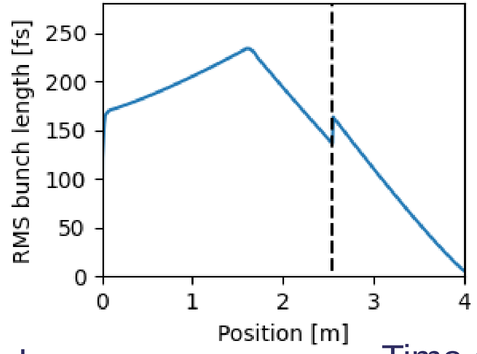


$$\Delta t = \sqrt{\Delta t^2_{Bunch\ length} + \Delta t^2_{Jitter}}$$

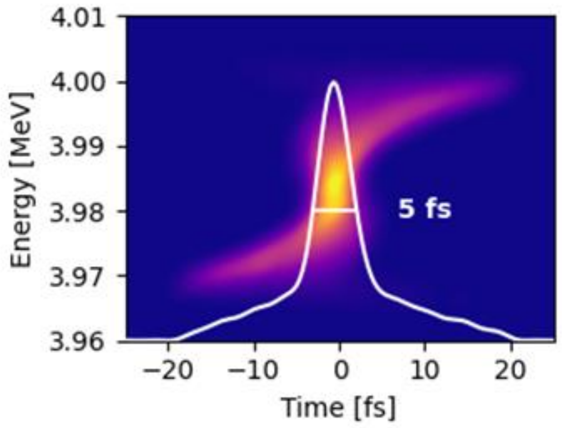
RF compression

- To get a shorter bunch we need to compress the beam.
- At 4 MeV particles of different energies move at different speeds.
- An RF buncher cavity is used to accelerate the back of the beam and decelerate the front. The faster back of the bunch catches up with the front.
- The buncher cavity is another source of jitter.
- RF compression produces short bunches but has large time of arrival jitter.

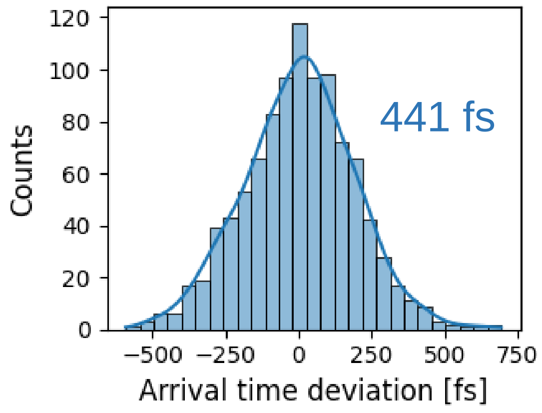




Longitudinal phase space



Time of arrival histogram



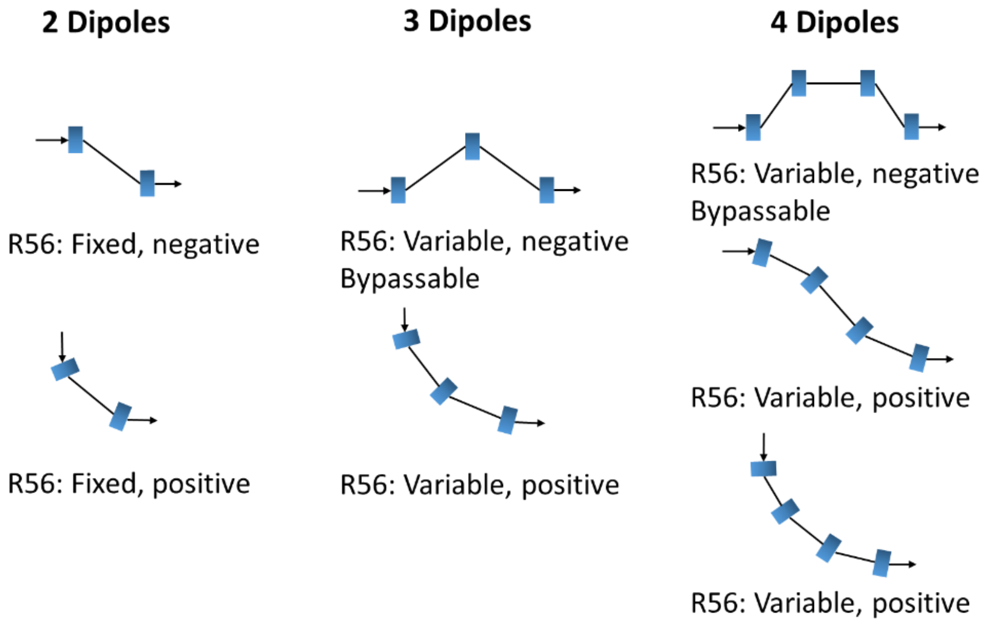
$$\Delta t = \sqrt{\Delta t_{Bunch\ length}^2 + \Delta t_{Jitter}^2}$$

Magnetic compression

- Magnetic compressors use the difference in path length through a beamline to compress.
- There are many possible designs.
- Variable R56 is desirable for operational flexibility.
- Requires a more complicated beamline than RF compression.
- Better for jitter than an RF compressor.

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

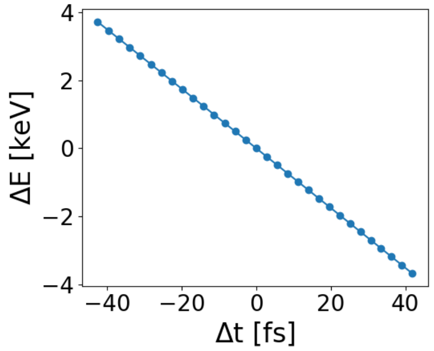
Possible dipole layouts



$$\Delta t = \sqrt{\Delta t_{Bunch\ length}^2 + \Delta t_{Jitter}^2}$$

Jitter suppression

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

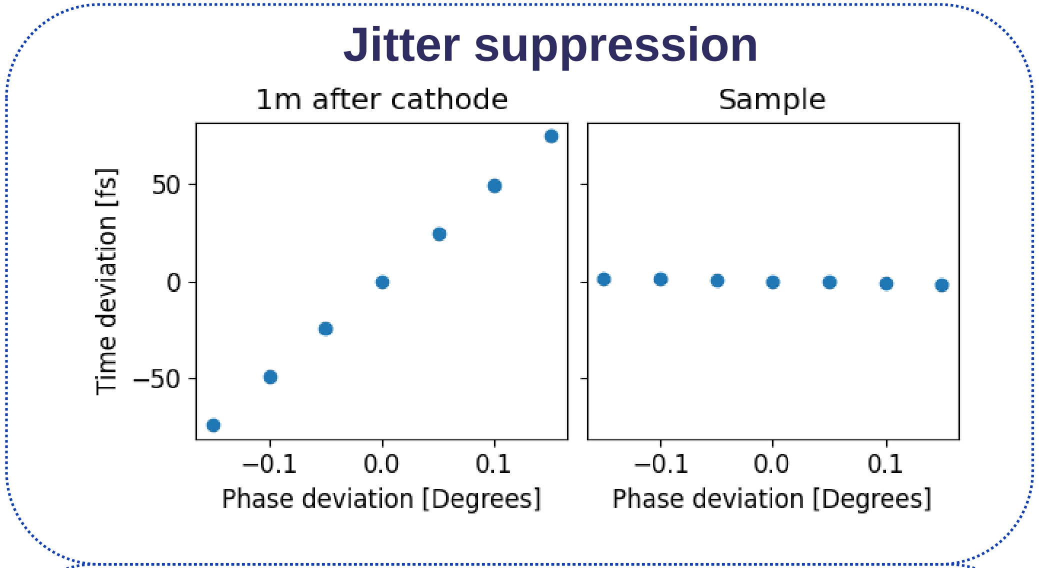


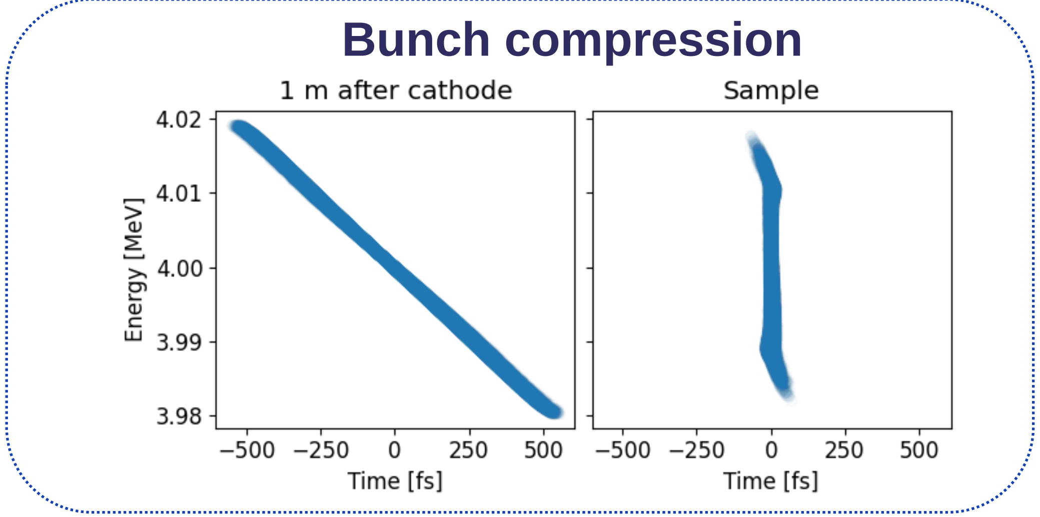
- Set magnetic R56 to the opposite of the gun $\frac{\Delta E}{\Delta t}$ jitter to cancel it

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

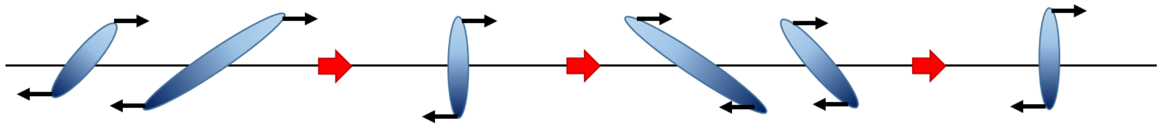
- Set electron beam chirp *(using space charge)* to enable simultaneous compression and jitter cancellation
- Experimentally proven by KAERI

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



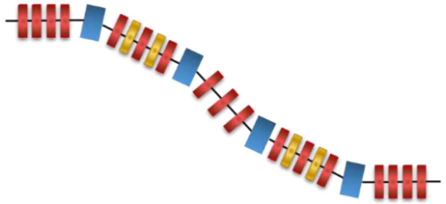


Low energy effects



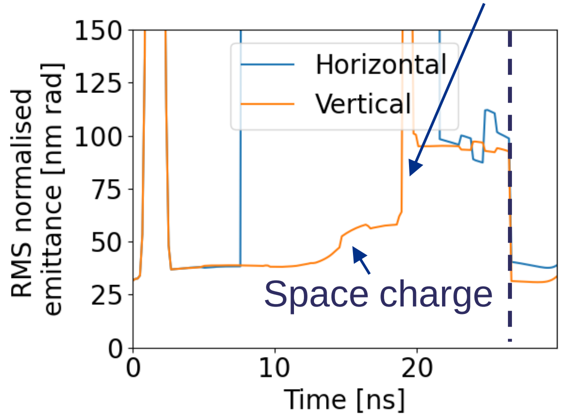
- At 4 MeV the compression is a hybrid of magnetic and ballistic requiring at least one over-compression.
- Space charge forces are strongest when the bunch is short.
- Space charge can cause transverse emittance and bunch length growth.
- Few over-compressions = better performance.
- One over-compression beamlines are best.

Four dipole arc



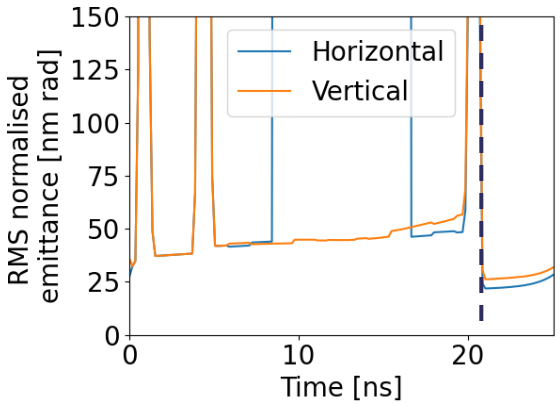
Three over-compressions

Chromatic aberration



Triple bend achromat

One over-compression



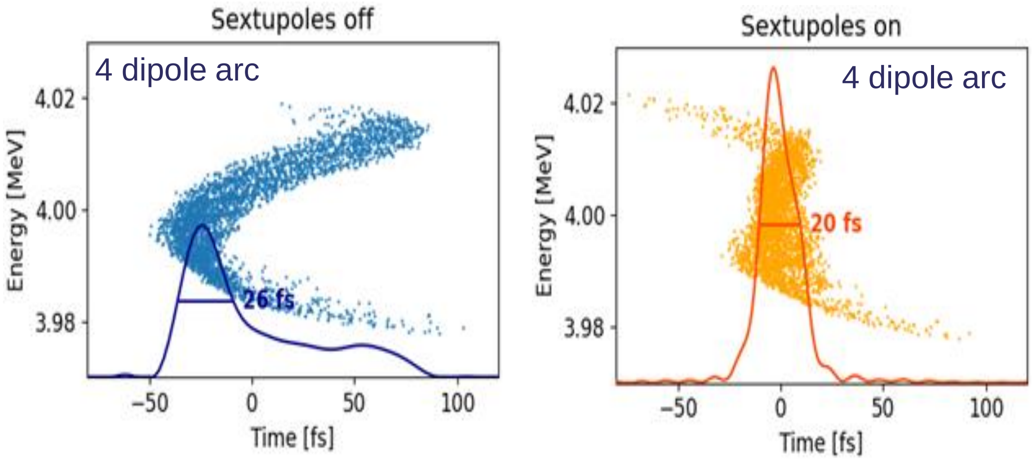
$$\Delta t = \sqrt{\Delta t_{Bunch\ length}^2 + \Delta t_{Jitter}^2}$$

Breaking the 10 fs barrier

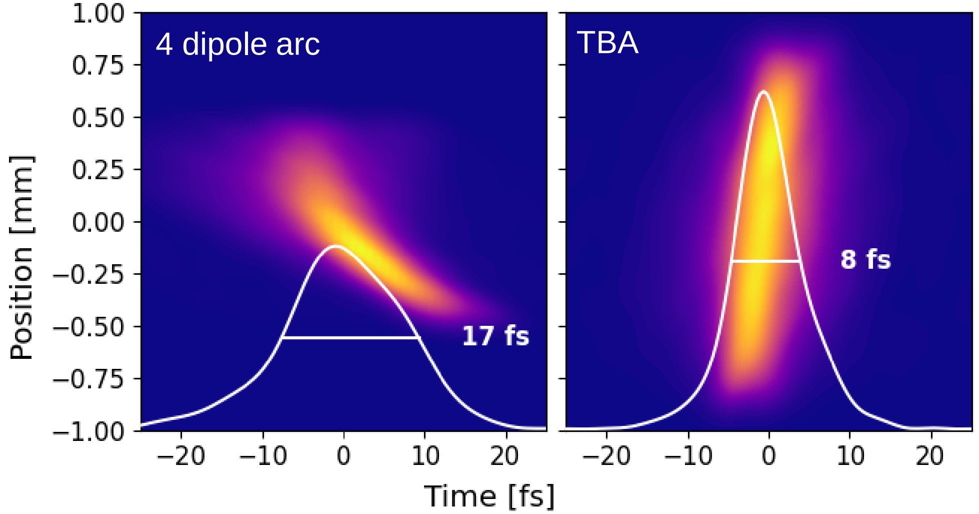
- Getting from an FWHM bunch length of 20-30 fs to < 10 fs requires correcting two effects:

1. **Second order longitudinal dispersion**:
   - **Solution**: Add sextupoles.
2. **Space charge induced residual dispersion:**
   - **Solution**: Tune the optics to suppresses the residual dispersion similar CSR mitigation schemes.

Sextupoles



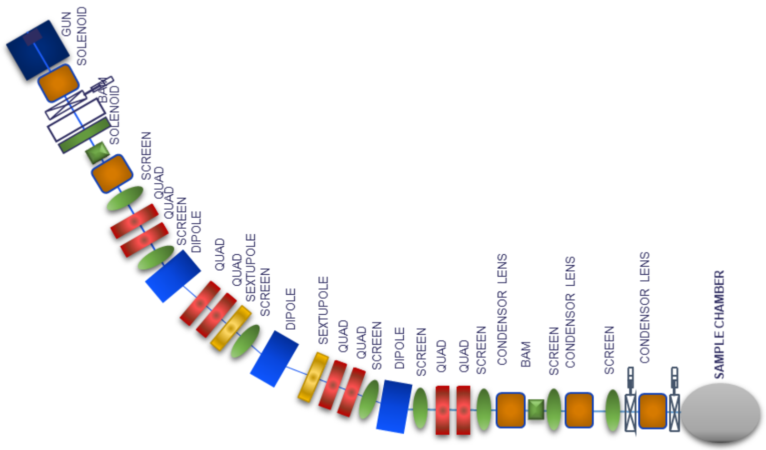
Residual dispersion suppression

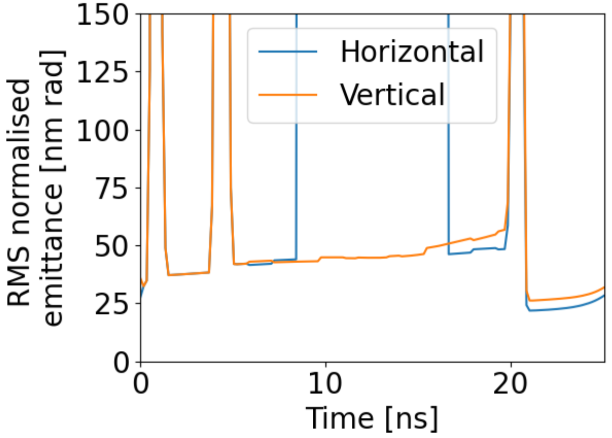


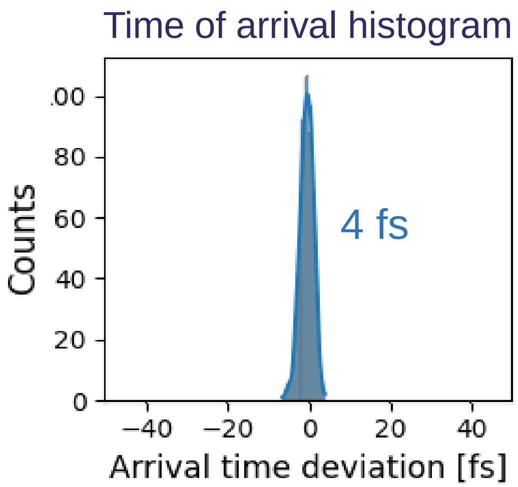
$$\Delta t = \sqrt{\Delta t_{Bunch\ length}^2 + \Delta t_{Jitter}^2}$$

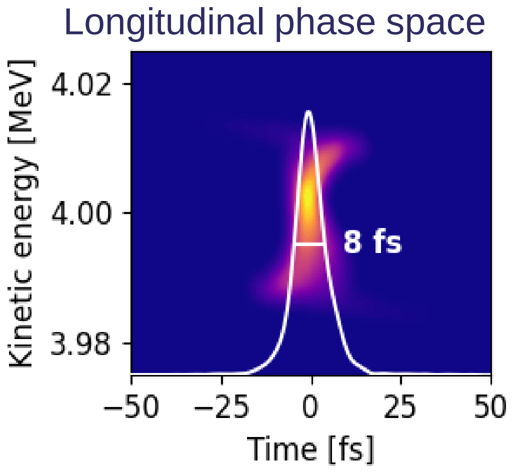
Triple bend achromat compressor

- The preferred RUEDI diffraction beamline design is a triple bend achromat compressor.
- This design compresses the bunch to < 10 fs, has few fs timing jitter and has small emittance growth through the arc.









Conclusions

- RUEDI is an electron diffraction and imaging user facility which is going to be built at Daresbury laboratory.
- It has two beamlines optimised for their specific purposes.
- The diffraction beamline uses a triple bend achromat magnetic compressor.
- The beamline suppresses the time of arrival jitter to be to a few fs.
- The bunch length is compressed to < 10 fs by using sextupoles to correct non-linearities and suppressing the space charge residual dispersion with the optics.

Acknowledgements

- Thanks to the TDR team!

RELATIVISTIC ULTRAFAST ELECTRON DIFFRACTION & IMAGING (RUEDI) NATIONAL FACILITY

TECHNICAL DESIGN REPORT

VERSION 1.1 [02/04/2024]

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