INFRARED FREE ELECTRON LASER (IR-FEL) TRIUMF WORKSHOP

3/19/2024

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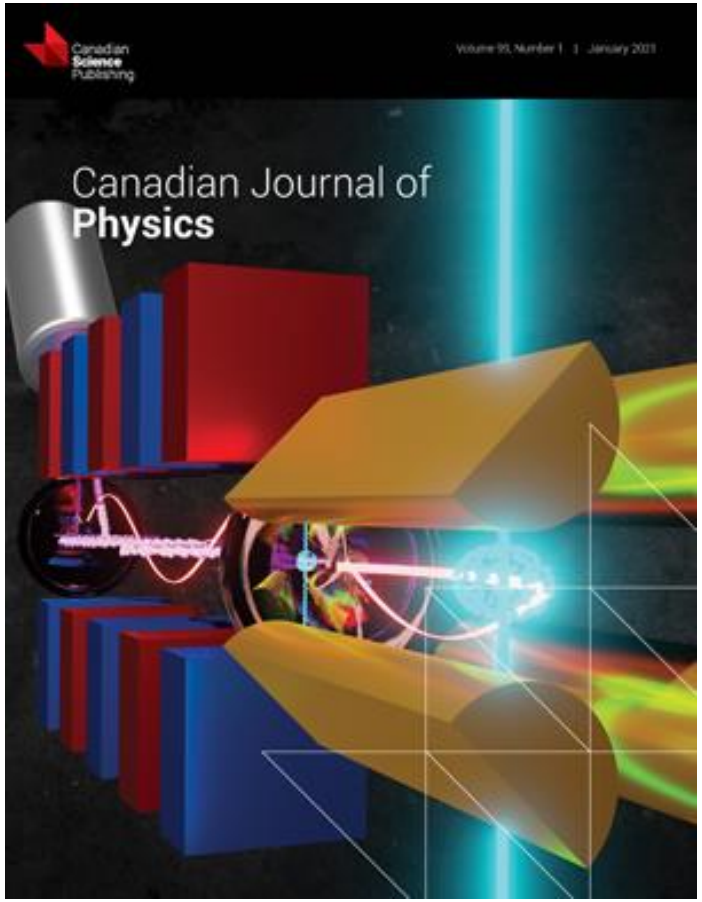
UNIVERSITY OF WATERLOO | FACULTY OF SCIENCE

Outline

- Project Overview
- What is a free electron laser (FEL)?
  - The FEL Design
  - The *e*-beam specifications
  - The IR specifications
- Location & Timeline
  - 5-year plan
  - Facility location/design
- Applications & Research Directions
  - Short-term (year 3+)
  - Mid-term (year 5+)
  - Long-term (year 10+)



Can. J. Phys. **97:** vii–x (2019) dx.doi.org/10.1139/cjp-2019-0238

PROJECT OVERVIEW

The History

- Initially conceived in 2014.
- Workshops at TRIUMF and CLS
  - Leadership team established
  - *Can. J. Phys.* Editorial (2019)
- Successful CFI, ORF, BCKDF 2023

CFI: $6.0 million $3.6 million $0.4 million

ORF: $6.4 million **BCKDF**: $3.6 million


Scott Hopkins


Taka Momose


Oliver Kester

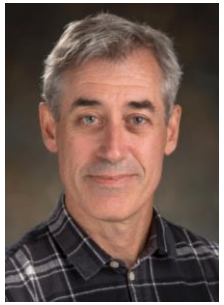

Francois Lagugne-Labarthet


Yunjie Xu


Amy Stevens


Mark Boland


Travis Fridgen


Steve Dodge


Donna Strickland

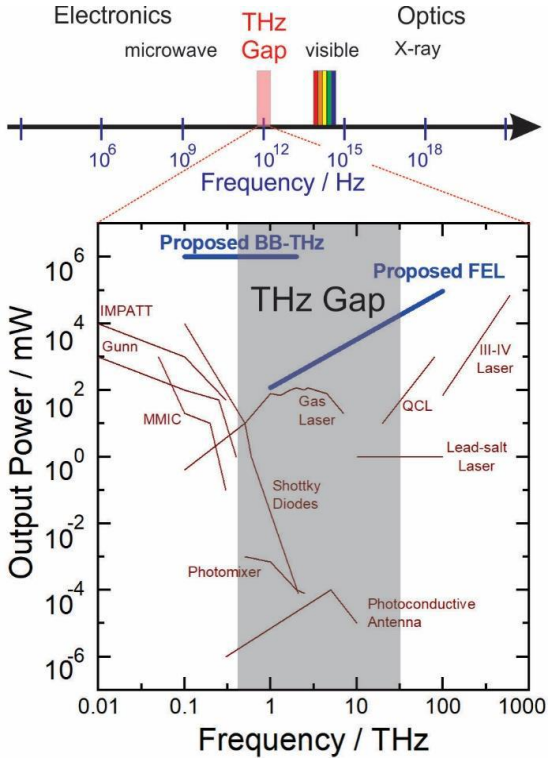

German Sciaini


Victor Verzilov

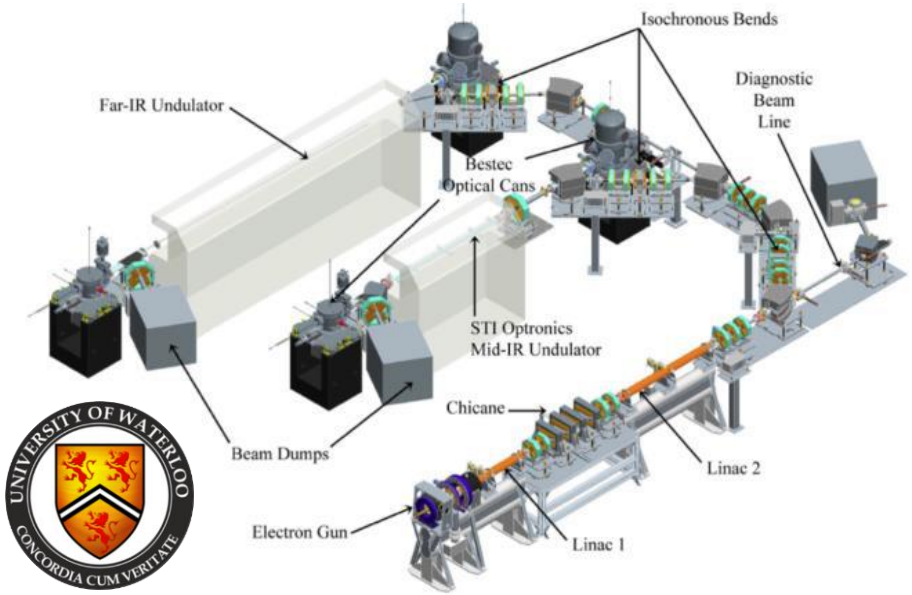

Mike Ditty

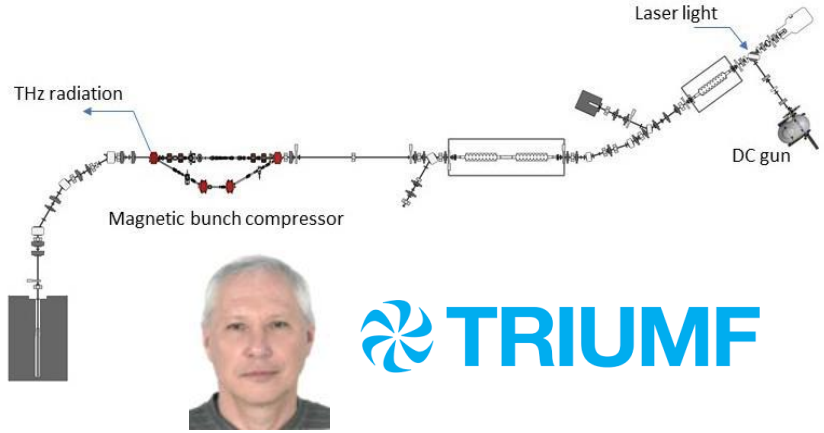

Christian Ieritano

The Gap

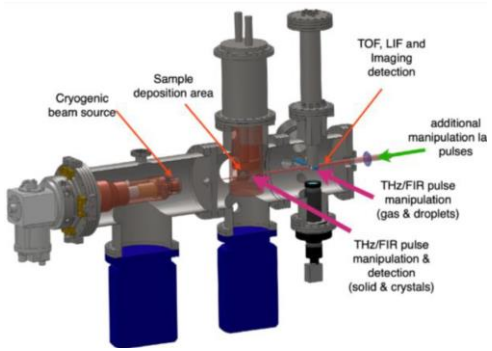


Closing the THz gap will open new research in areas ranging from materials development to astrochemistry





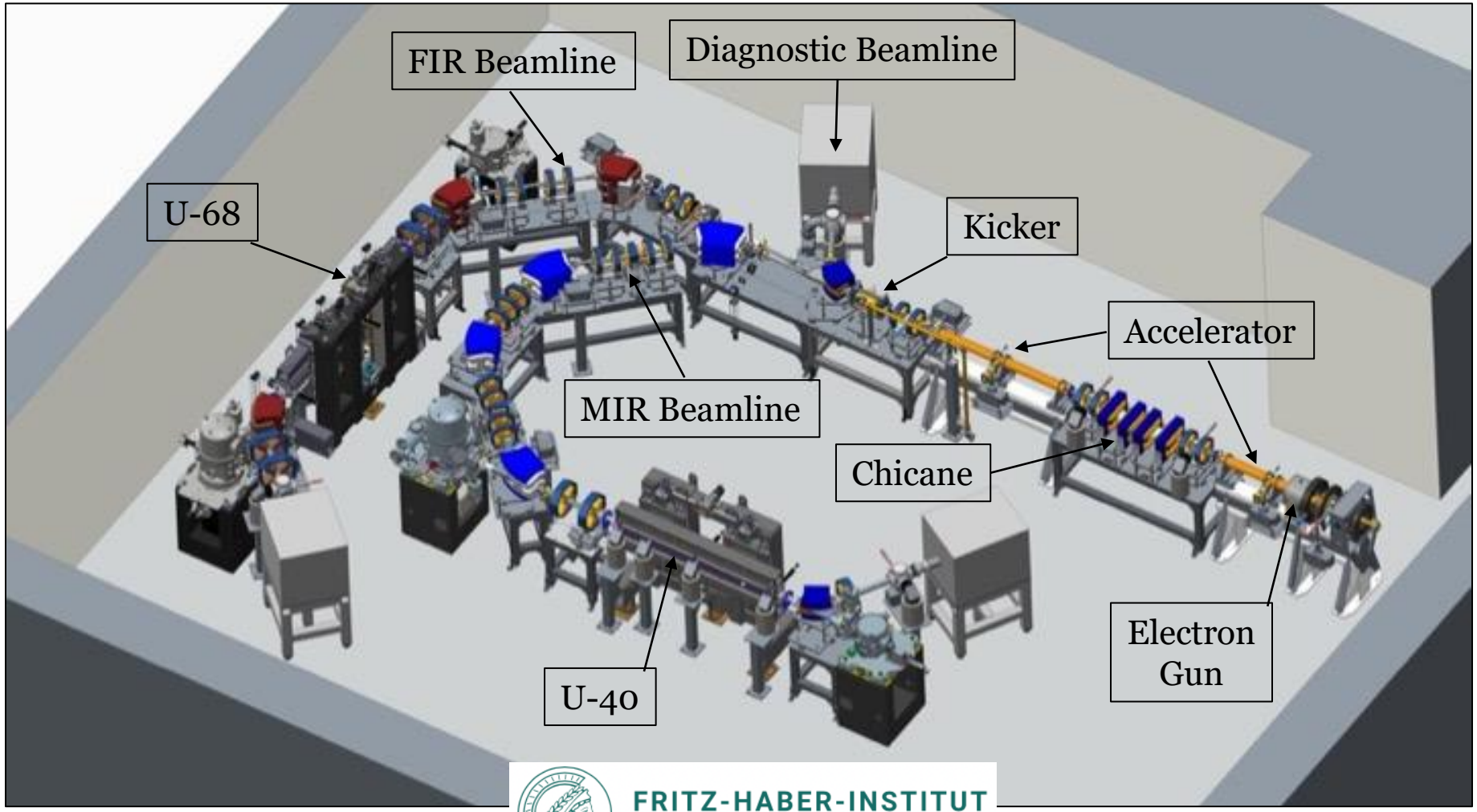
TRIUMF



Linear accelerator-based light sources can provide tunable, high-power THz radiation

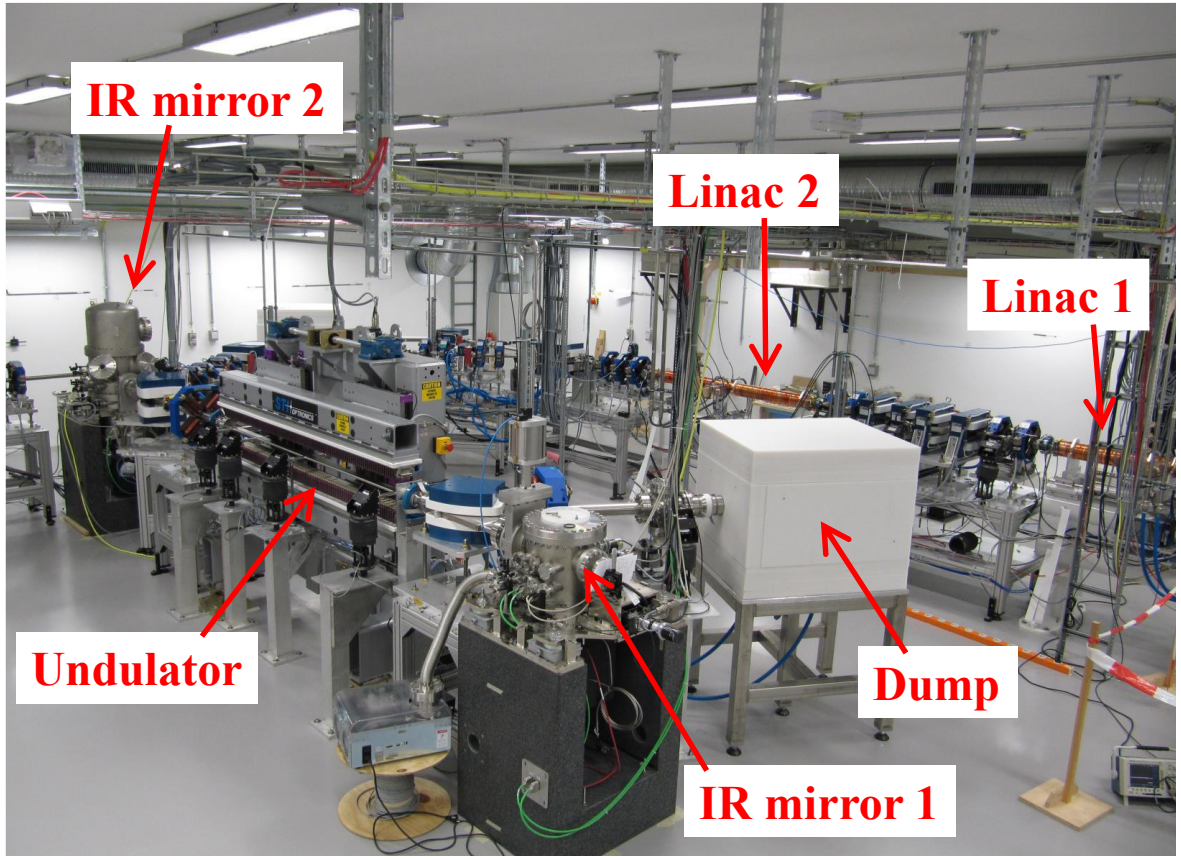
THE FREE ELECTRON LASER

Free Electron Lasers (FELs)



FRITZ-HABER-INSTITUT
MAX-PLANCK-GESELLSCHAFT

The IR-FEL at the Fritz Haber Institute



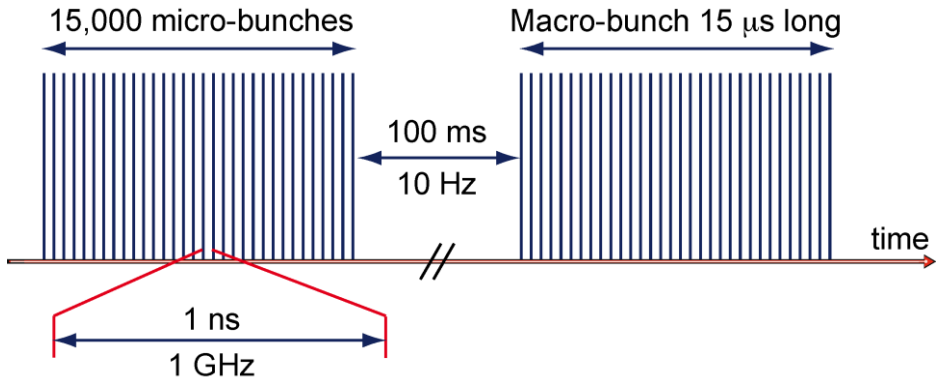
FRITZ-HABER-INSTITUT
MAX-PLANCK-GESELLSCHAFT

Linac Specifications

Normal-conducting S-band accelerator:

electron energy:	15 - 50 MeV
rf frequency:	3 GHz
bunch rep. rate:	1 GHz
bunch charge:	> 200 pC
bunch length:	1 - 5 ps
macro-bunch length:	15 μs
macro-bunch rep. rate:	10 Hz
energy spread:	< 50 keV
energy drift:	< 0.1% per hour
norm. transverse emittance:	20 p mm mrad
beam power:	up to a few kW

Macro-bunch temporal structure



Design and construction in consultation with Dr. Alan Todd, AES Inc.
In collaboration with CLS, TRIUMF, and FHI

IR-FEL Specifications

Mid-IR

IR wavelength: 4 – 50 μm (75 – 6 THz; 2500 – 200 cm^{-1})

IR cavity length: 5.4 m

Undulator: planar hybrid, NdFeB

period:	40 mm:	length:	2 m
# periods:	50	rms-K:	0.5 – 1.6

Far-IR

IR wavelength: 10 – 100 μm (30 – 3 THz; 1000 – 100 cm^{-1})

IR cavity length: 7.2 m

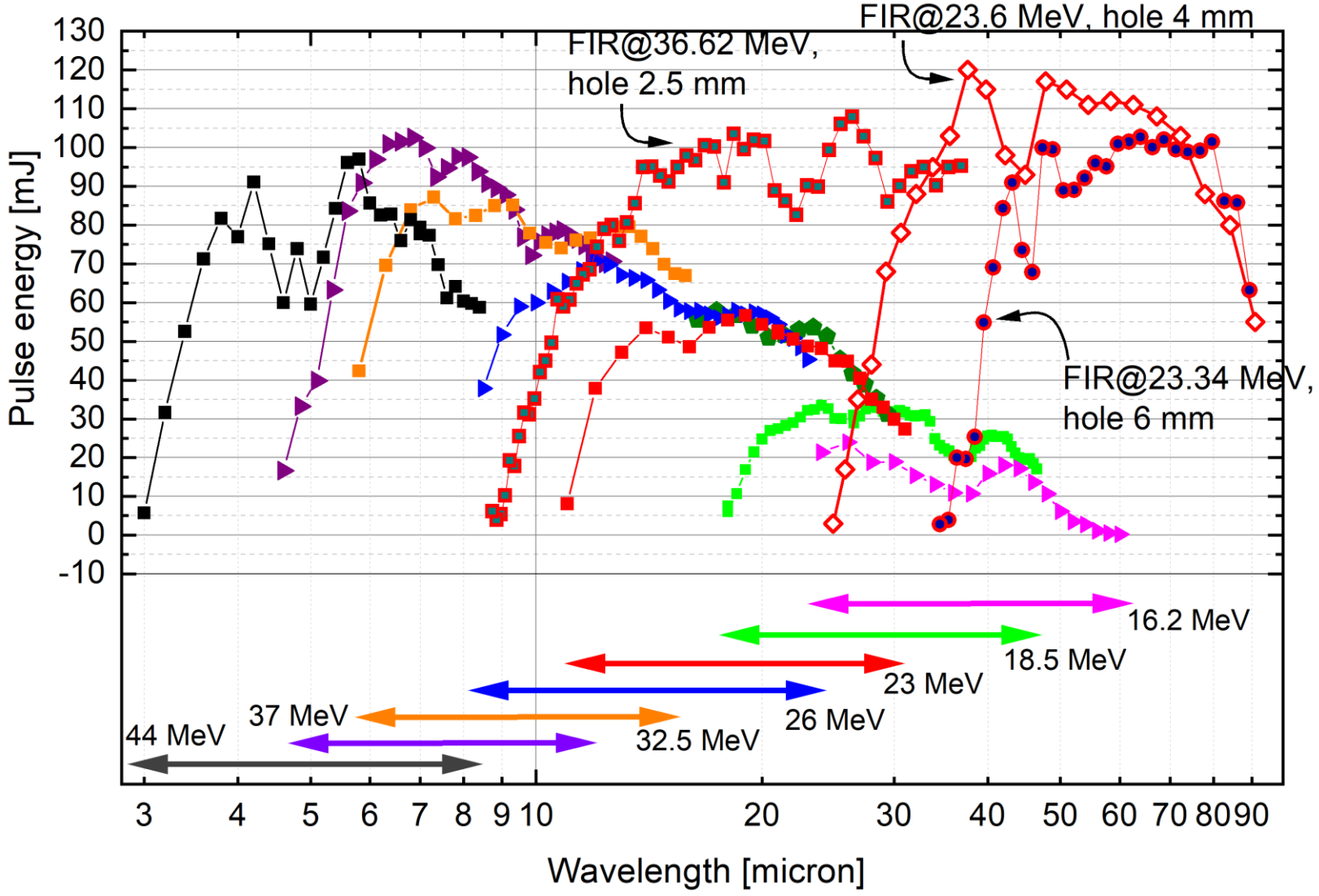
Undulator: planar hybrid, NdFeB

period:	110 mm:	length:	4.4 m
# periods:	40	rms-K:	1 – 3

*bandwidth *ca.* 0.45% ($\Delta\lambda/\lambda$)

**based on output achieved at FHI (state of the art).

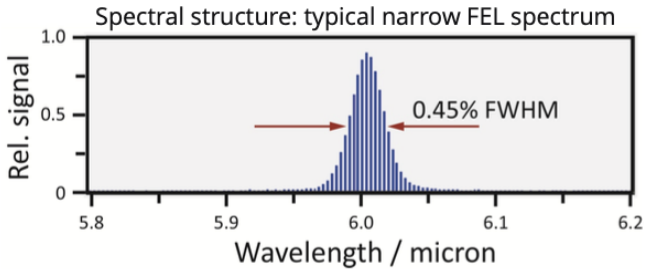
IR-FEL Specifications



Lower *e*-beam energies

⇩

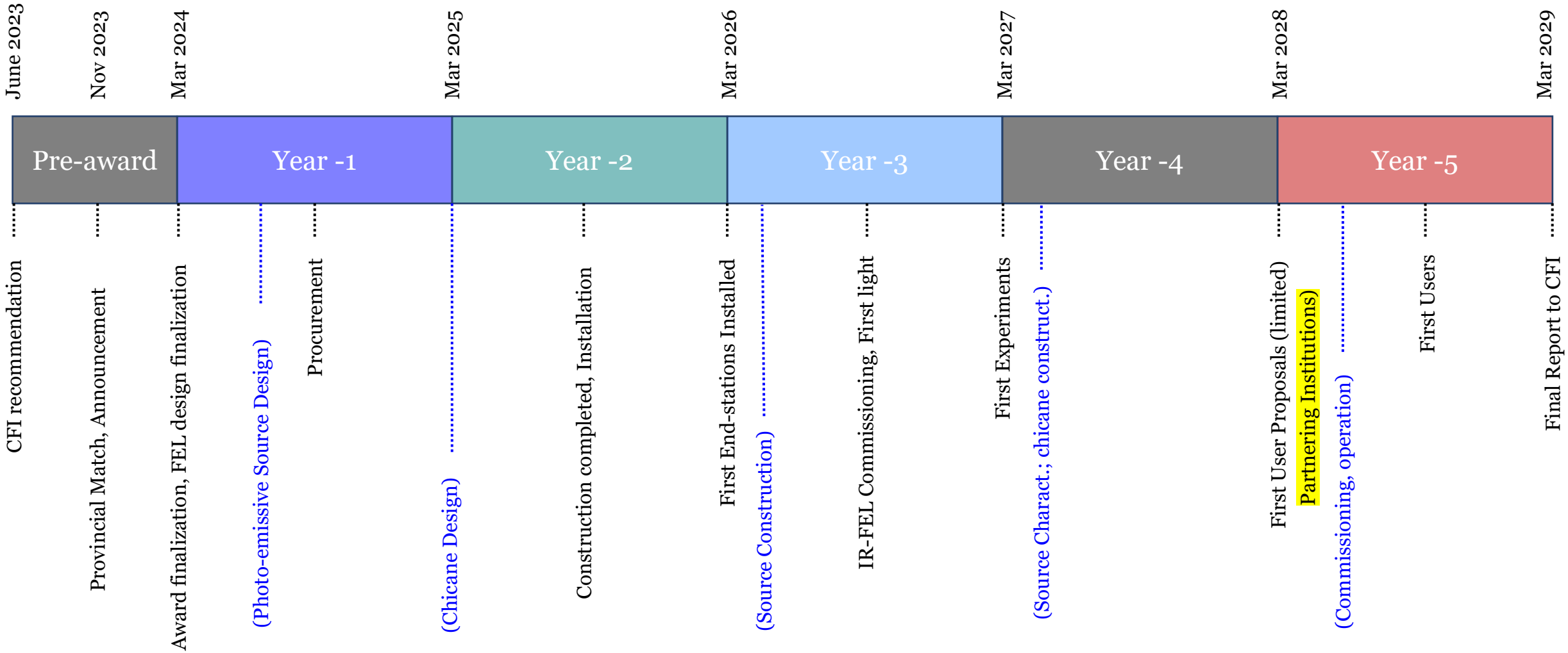
Longer wavelengths



λ / μm	$\bar{\nu}$ / cm^{-1}	Bandwidth	
		Δλ	Δ$\bar{\nu}$
4	2500	±0.009	±5.64
50	200	±0.113	±0.45
100	100	±0.225	±0.23

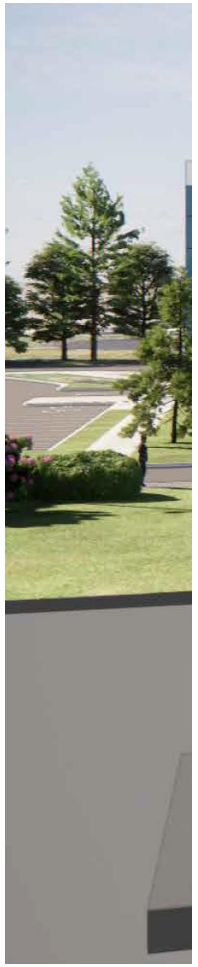
LOCATION & TIMELINE

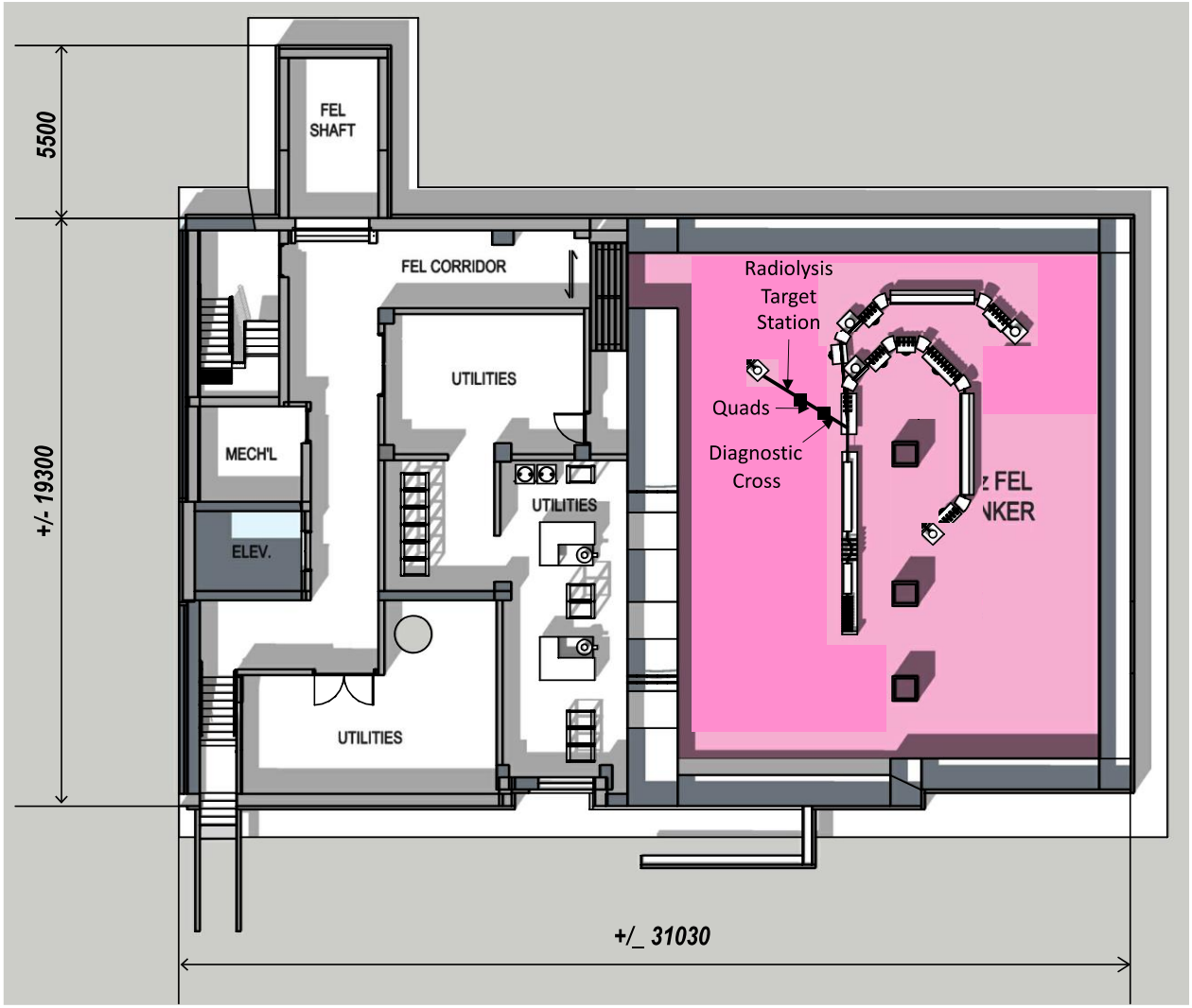
Project Timeline (Years 1-5)

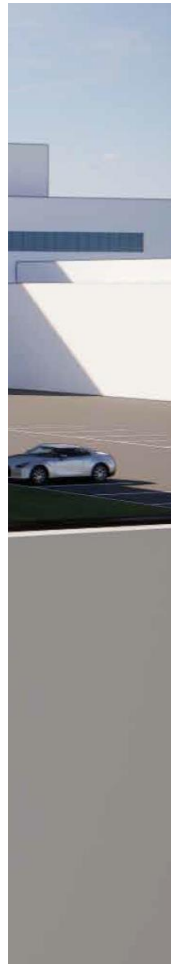


Location – North Campus

Preliminary Concept Drawings (now under revision)

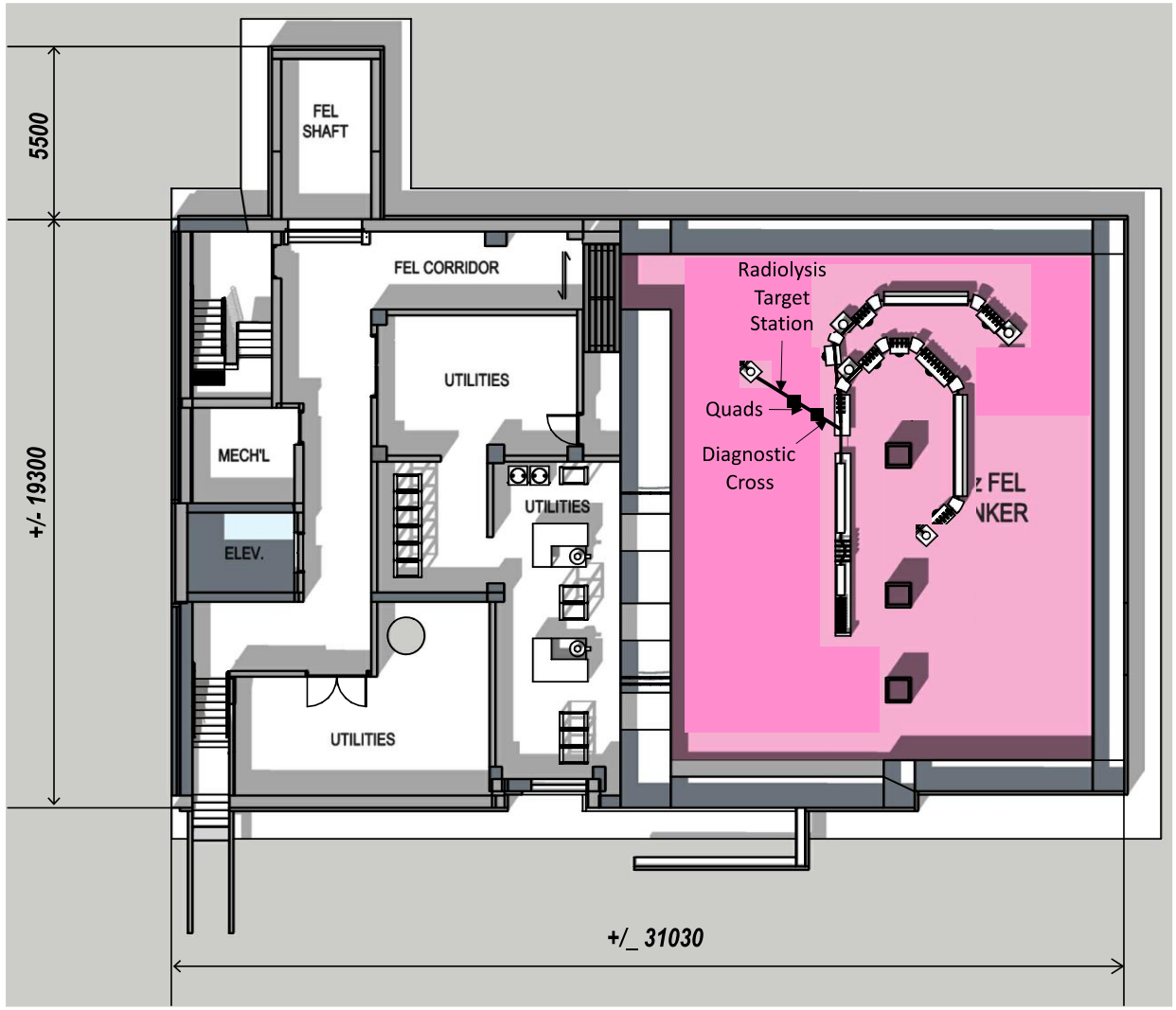




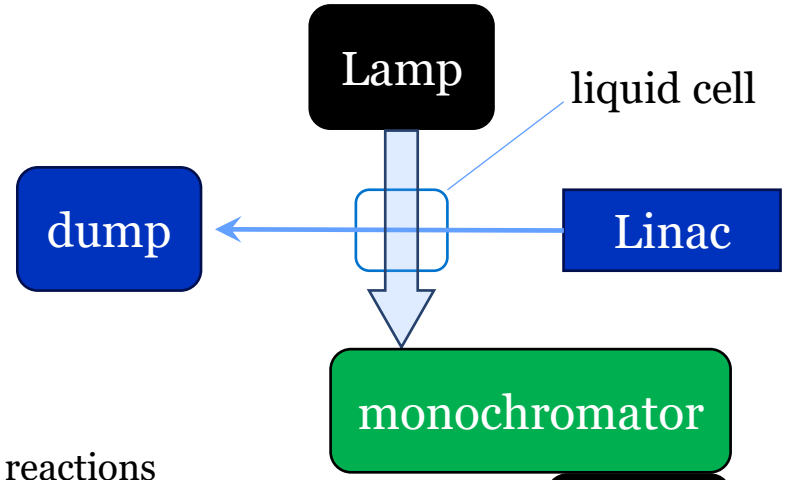


RESEARCH DIRECTIONS

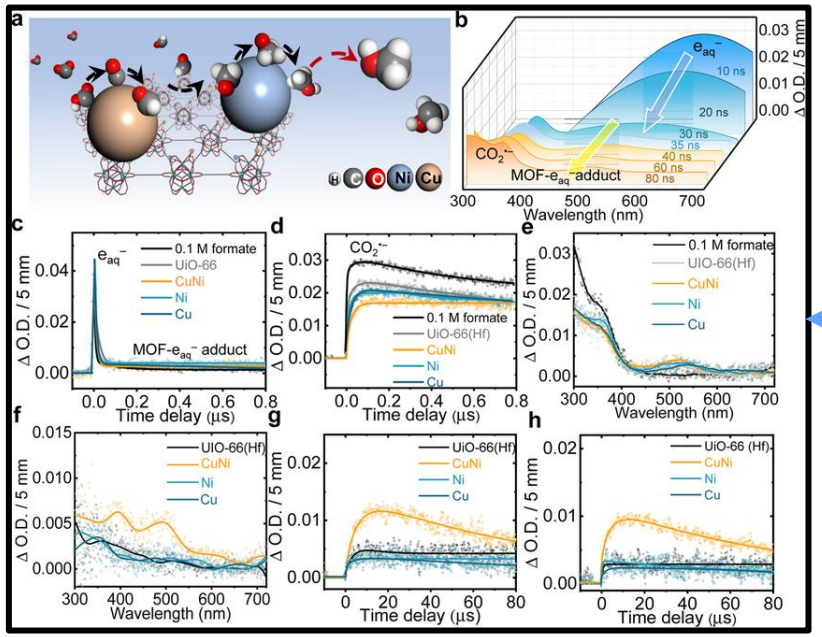
Short-term (Year 3+): *e*-beam techniques



Pulse radiolysis:



Time-evolution of reactions



Nature Communications **volume 14**, Article number: 4767 (2023)

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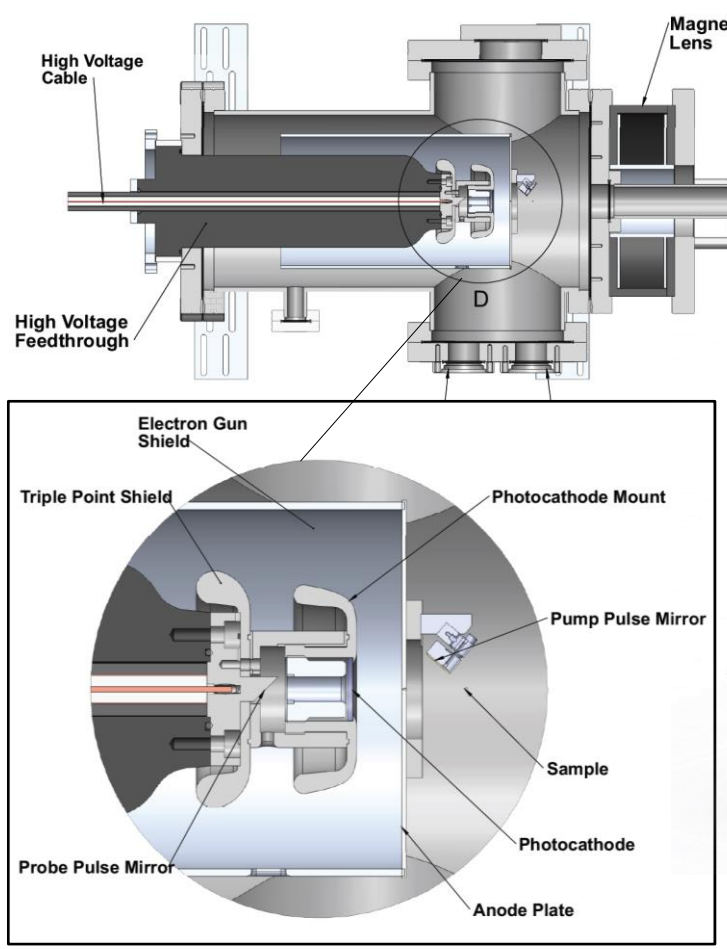
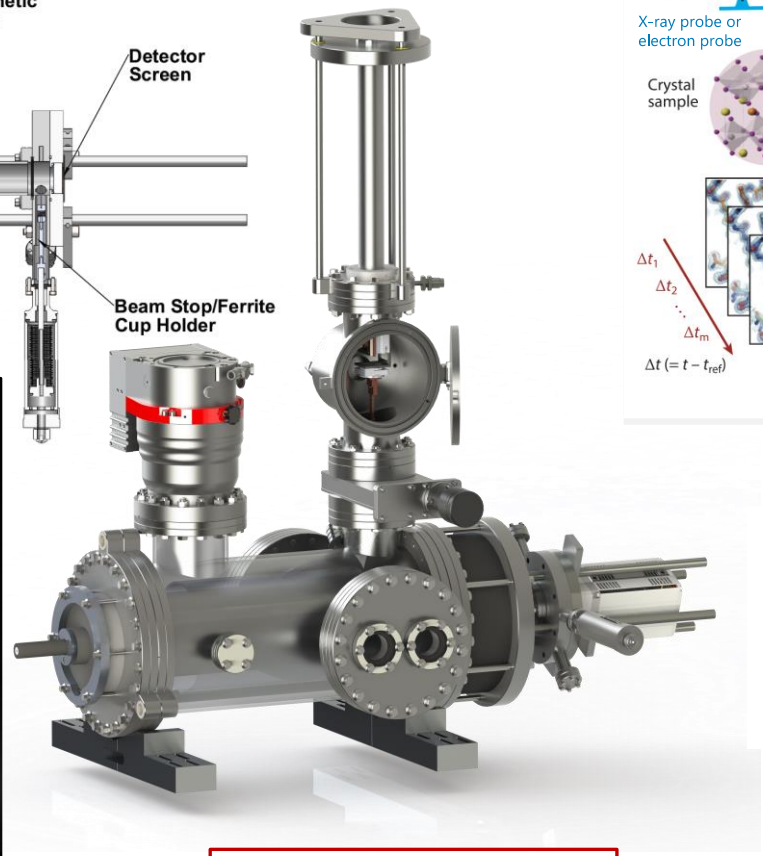
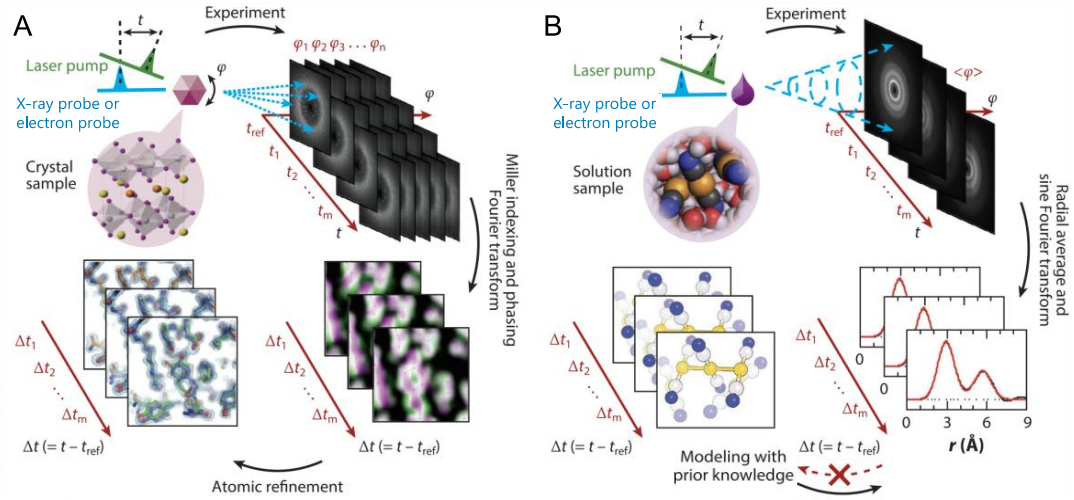
Short-term (Year 3+): *e*-beam techniques

Ultrafast Electron Diffraction (UED):





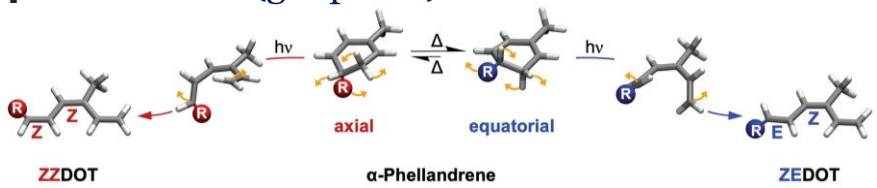


Synchronized with IR beyond year-5.

RESEARCH

CHEMICAL PHYSICS

Conformer-specific photochemistry imaged in real space and time (gas phase)



Science, 7 Oct 2021, Vol 374, Issue 6564, pp. 178-182

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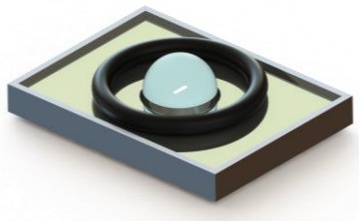
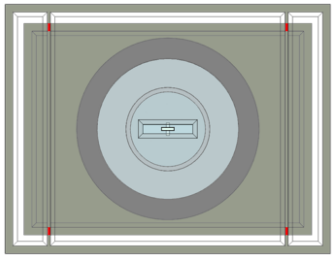
Short-term (Year 3+): Imaging

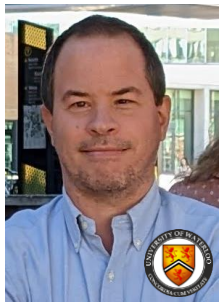




Adeno-associated virus ▶ imaged with e^- microscopy (200 kV)

▲ Imaging of thin film biological samples reveals native structure

Gold nanoparticles imaged ▶ with e^- microscopy (300 kV)



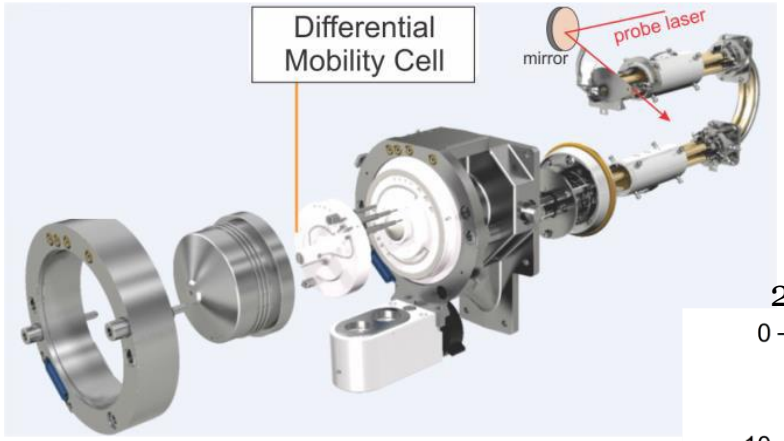
German Sciaini

Coupling with IR-FEL enables pump/probe experiments to observe real-time motion of atoms

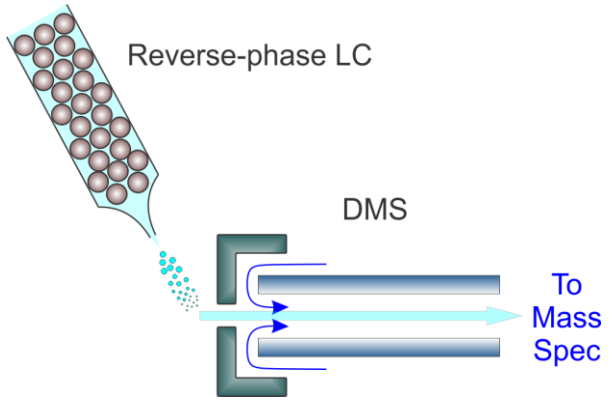
e.g., structure & dynamics of drug-protein complexes

Short-term (Year 3+): IR techniques

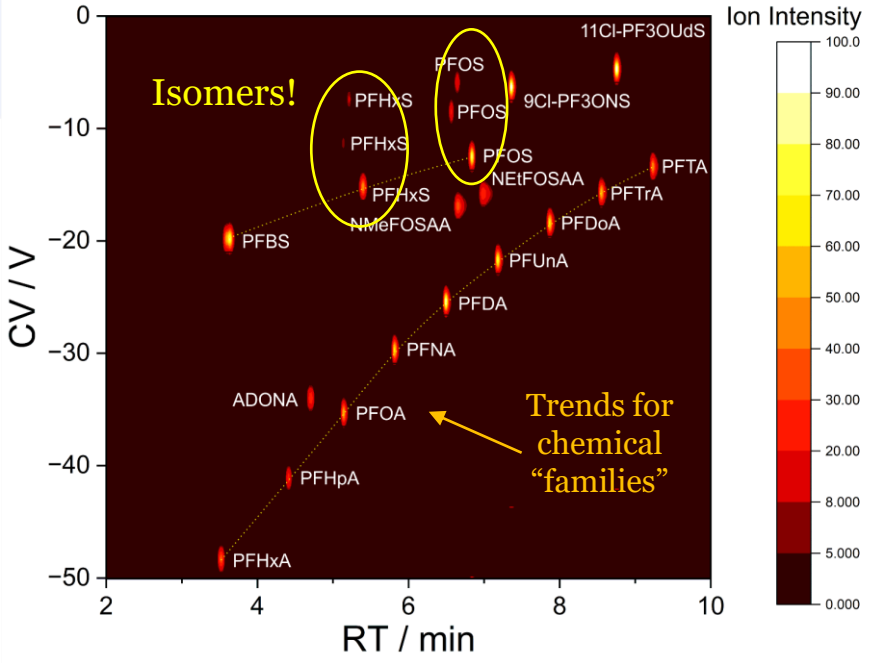
Infrared Multiple Photon Dissociation (IRMPD)

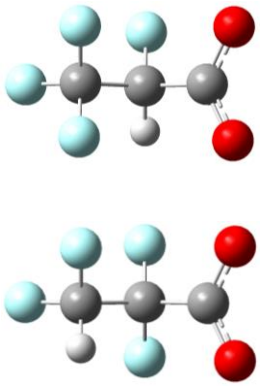


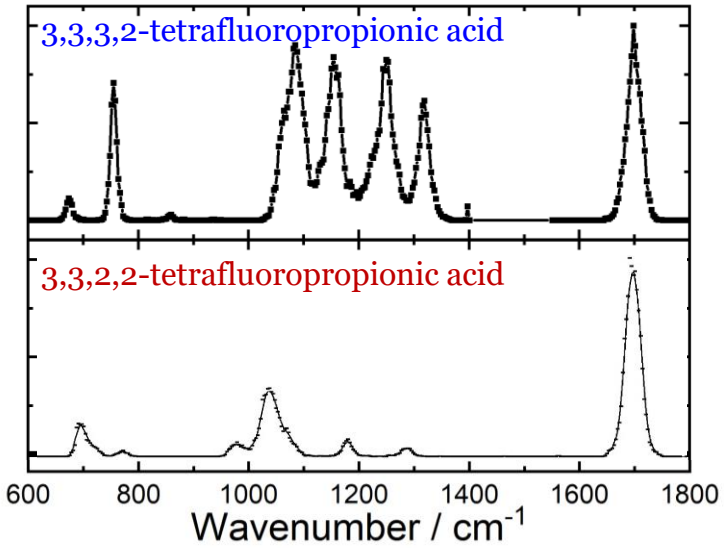
Chromatographic-, mobility-, and mass-selection



2D (LC×DMS)-MS/MS of PFAS mixture







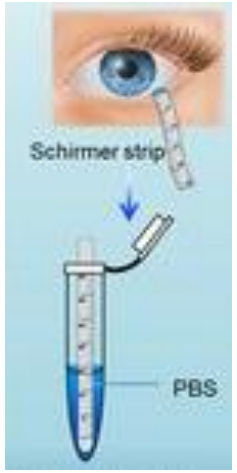
Applications in:

- Environmental monitoring
- Metabolomics
- Lipidomics
- Proteomics

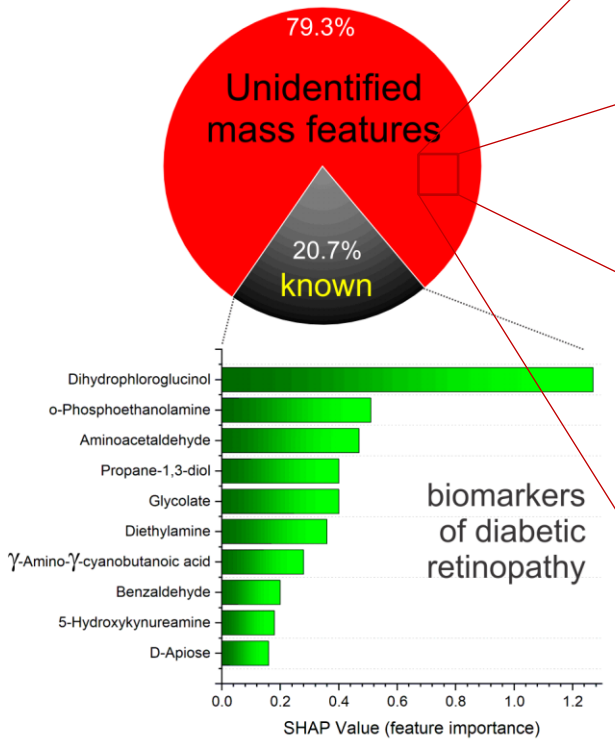
Short-term (Year 3+): Biomarkers

CEVR | The Hong Kong Polytechnic University 香港理工大學

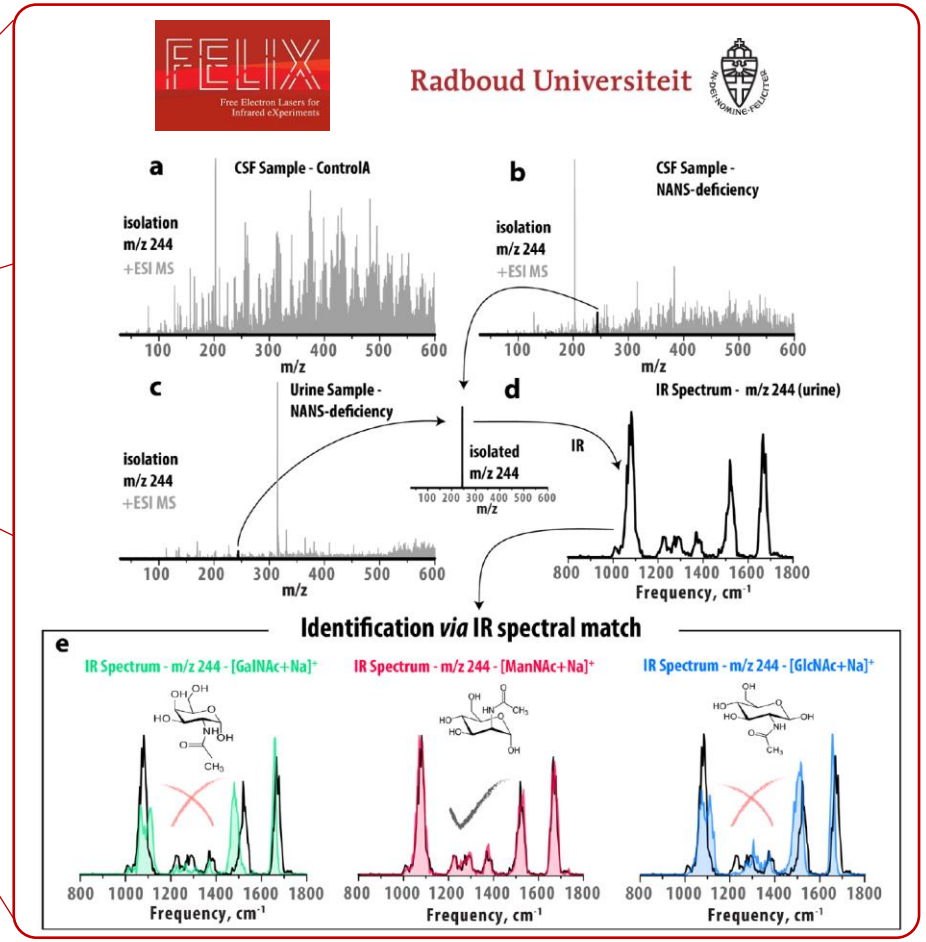
Diabetes w/o diabetic retinopathy (n = 30)
Diabetes w/ diabetic retinopathy (n = 25)



Non-invasive sampling of tear fluid

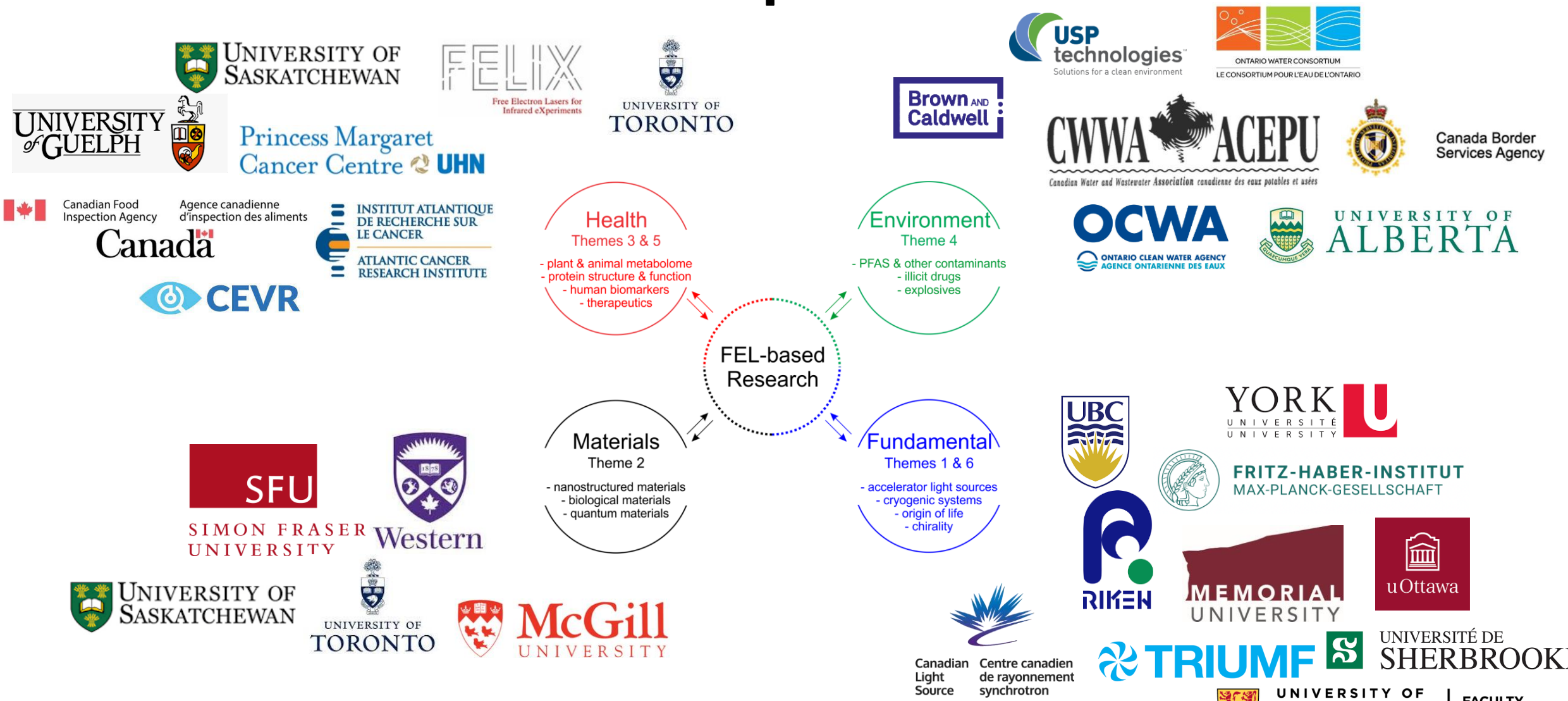


Mass Spec + ML identifies biomarkers of DR



IR spectroscopy identifies unknown metabolites

Short-term (Year 3+): Partnerships



Mid-term (Year 5+)

- 2-colour pump-probe operation
- e^- pump / IR probe (& vice versa)
- High-resolution mass spectrometry
- Velocity map imaging
- Coulomb explosion imaging

Francois Lagugne-Labarthet

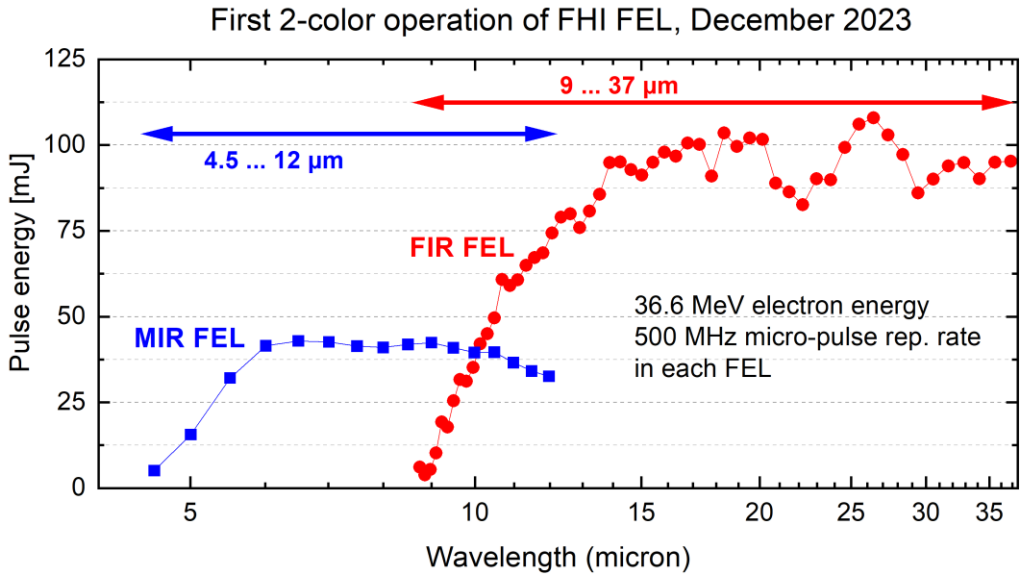
Western University · Canada

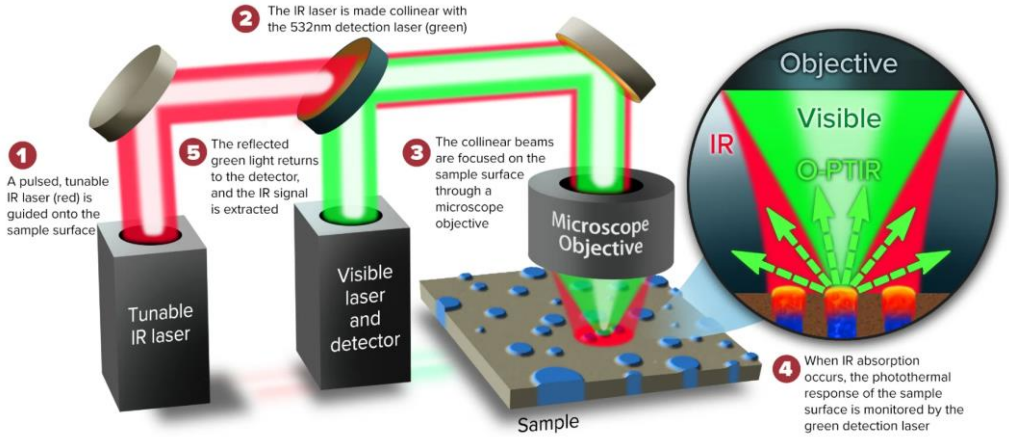
University of Saskatchewan

Ian Burgess

Canadian Centre of Excellence in Infrared Imaging and Nanospectroscopy

- NanoIR Spectrometer
- Confocal IR microscope
- Confocal Raman microscope





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- NanoIR Spectrometer
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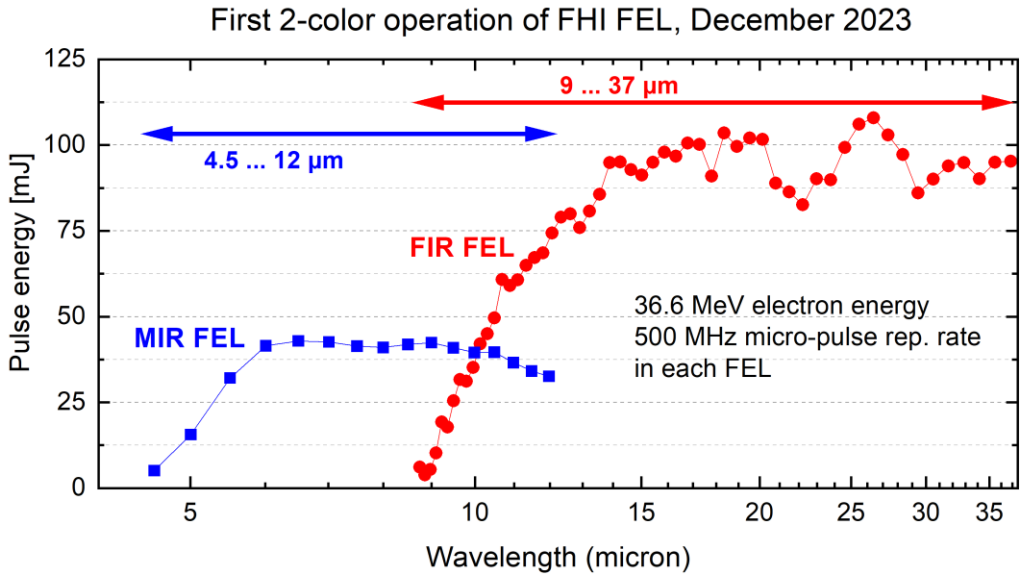

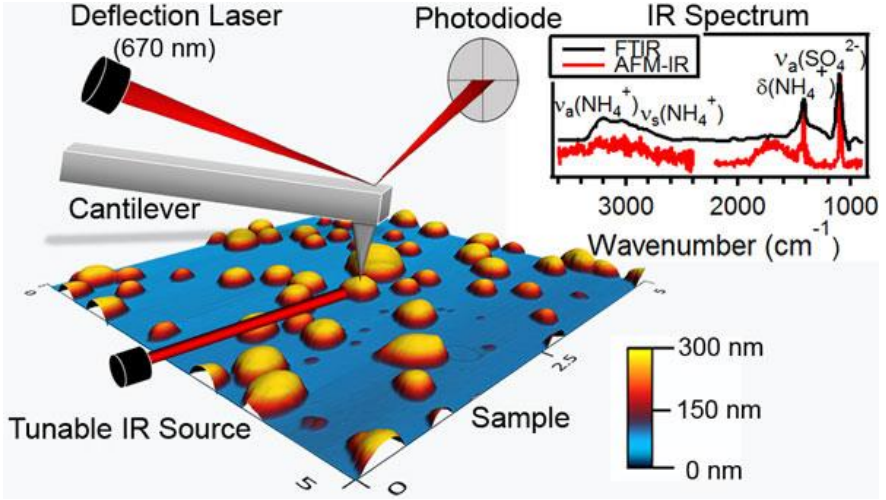

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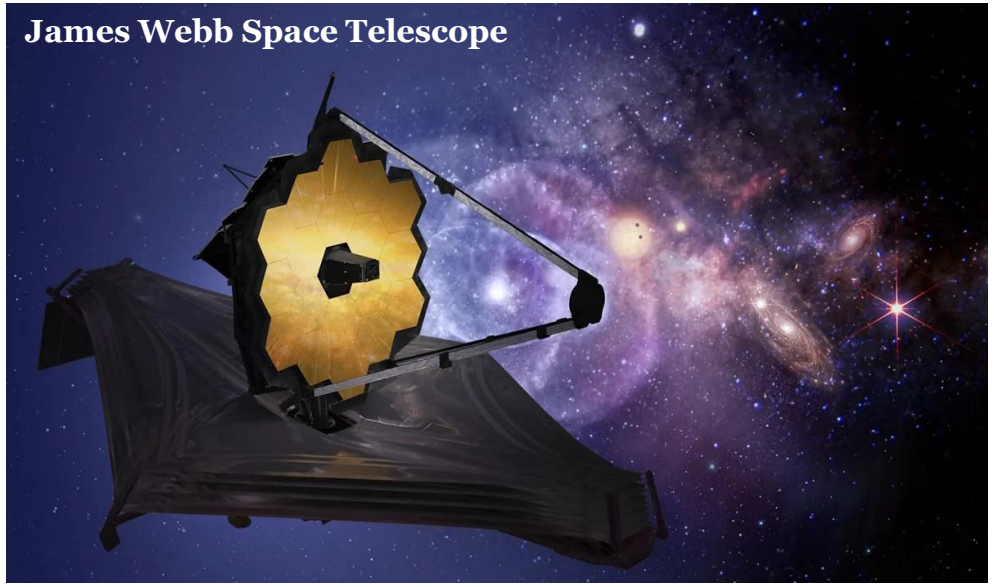
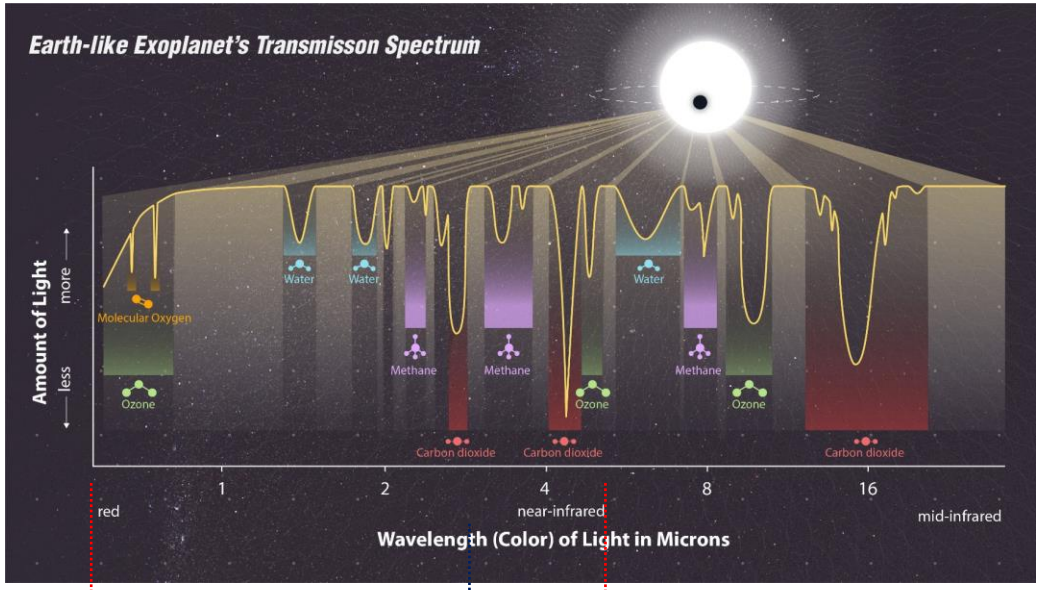
Mid-term (Year 5+)

The Origin of Life & the Search for Extra-terrestrial Life





Taka Momose

Ilsa Cooke

Benchtop lasers

120 μm

WaterFEL

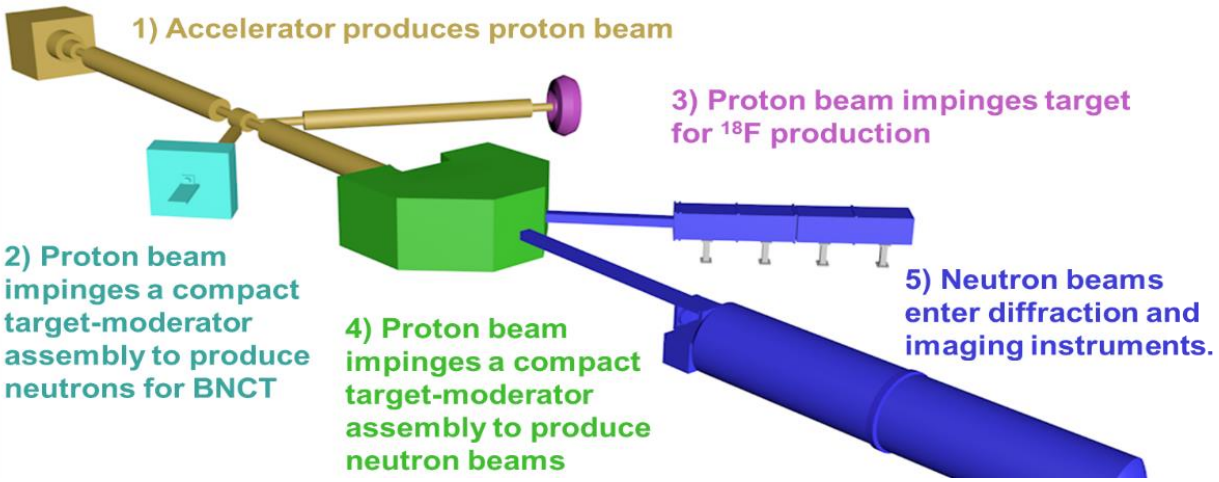
Homochiral genesis in space

Evidence of biosignatures in exoplanetary atmospheres

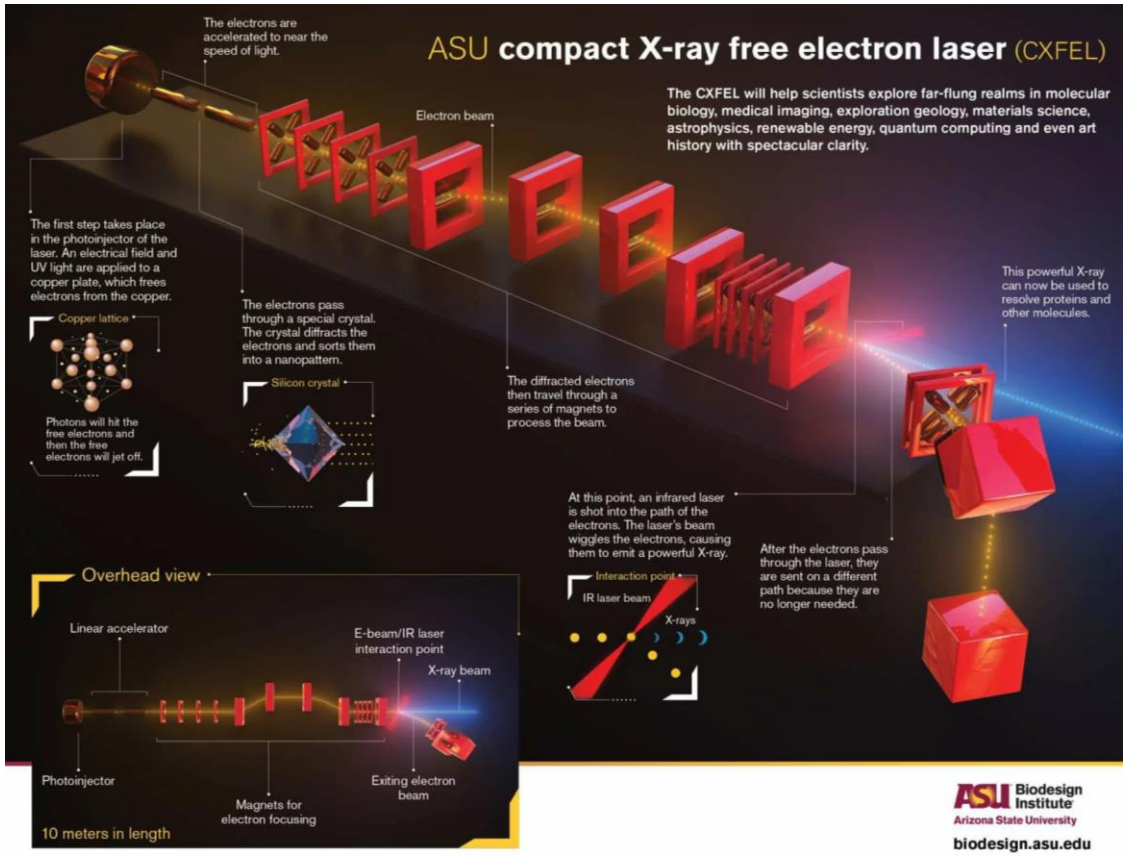
Long-term (Year 10+): Possible Directions?

Compact Neutron Scattering Source:

Neutron source based on a proton linear accelerator.



Compact X-FEL:



DISCUSSION

Points for discussion:

1. Sourcing & procurement (in general).
2. Gun procurement & front-end design.
3. RF frequency and structure design.
4. Possibility of repurposing existing magnets, diagnostics, etc.
5. Beam position monitor fabrication.
6. Undulator design, mapping, and fabrication.
7. Qualified optical fabricators.
8. Building/facility design.

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FACULTY OF SCIENCE

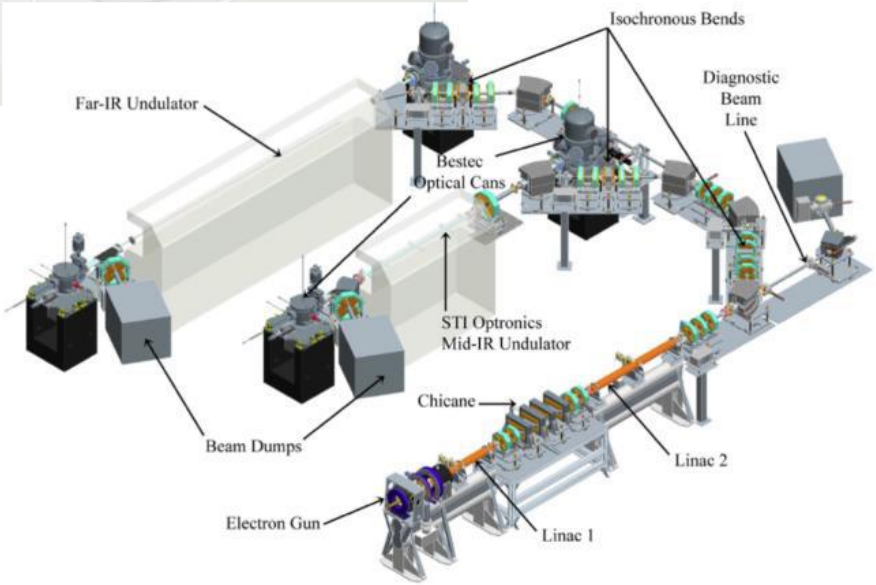
Thank you!

EXTRA SLIDES

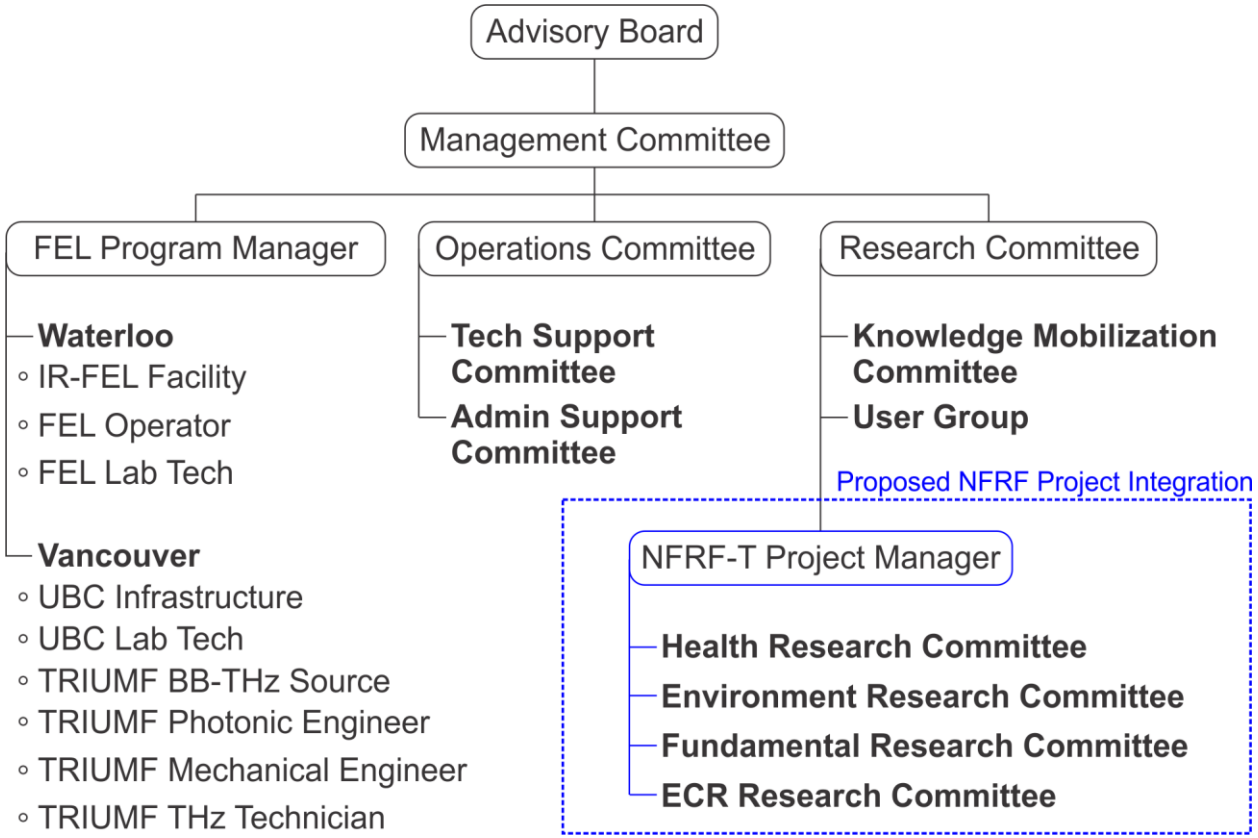
Space Requirements:

1. **THz FEL bunker**. 277.3 m^2 (2985 ft^2); 15.1 m × 19.0 m This area will accommodate: (a) the THz FEL accelerator, undulators, and the diagnostic electron beamline, (b) the laser seeding setup (objective 1.3), and (c) the electron beam station (objective 3.1). Laser seeding and *e*-beam experiments will be conducted remotely when the THz FEL is operating.
2. **Power service room**. 126.3 m^2 (1359 ft^2); 11.2 m × 11.2 m. This area (d) will accommodate the modulators, klystrons, power supplies, etc. for the THz FEL.
3. **Optics base**. 11.0 m^2 (118 ft^2); 3.3 m × 3.3 m. This area (e) will accommodate the calibration and power monitoring instrumentation for the THz FEL. It is a diagnostics lab for monitoring the FEL THz output. (Could be in RAC-1)
4. **IT and Control Room**. 32.6 m^2 (351 ft^2); 3.4 m × 9.6 m. This area will accommodate (f) the IT and controlling instrumentation for the THz FEL. (Could be in RAC-1)
5. **DMS-MS laboratory**. 38.8 m^2 (418 ft^2); 5.5 m × 7.0 m. This area (g) will accommodate the DMS-MS mass spectrometer, which will be used to accomplish objective 3.2.
6. **Cooling water service room**. 32.6 m^2 (351 ft^2); 3.4 m × 9.6 m. This area will accommodate (h) the deionized water-cooling system for the THz FEL.
7. **Expansion areas (left of floor plan)**. *Mass spectrometry suite*. 108.8 m^2 (1171 ft^2); 11.2 m × 9.7 m plus a storage area of 3.8 m × 3.8 m. This area will accommodate future mass spectrometry-based experiments. *Surface science suite*. 125.5 m^2 (1351 ft^2); 11.2 m × 11.2 m. This area will accommodate future surface and materials science experiments.

Christine Hancock
Plant Ops



Governance:



IR-FEL is a UW core facility:

- Safety
- HR
- Finance
- Etc.

} Under UW umbrella

BB-THz infrastructure:

O&M under TRIUMF umbrella

Management Committee:

Hopkins	Boland
Momose	Strickland
Kester	Santoro (external; industry)

Dr. Domenico Santoro
Dir. Research
USP Technologies Inc.
Adj. Prof. UWO

Infrastructure & Personnel Budget:

Table 2. Cost breakdown of System 1. Prices in $CAD.

Item	Eligible Cost	In-kind	Cash Required
Photo-emissive Source			
1.1. 500 keV DC photocathode gun	$1,695,406	$330,077	$1,365,329
1.2. Drive laser & optics	$967,372	$188,337	$779,035
1.3. Photonic Engineer	$489,921	$0	$489,921
Chicane Compressor			
1.4. Beamline components	$1,489,712	$290,030	$1,199,682
1.5. THz production, transport, diagnostics	$326,113	$63,491	$262,622
1.6. Mechanical Engineer	$452,518	$0	$452,518
System 1 Total	$5,421,042	$871,935	$4,549,107

Table 3. Cost breakdown of System 2. Prices in $CAD.

Item	Eligible Cost	In-kind	Cash Required
2.1. Accelerator Systems	$1,247,384	$242,852	$1,004,532
2.2. Magnetic Components	$908,924	$176,957	$731,967
2.3. Power Supplies	$238,494	$46,432	$192,062
2.4. RF Systems	$3,746,064	$729,317	$3,016,747
2.5. Ancillary Systems	$1,332,860	$259,493	$1,073,367
2.6. Beamline Systems	$387,070	$75,358	$311,712
2.7. Undulators	$2,460,657	$479,063	$1,981,594
2.8. Optical Systems	$1,618,836	$315,169	$1,303,667
2.9. *e*-beam Beamline	$504,854	$98,289	$406,565
2.10. Design, Labor	$1,305,769	$254,219	$1,051,550
2.11. Shipping, Installation	$1,727,678	$336,360	$1,391,318
2.12. Wavemeters, enclosures, etc.	$317,890	$61,890	$256,000
2.13. Safety interlocks, etc.	$95,014	$18,498	$76,516
2.14. Custom control software	$40,515	$0	$40,515
System 2 Total	$15,932,009	$3,093,897	$12,838,112

Table 4. Cost breakdown of System 3. Prices in $CAD.

Item	Eligible Cost	In-kind	Cash Required
3.1 Vacuum Components	$855,421	$166,541	$688,880
3.2 Spectrometers	$989,331	$192,612	$796,719
3.3 Irradiation Sources	$200,160	$38,969	$161,191
3.4 Mechanical Engineer	$156,544	$0	$156,544
System 3 Total	$2,201,456	$398,122	$1,803,334

Table 5. O&M 5-year budget breakdown.

Location/Expense	THz FEL	BB-THz Source	Cryogenic Spectrometer	Total
Personnel				
Project Coordinator	*$500,325 (across all sites)*			*$500,325*
FEL Operator (years 3-5)	*$270,000*	*$-*	*$-*	*$270,000*
Lab Technician (years 3-5)	*$240,000*	*$-*	*$-*	*$240,000*
Photonic Engineer	*$-*	*$157,579*	*$-*	*$157,579*
THz Beamline Technician	*$-*	*$95,469*	*$-*	*$95,469*
Mechanical Engineer	*$-*	*$144,226*	*$182,726*	*$326,952*
Subtotal Personnel	$676,775	$564,049	$349,501	$1,590,325
Consumable Supplies	$150,000	$100,000	$50,000	$300,000
Maintenance & Repairs	$261,950	$200,000	$50,000	$511,950
Services (*e.g.*, power, water)	$1,000,000	$-	$100,000	$1,100,000
Total O&M	**$2,088,725**	**$864,049**	**$549,501**	$3,502,275

*Personnel salaries from IOF (committed)