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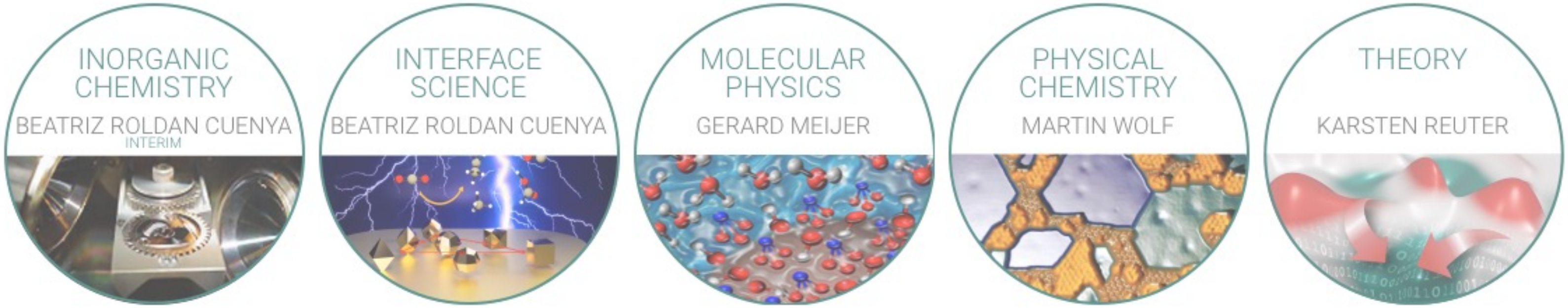
The WATERFEL Project

- Goal: Establish a Mid to Far IR FEL User Facility (~ 3 to 165μ) at the University of Waterloo and a THz beamline at TRIUMF/UBC for Physical Chemistry R&D, funded by CFI and the Provinces of Ontario and British Columbia
- Timeline: 5 Years
- Baseline Assumption: Where possible, build upon the highly successful FEL at the Fritz-Haber-Institut (FHI) der Max-Planck-Gesellschaft (MPG)
- Desired workshop outcome for WATERFEL: Identify possible points of departure from the existing FHI FEL design in the process of selecting a baseline design for key components that will enable final physics and engineering design to proceed

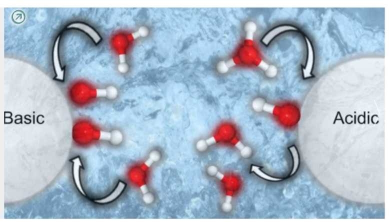
Outline

- The FHI FEL specifications, performance to date and how it operates
- Addition of a Radiolysis target station (presently deferred)
- Possible deviations from the FHI FEL design & known vendor issues
  - Redesign of front end for new electron gun
  - RF frequency selection (NA or Euro S-band?) => use of existing CLS linacs or build to print of existing AES/FHI drawings
  - Selection of potential undulator vendors – undulators must be rad-hard (FHI U-40 has been in use for 12 years with no present sign of degradation)
  - Use of existing diagnostics and magnets
  - Other
- Discussion

The Fritz-Haber-Institut (FHI)

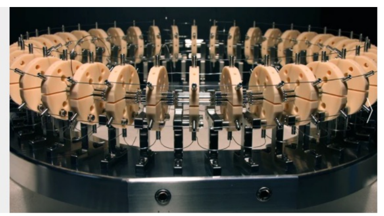


Electronic structure of aqueous-phase anatase titanium dioxide nanoparticles probed by liquid jet photoelectron spectroscopy

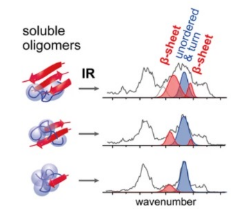


Home of the molecular synchrotron

A milestone for molecular beams

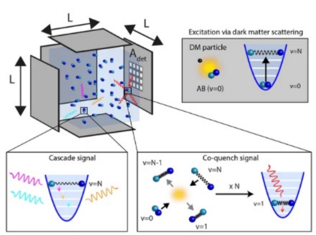


Molecular Stew Analysis Produces World´s First Description of Amyloid Intermediate Structures



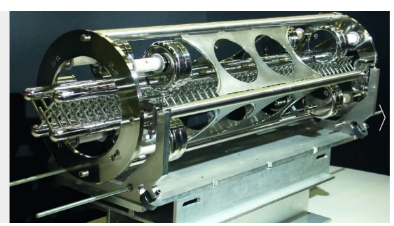
Molecules as a light dark matter detector

Internal degrees of molecules are a great sensor for light dark matter

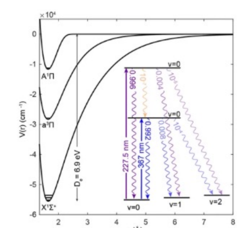


Stark decelerator

The ultimate molecular control tool



Laser cooling of diatomic polar molecules



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Timeline of FHI Project

- Max-Plank-Gesellschaft (MSG) approves FHI FEL funding in 2008
- Advanced Energy Systems (AES) selected to build FHI FELs in February 2009
- First lasing of Mid-IR FEL at 16 microns on Valentine’s Day 2012
- User facility for 3 to 60 micron radiation from mid 2012 on
- Far-IR project initiated under FHI direction with former AES personnel in 2019
- First Far-IR lasing achieved at 8 microns on June 8, 2023, following long COVID-19 delays
- Remarkably, first simultaneous two-color lasing achieved after half a day of commissioning at 18 and 55 microns on December 8, 2023
- Lasing achieved at 176 microns from the FIR-IR FEL with 16.75 MeV beam energy on February 12, 2024
- An 11 MeV beam has been demonstrated in February 2024 which could be used on the WaterFEL Radiolysis beamline
- To date the FHI FELs have generated ~ 100 refereed publications in basic physical chemistry research with FIR and two-color research yet to begin in earnest
- First FIR User experiments are anticipated later this year with potential research over the next few years performing FEL pulse structure characterization by balanced optical cross-correlation, pump-probe experiments in doped semiconductors, four-wave-mixing microscopy and other topics

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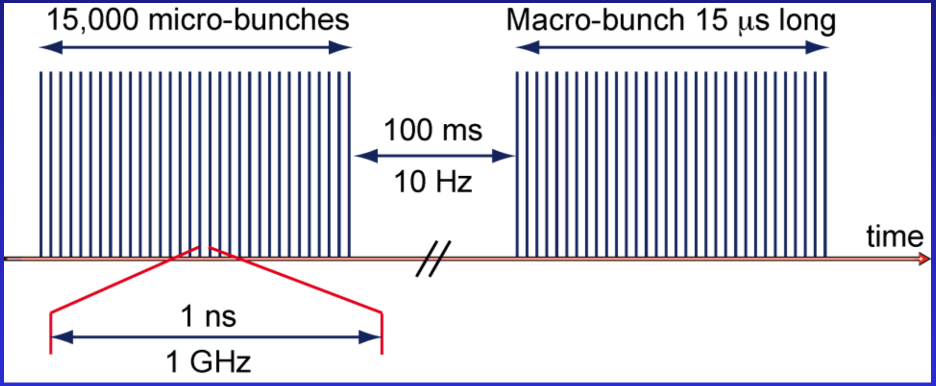
Linac specs summary

Normal-conducting S-band accelerator:

electron energy: 18 - 50 MeV
rf frequency: 3 GHz
bunch rep. rate: 1 GHz
bunch charge: > 200 pC
bunch length: 1 - 5 ps
macro-bunch length: 20 µs
macro-bunch rep. rate: 20 Hz
energy spread: < 50 keV
energy drift: < 0.1% per hour
norm. transverse emittance: 20 π mm mrad
beam power: up to a few kW

Macro-bunch temporal structure



Design and construction of linac and e-beamline:
Advanced Energy Systems, Inc., Medford, NY, USA

→Talk WEOC04 by Alan Todd

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Specs of FHI FEL

Mid-IR:

IR wavelength: ~4 – ~50 μm
IR cavity length: 5.4 m
IR waveguide: none

Undulator: planar hybrid, NdFeB
- period: 40 mm
- number of periods: 50
- length: 2 m
- rms-K: 0.5 – 1.6

Far-IR:

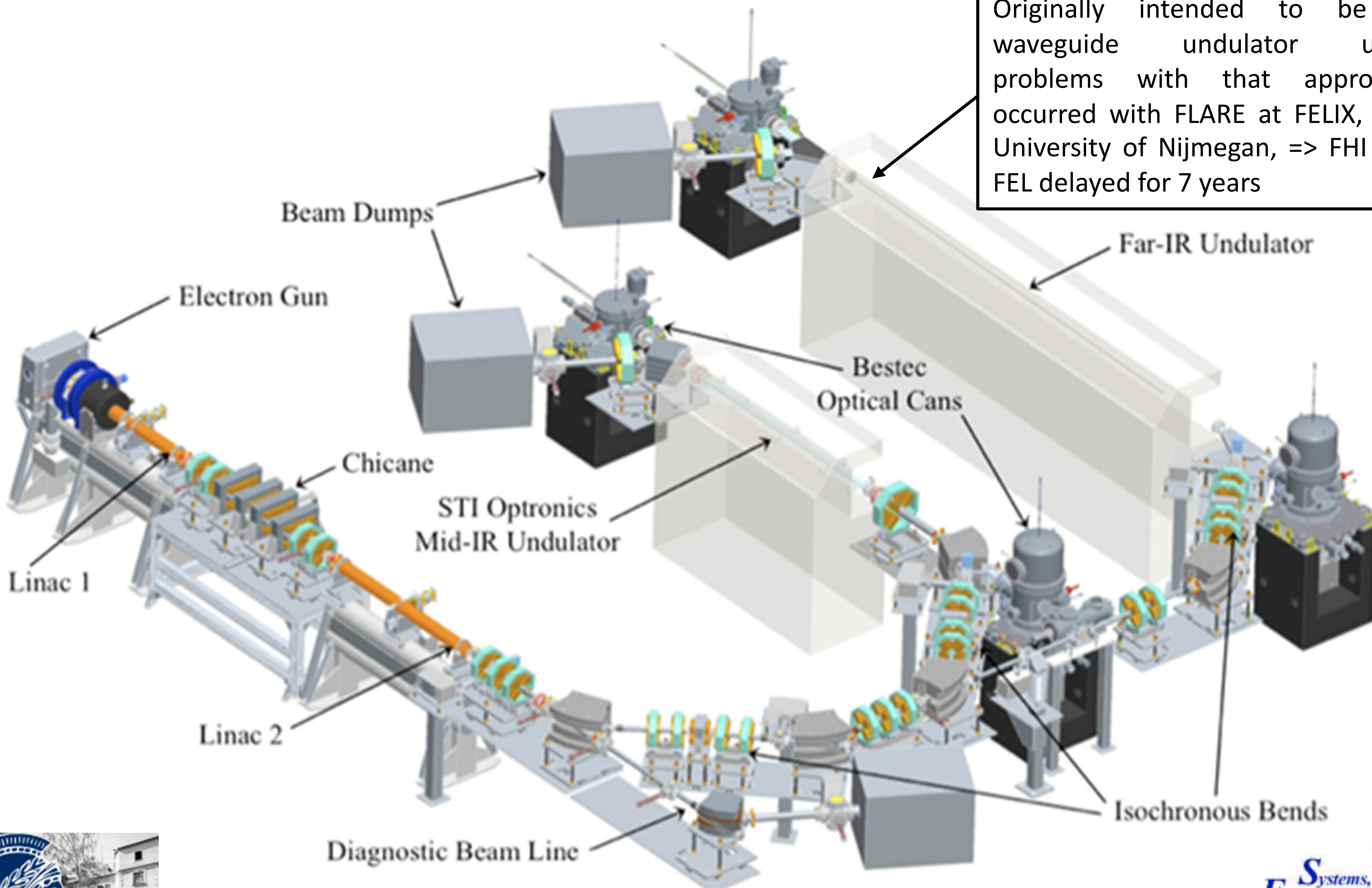
IR cavity length: 5.4 m
IR wavelength: 4.5 – 176 μm

Two-color lasing => equal length MIR & FIR optical cavities

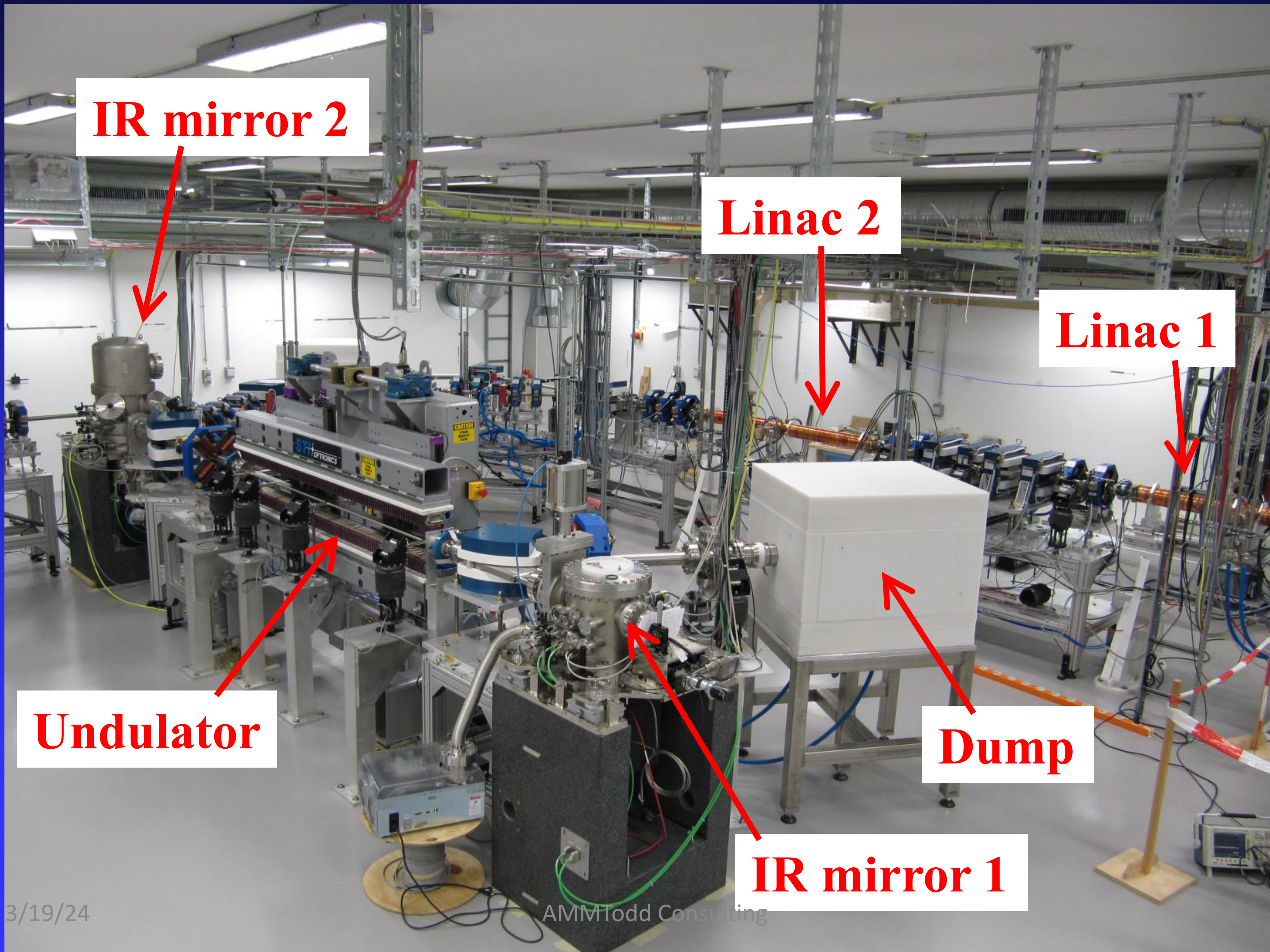
Undulator: planar hybrid, NdFeB (Short Rayleigh Range)
- period: 68 mm
- number of periods: 33
- length: 2.28 m
- rms-K: 0.46 -2.29

Original FHI FEL Layout

Originally intended to be a waveguide undulator until problems with that approach occurred with FLARE at FELIX, the University of Nijmegan, => FHI FIR FEL delayed for 7 years



Photograph of FHI FEL

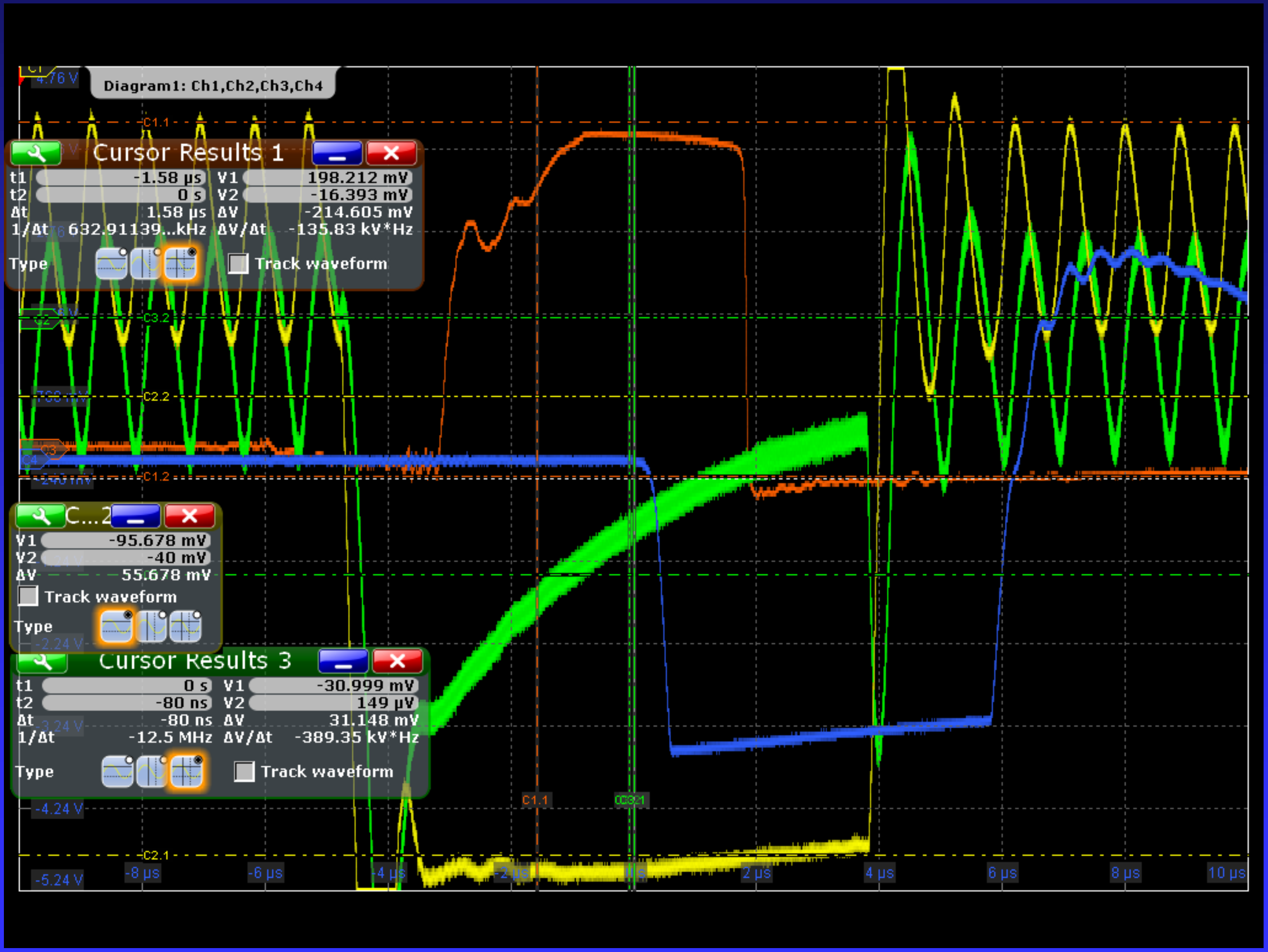


First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

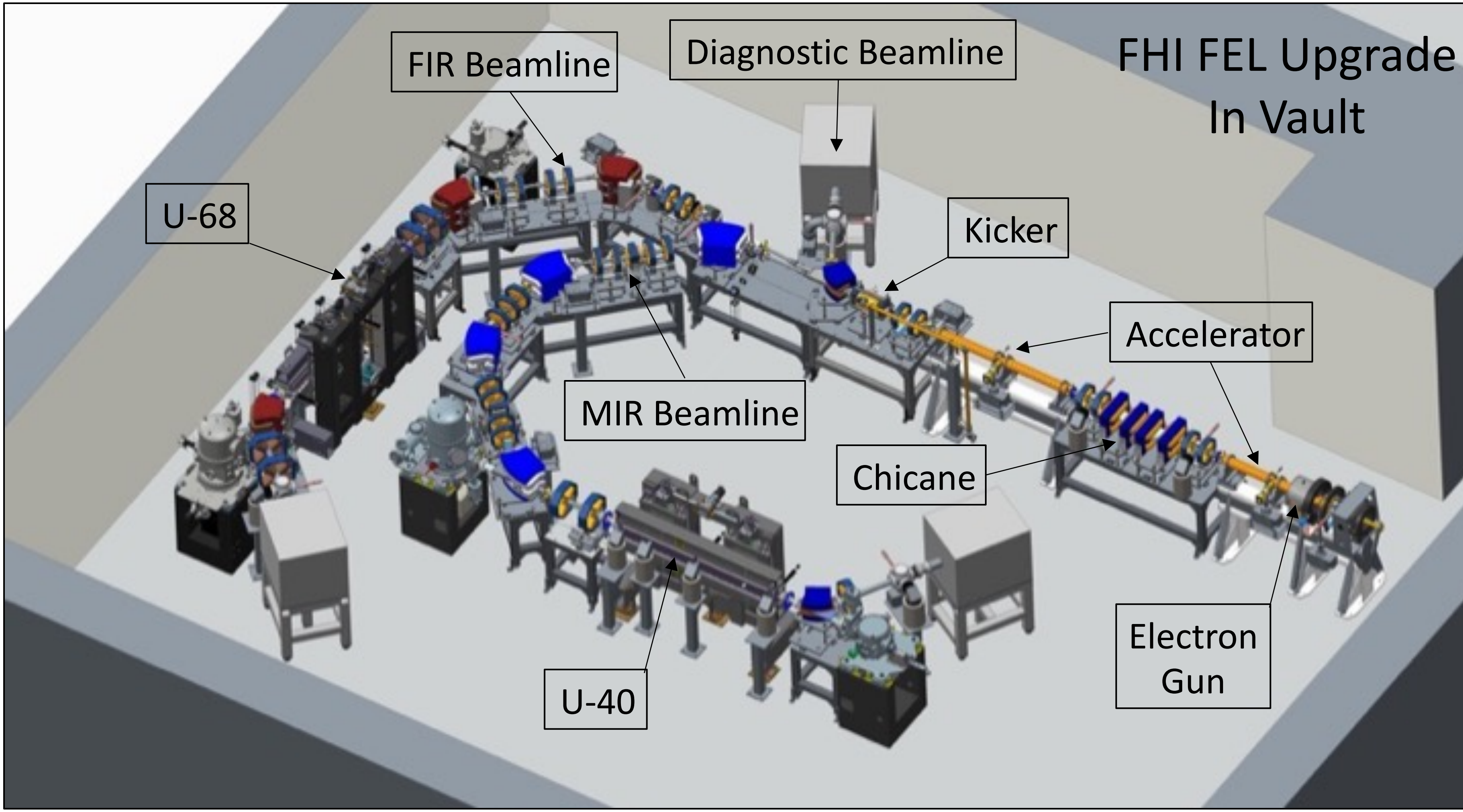
ΔL = 60 μm



E_{El} = 28 MeV

λ_{IR} = 16 μm

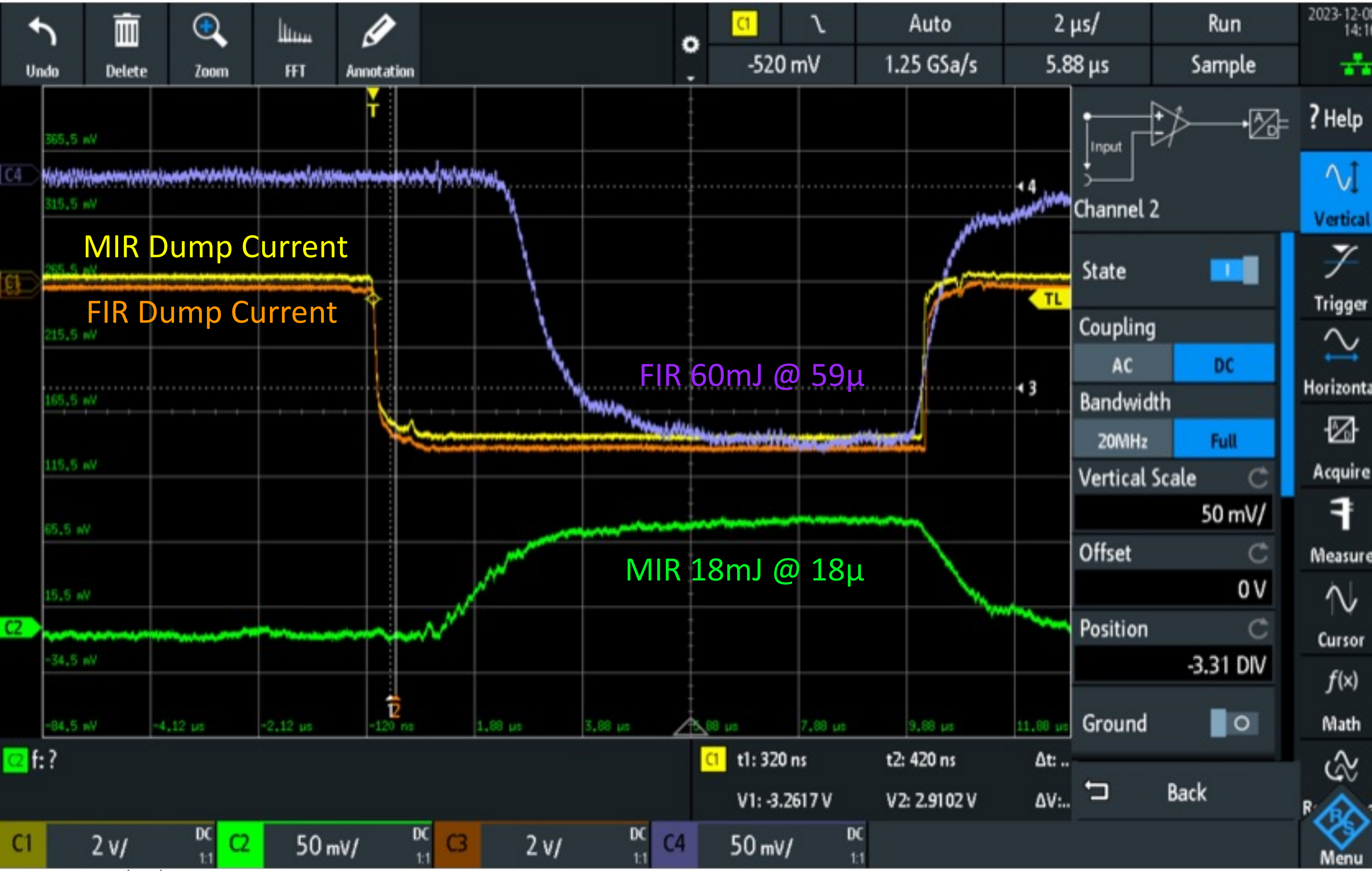
Revised FHI FIR FEL Layout



- Discovered unexpected space charge emittance growth in original FIR beamline design
- Design modified to reduce the undesired emittance growth impact and introduce two-color lasing concept – new short Rayleigh range undulator design delivers 4.5 to 176 micron radiation with optical cavity length identical to MIR

FIR FEL Beamline Collage

First Two-Color Lasing 12/8/23



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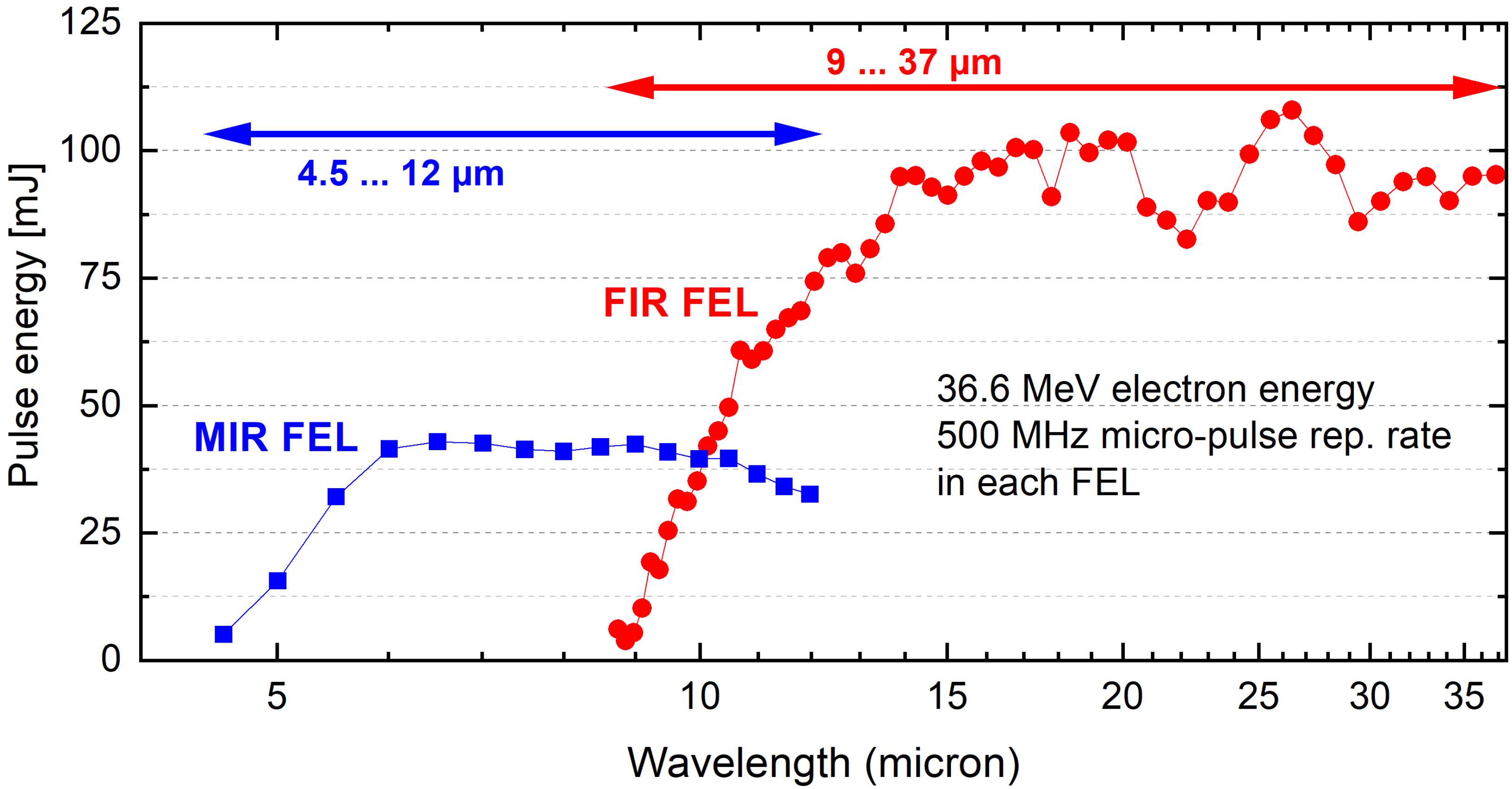
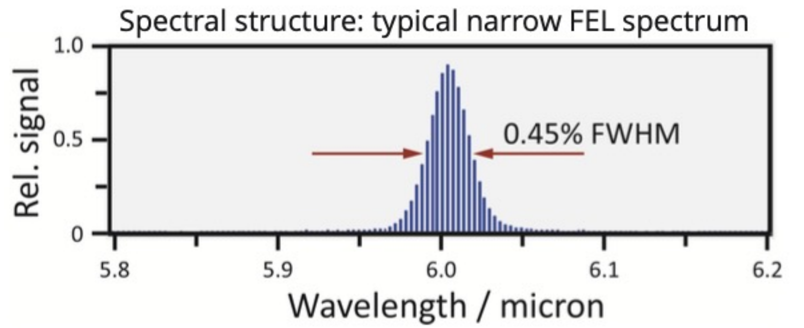
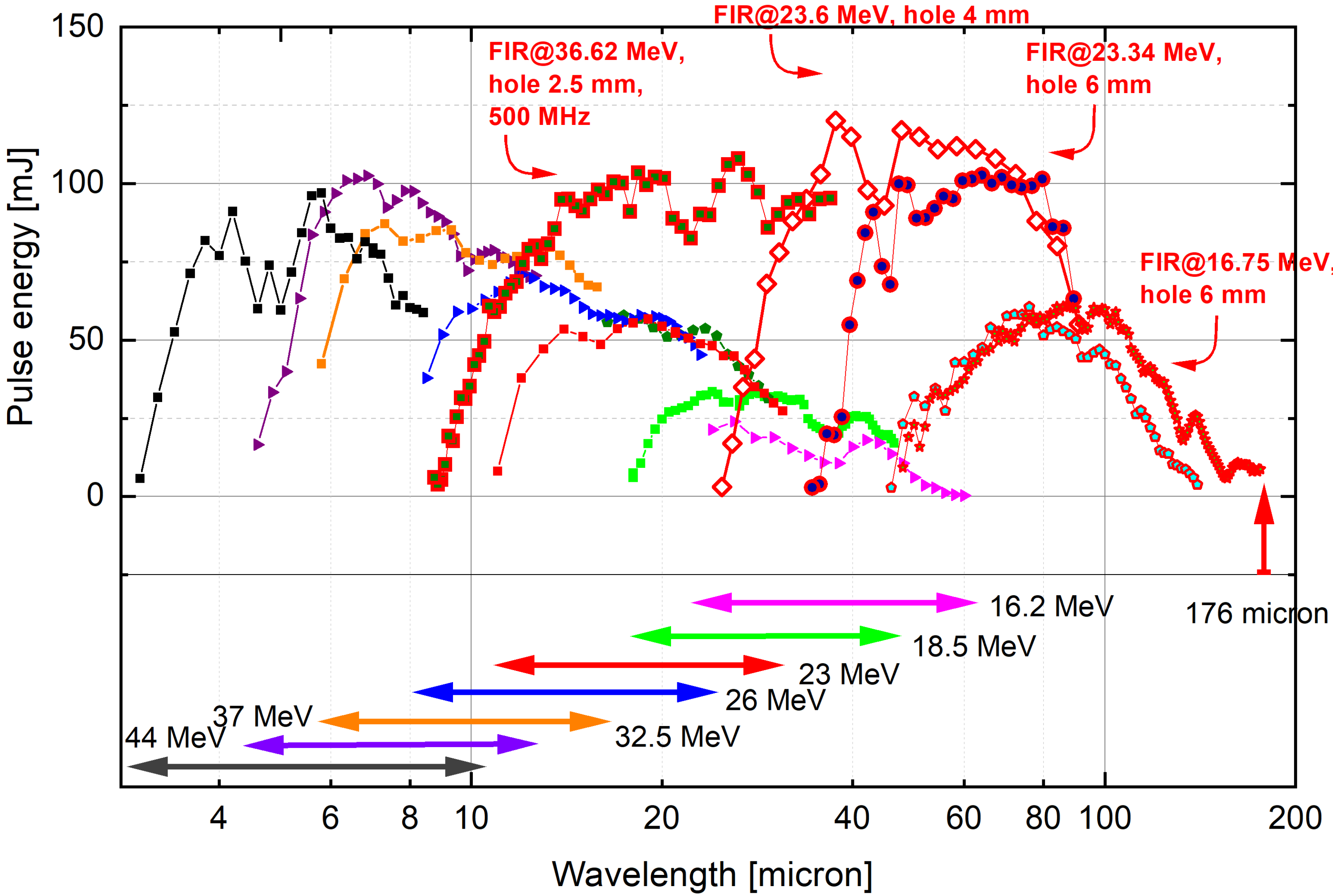
Two-Color Gap Scan 12/23



- High and quite reasonably uniform FIR radiation power for early gap scans
- > factor of four in FIR single gap scan radiation spectrum (9 to 37 micron)
- Nearly factor of three in MIR single gap radiation spectrum (4.5 to 12 micron)

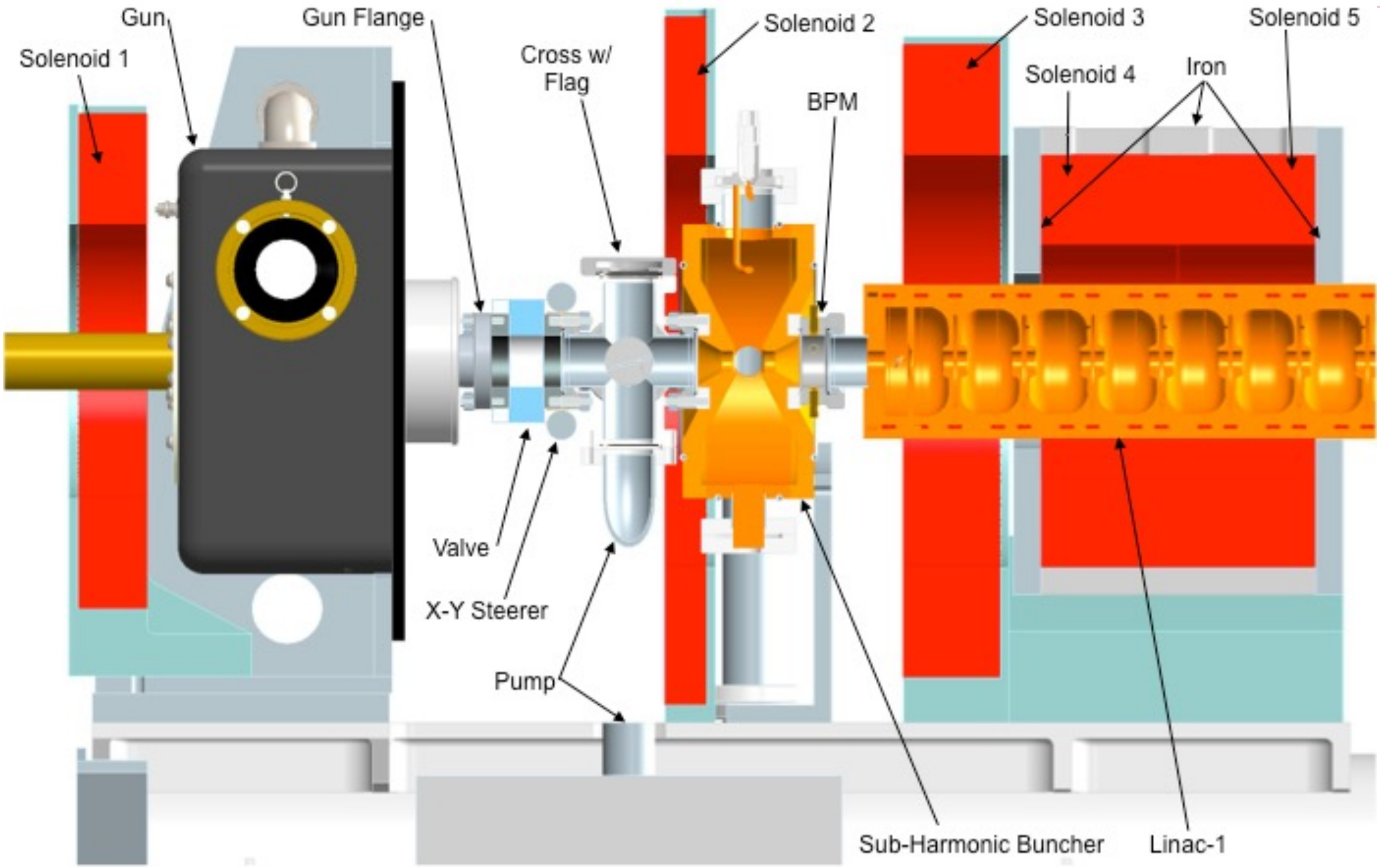


FHI FEL Wavelength Range Achieved To Date (2/12/2024)



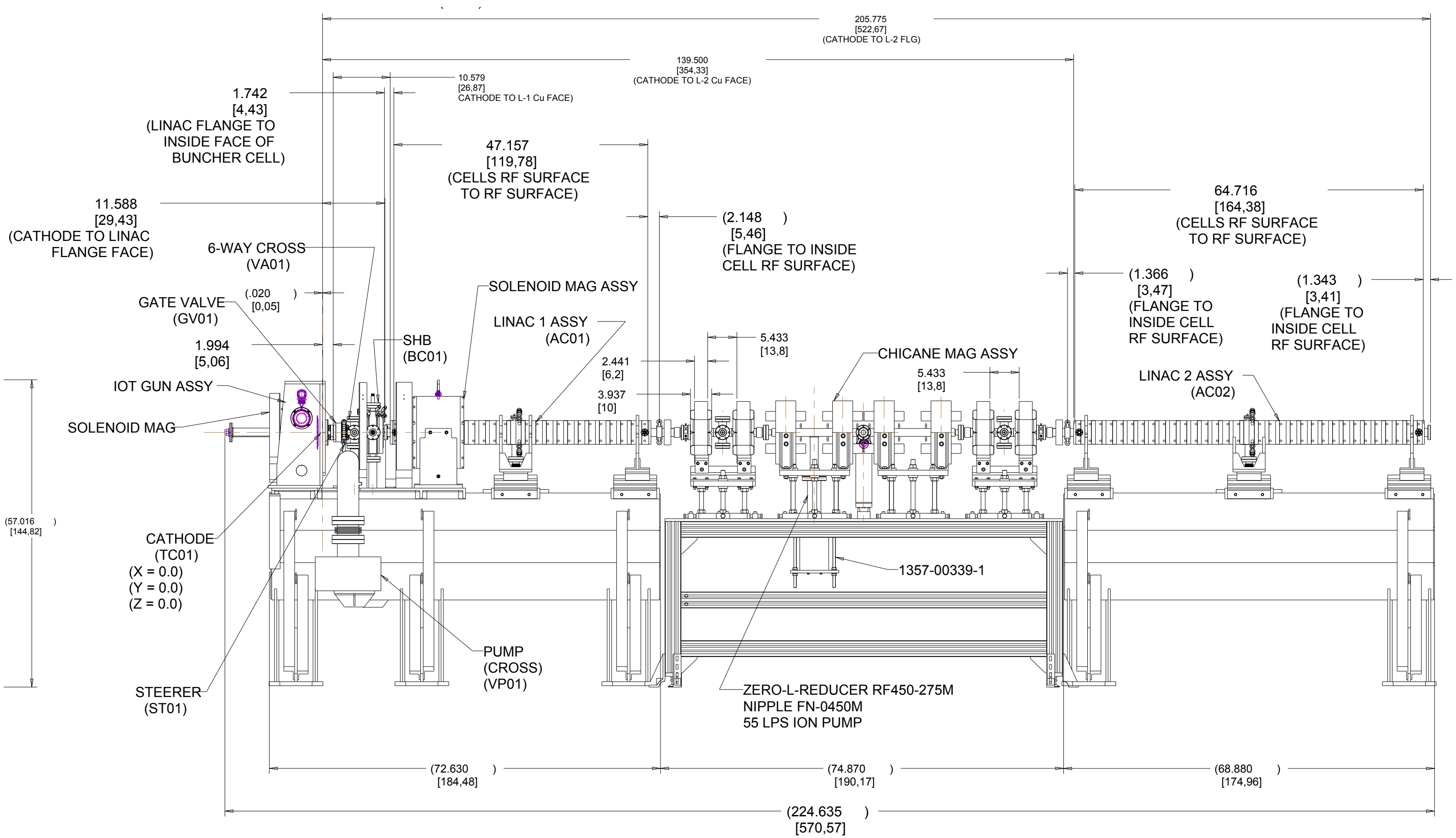
- Achieved wavelength range is presently ~ 2 (@48 MeV) to ~ 176 microns (@16.75 MeV)
- Any thoughts on the somewhat random holes – FHI & friends are puzzling about this?

The FHI FEL Front End



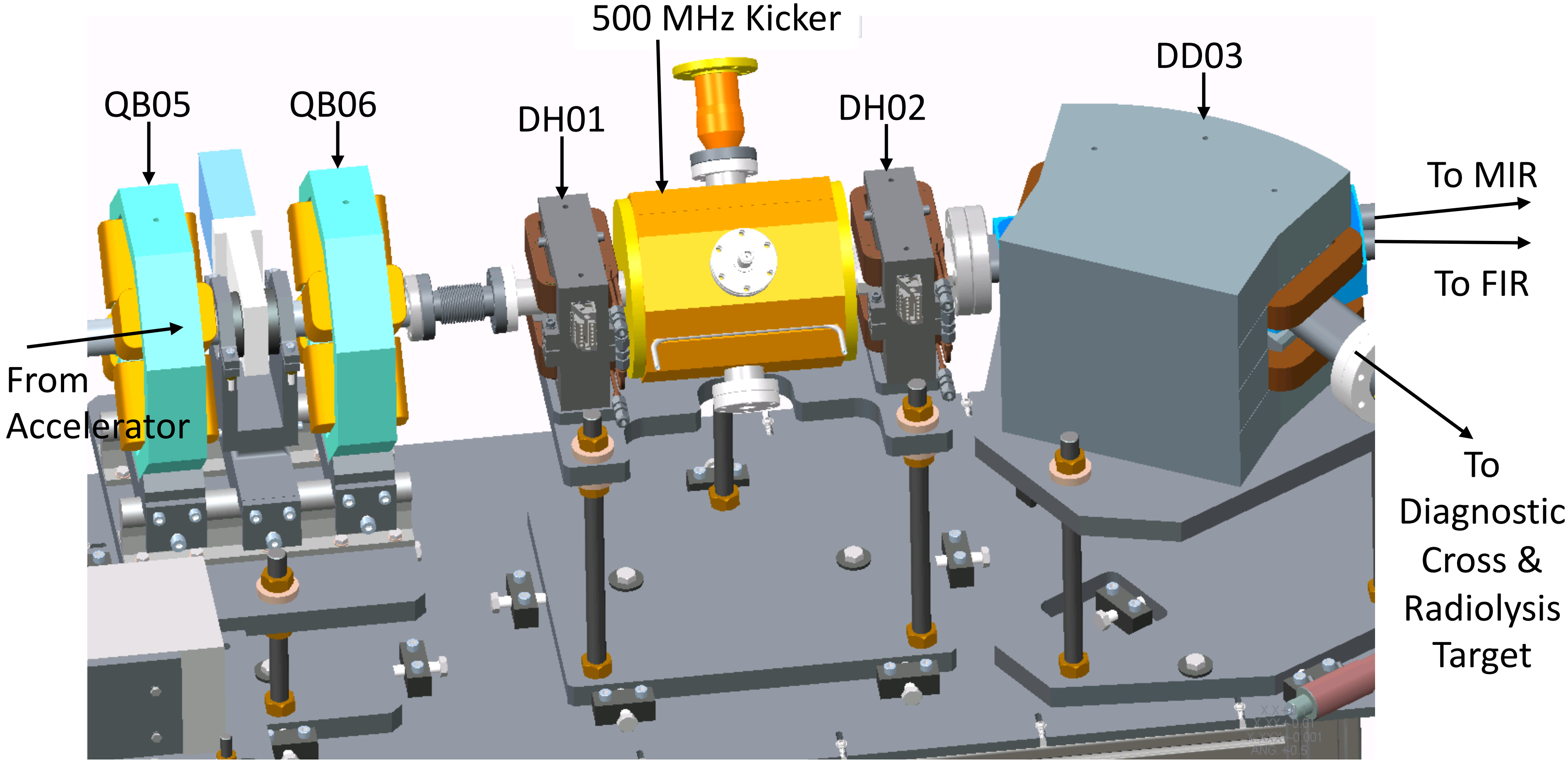
- CPI IOT electron gun no longer in production – requires a replacement. Grid RF voltage pulsed at 1 GHz. Spacings are tight and crucial at 40 kV
- 1 GHz SHB bunches electron pulses for acceptance into the 3 GHz accelerators
- Linac 1 has a resonant bunching cell followed by a half cell and then two foreshortened cells

FHI FEL Accelerator Section



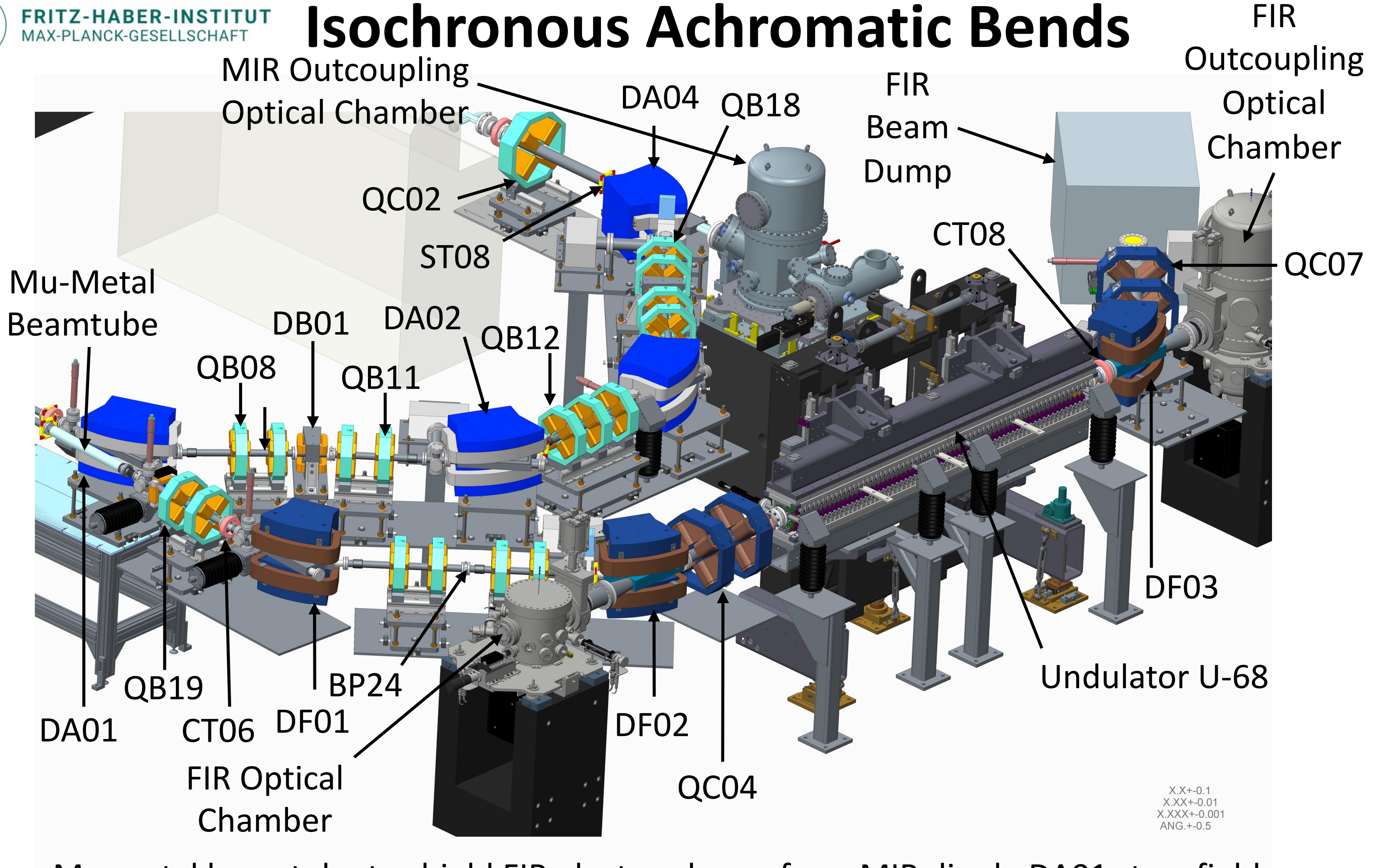
- Linac 1 always accelerates the electron beam to ~ 20 MeV while Linac2 further accelerates or decelerates the beam to deliver 11-48 MeV (achieved to date)
- The chicane compresses the bunch to nominally 1 psec after which point the bunch length is locked in because of the achromatic isochronous bends

Kicker Cavity & Diagnostic Beamline



- MIR beamline => DH01, DH02 & kicker off. FIR beamline => DH01 = DH02 = -2 degrees, kicker off. 2-color operation => DH01 = DH02 = -1, kicker = ± 2 degrees
- 4 degree separation between MIR and FIR beamlines
- DD03 on for beam to diagnostic beamline and radiolysis target station

Isochronous Achromatic Bends



- Mu-metal beamtube to shield FIR electron beam from MIR dipole DA01 stray fields
- MIR isochronous achromat dipoles +48, -6, +48 degrees. FIR achromat (not quite isochronous) dipoles +47, +47 degrees

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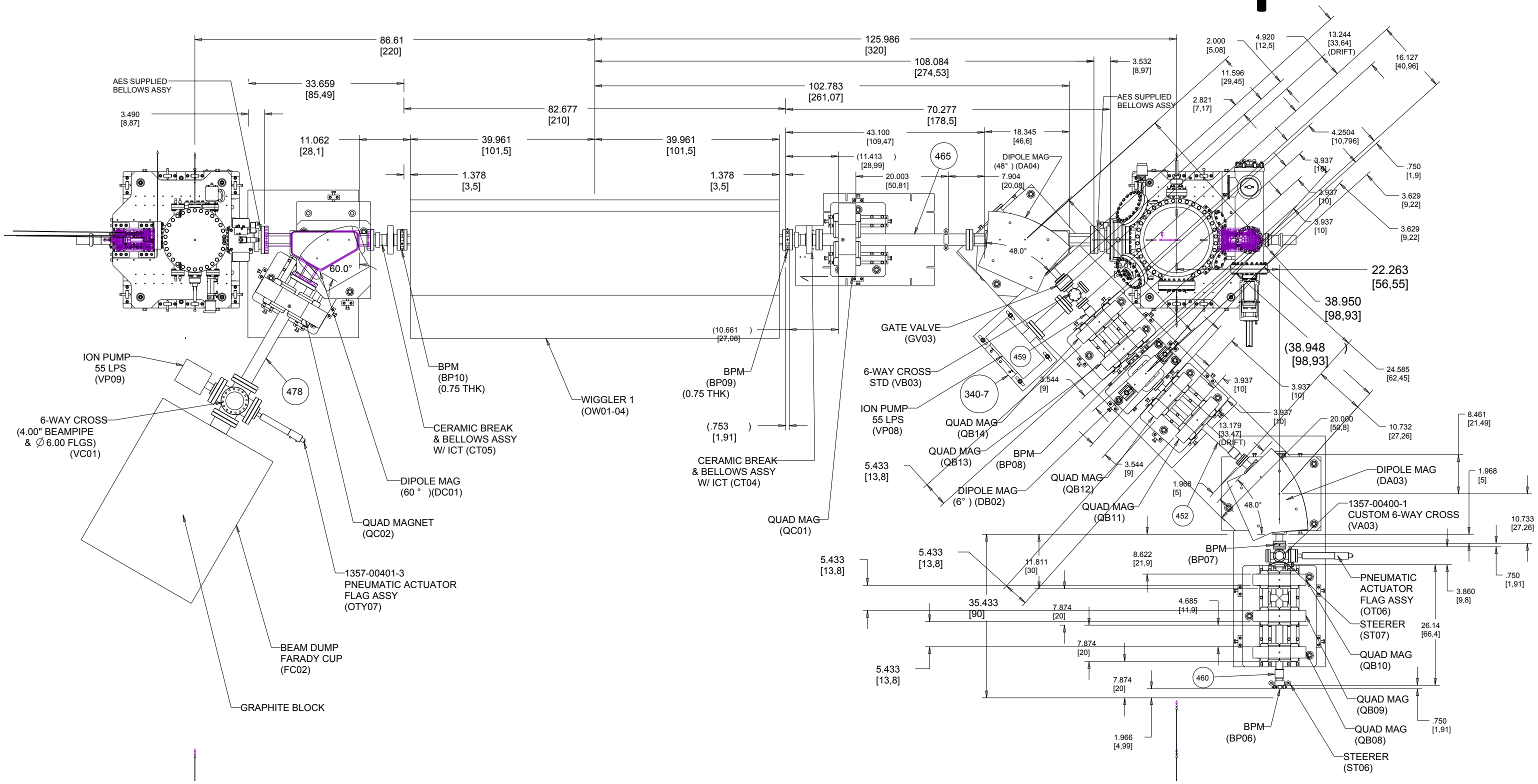
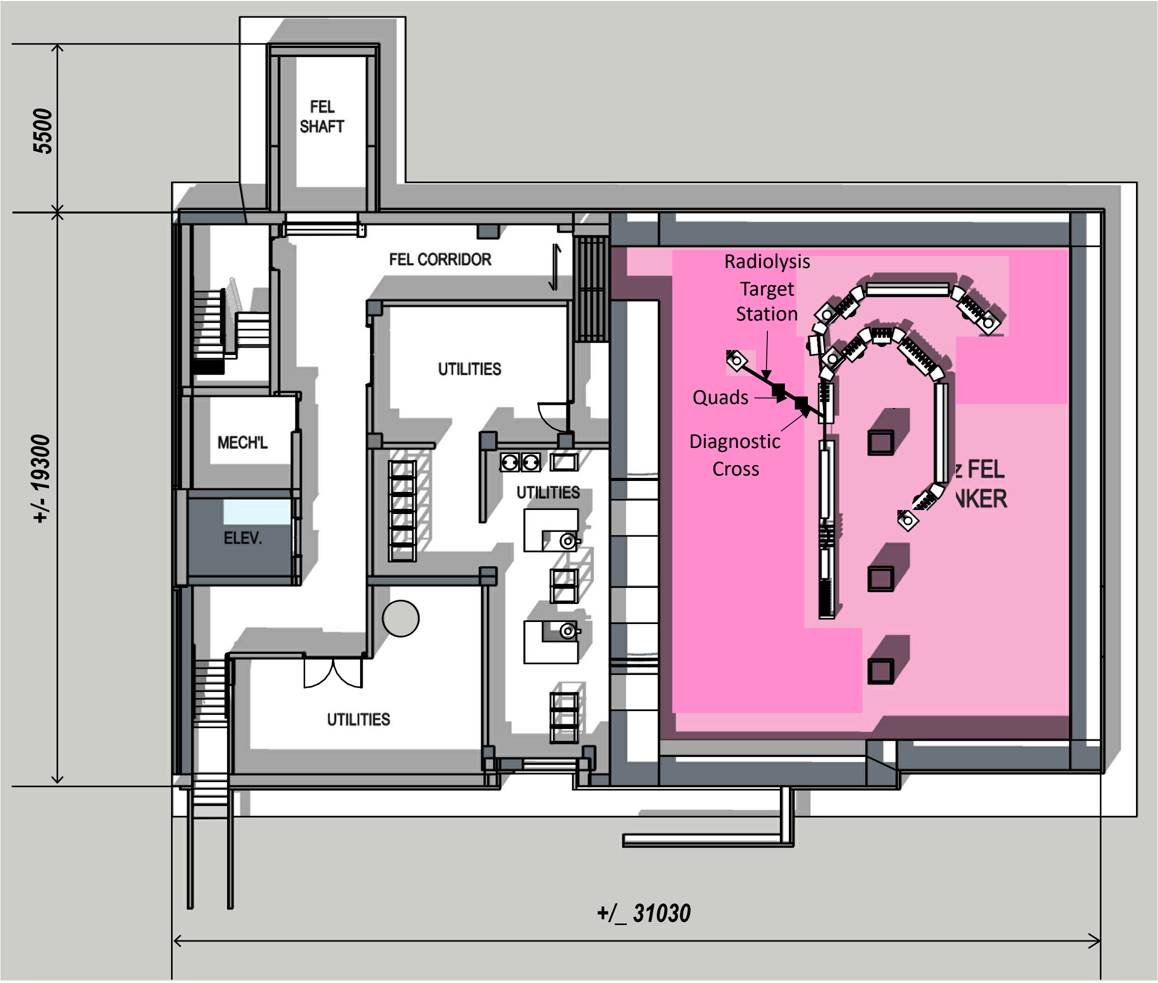
Advanced Energy Systems, Inc.

U-40 Undulator, MIR Optical Chambers & Beam Dump



- Rad-hard MIR U-40 undulator designed and manufactured by STIOptronics (STIO), Bellevue, Washington, USA
- Rad-hard FIR undulator designed by STIMagnetics (STIM), an offshoot of STIO, Woodinville, Washington, USA, assembled by FHI with STIM remote assistance and measured at FHI with STIM on-site assistance
- MIR and FIR optical chambers manufactured by Bestec GmbH, Berlin, Germany https://www.bestec-berlin.de

Possible WaterFEL Configuration



- Eventual radiolysis target station shown beyond diagnostic cross where beam energy and energy spread can be measured. Minimum energy for radiolysis is 11 MeV.
- The pillars are a pain.

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Electron Injector Options

- CPI no longer manufacture the resonant 1 GHz IOT electron guns that were used for FHI so we need a new vendor

Electron Gun Parameters		
Bunch Charge	220	pC
Micropulse & Grid Bias Voltage PRF	1	GHz
Macropulse & Gun HV PRF	20	Hz
Macropulse Length	20	µsec
Peak Current	220	mA
Duty Factor	0.04%	
<Current>	88	µA
Bunch Radius	< 0.5	cm
Normalized Emittance	< 20	π mm-mrad
Voltage	45	kV
Grid Bias Voltage	~ -180	V

- Possible vendors: Heat Wave Labs. https://www.cathode.com (US$66K + Options)
  Stellant Systems https://stellantsystems.com
  ~~AcceleRAD Technologies https://accelerad.com/products~~
  ~~Altair https://altairusa.com/electron-guns~~
  Kimbal Physics https://www.kimballphysics.com
  Calabazas Creek https://calcreek.com
  ~~CPII https://cpii.com~~
  Triumf?
  Other?

No Response to RFI

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RF Frequency Options

- CLS has available linacs that the project can use on-loan, but the consequences are worrying
- FHI uses Euro S-band, CLS has NA S-band linacs
- Consequences: 1) can the CLS structures fit the accel-decel operational mode required for flexible FEL operation & deliver 11-50 MeV in two sections else the layout gets worrisome, 2) there will be an impact on beamline spacing & it will require re-engineering the SHB & Kicker as well as reworking the beam dynamics physics design and matching => $$$, 3) is there a suitable 20kW/20MW klystron at NA S-band – we do know Thales is making the Euro S-band TH2130 again (CLS used 15MW klystrons), 4) probably means the FHI electronic schematics for preamps, pulser, SHB supply and other RF components need rework and require slightly different components
- Radiabeam ROM RF quote for structures was CAD$2.024M! RI ROM RF quote was €486K (~CAD$716K). Our inflated budget estimate was CAD$755K)
- Scandinova modulator + klystron quote is CAD$2.6M whereas we had budgeted an inflated cost of CAD$1.9M => so a problem here unless we can get a price break
- Thoughts?

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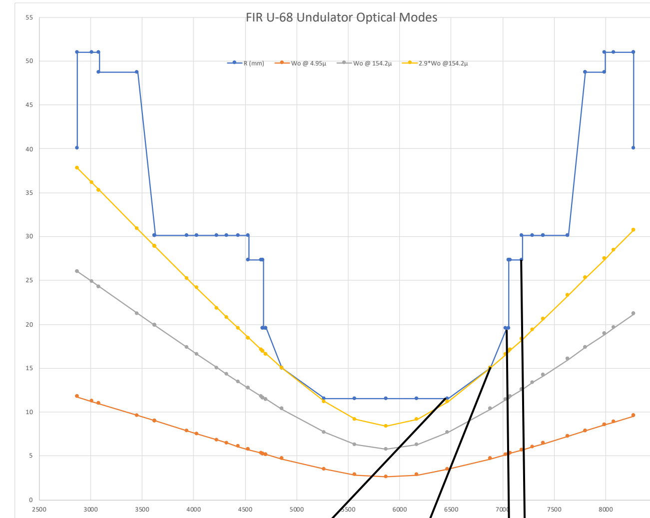
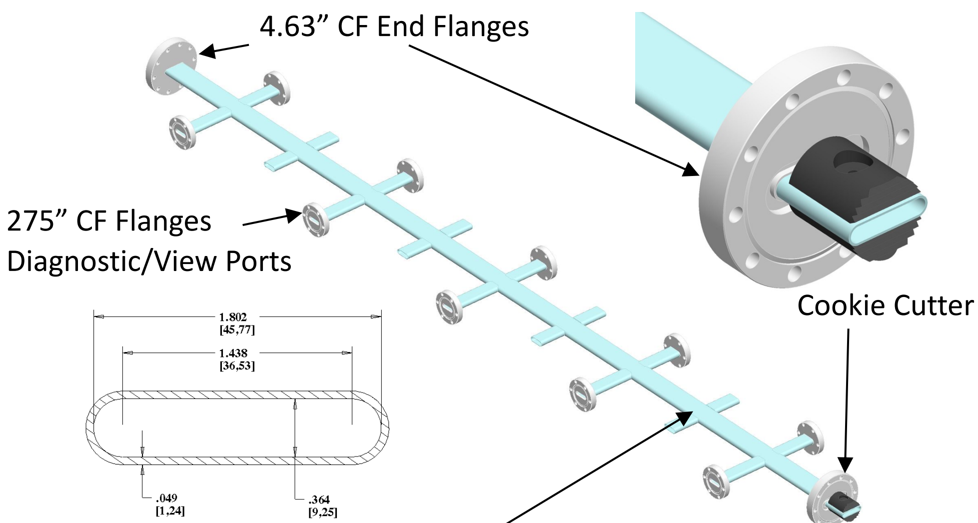
Undulator Options

- Very comfortable with FHI vendor STIMagnetics but it is an area where CLS may be able to contribute
- Key question is can anyone else beat the STIMagnetics price which we know is US$140,000 + material (quote to me from Steve Gottschalk for STIM IP, material procurement, fabrication oversight, magnetic measurement and tuning) for two undulators known to work and to survive the ugly FHI radiation environment? My inflated FHI material cost is US$1,200,000 for a total of $US670,000 per undulator – not bad, I think. The price of PM material is very high right now.
- The STIM tooling exists for both undulators => another cost savings
- Not enamored of KYMA or the Cornell spin-off company. Not keen on China e.g. SDM Magnetics & understand there may be Canadian political issues. Danfysik has folded on undulator production.
- An area that could be improved is to taper the input and output of the MIR undulator to follow the approach used on the FIR line, which is much more operator-friendly and able to achieve much lower beam energy by greatly reducing the electron and photon beam scrape offs. We do know the FIR DF family dipoles with the very large apertures work.
- Thoughts?

AES Undulator Beam Tube Designs for FHI FEL

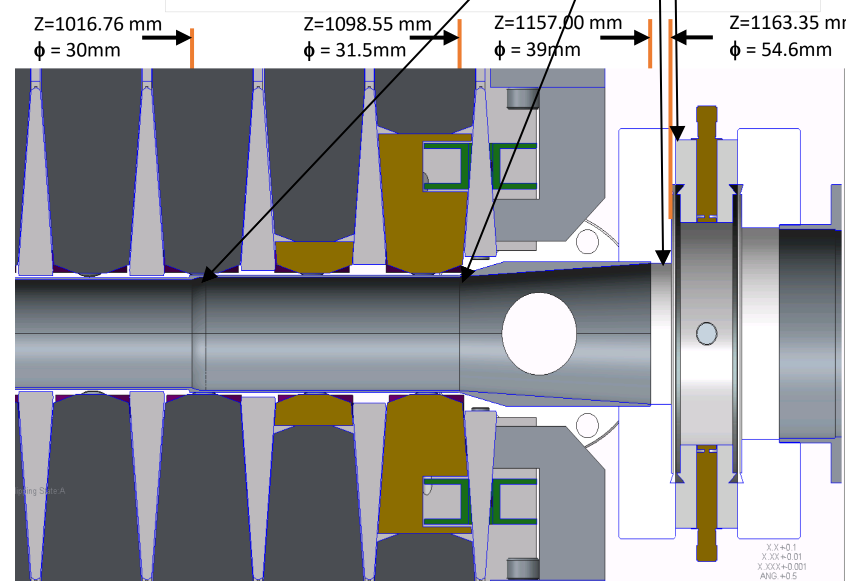
- U-40 MIR (left) and U-68 FIR undulator beam tubes (right)
- The MIR cookie cutter was not installed because it was calculated to increase the radiation load on the PM material – it would be a great help if this undulator was also tapered
- The U-40 MIR beam tube shape forced the prior BPM design
- Notice the tapering of the U-68 tube - a very tricky high-tolerance machining exercise with some extremely thin points to minimize the minimum undulator gap
- The upper right figure is not to scale vertically and horizontally





Tube Section in [mm]

U-40 MIR Undulator Beam Tube



U-68 FIR Undulator Beam Tube

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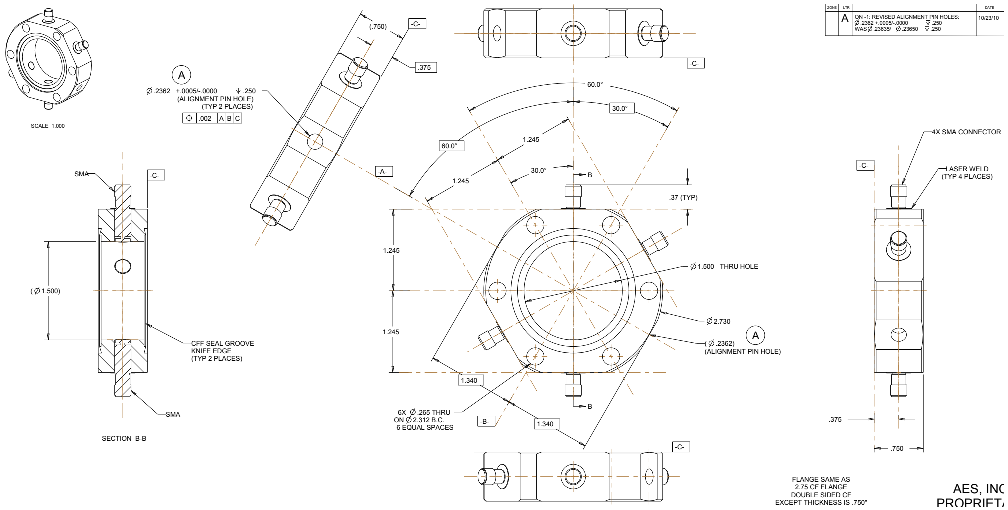
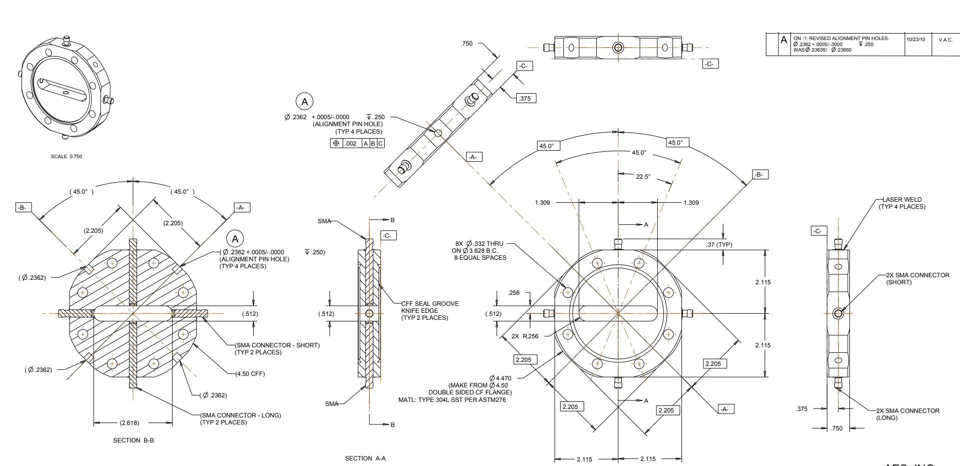
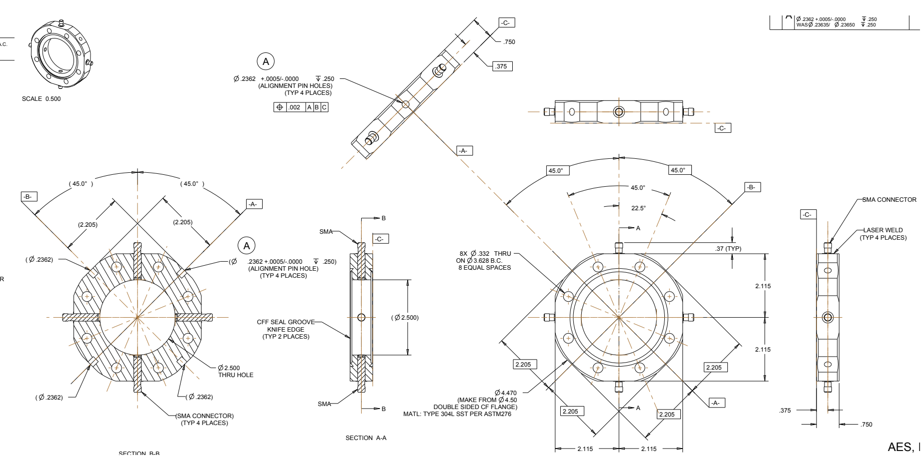
AES BPM Designs for FHI FEL



- Upper drawing is beamline BPM design throughout
- Lower drawings are used for the U-40 MIR undulator (left) and the U-68 FIR undulator (right) and are defined by the undulator beam pipes





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Diagnostic and Magnet Options

Family	Type	Length (mm)	Width (mm)	Strength[3] (T or kA-Turn)	Dipole Bend Angle (degrees @ MeV)	Dipole Bend Radius (mm)	Dipole Gap or Clear Aperture[4] (mm)	Entry/Exit Face Angles (degrees)	Steering X-Y Trim (T-m)	Field Tolerance[3] (% @ r mm)	Preferred Power Supply (V/A/W)	Number Required #
QB	Quadrupole	≤ 100		≥ 0.55			40		N/A	< 1 @ ±10	8V/10A/80W	25
QC	Quadrupole	≤ 150		≥ 0.5			65		$\pm 10^{-3}$	< 1 @ ±16	8V/10A/80W	7
DA	Reversible Dipole			0.34	48 @ 50	500	40	5/3.75 ± 0.5	$\pm 10^{-3}$	< 1 @ ±25	45V/140A/6300W[6]	4
DB	Wedge Dipole			0.22	6 @ 50	800	40	0/0 ± 0.5	N/A	< 1 @ ±19	40V/38A/1500W	2
DC	Rectangular Dipole	95.5		0.37	30 @ 20.5	191	38	Parallel Faces	N/A	< 1 @ ±80	40V/38A/1500W	4
DDA	Dipole			0.57	60 @ 50	300	30	18/18 ± 0.5	N/A	< 1 @ ±30	45V/140A/6300W	1
DDB	Spectrometer Dipole			0.57	60 @ 50	300	40	18/18 ± 0.5	N/A	< 1 @ ± 40	70V/90A/6300W	1
DF	Reversible Dipole	≤ 438	≤ 358	0.34	47 @ 50	500	> 65	0/7.75 ± 0.5	$\pm 10^{-3}$	< 0.1 @ ± 25	45V/140A/6300W[6]	3
DH	Rectangular Dipole	≤ 84	≤ 160	0.07	2 @ 50	2400	> 39	Parallel Faces	N/A	< 0.1 @ ± 25	20V/10A/200W[6]	2
SA	Solenoid	≤ 50		2.7			200 ≤ D ≤ 360		N/A		20V/10A./200W	1
SB	Solenoid	≤ 30		2.7			300 ≤ D ≤ 500		N/A		20V/10A./200W	1
SC	Solenoid	≤ 70		5.8			300 ≤ D ≤ 460		N/A		20V/10A./200W	1
SD	Solenoid	≤ 100		6			170 ≤ D ≤ 300	See[5]	N/A		20V/10A./200W	2
ST	Steerer	≤ 25					71		$\pm 10^{-3}$	< 1 @ ± 19	8V/10A/80W	14
SA	Steerer	≤ 25					71		See[2]	< 1 @ ± 19	8V/10A/80W	1
	TOTAL											69
Note 1	SA needs to Provide ± 10mrad @45keV - assumed to be aircore version of ST											
Note 2	Field tolerance: for quadrupoles is harmonic content / for dipoles is field uniformity											
Note 3	Strength is integrated gradient ($G*L_{eff}$) in Teslas for quadrupoles, dipoles field in Tesla for dipoles and kA-turns for solenoids											
Note 4	The radial extremes for the solenoid coils and case are defined by ID ≤ D ≤ OD in the clear aperture column											
Note 5	Each SD solenoid consists of an iron yoke which does not extend beyond 240mm											
Note 6	Two DA, DF and DH coils shall be wired in series with the preferred power supply											
Note 7	Cooling water pressure drop shall not exceed 3.8 bar for all cooled magnets											

- Diagnostics used at FHI include Faraday cups (3), current toroids (8), YAG screens (2), OTR screens (8), Be screens (8), BPMs (19) with Bergoz & Libera read out boards
- If magnets and diagnostics are available on loan that fit the existing layout and have the right specifications, then this is a no brainer
- FHI magnet fabricators were Scanditronix (QB, QC, DF, DH👍), Stangenes (DA, DB, DC, DDA, DDB, SA, SB, SC, SD👎), Radiabeam & AES (ST, SA). Radiabeam ROM quote was very steep. Promised Scanditronix ROM quote has not appeared yet.

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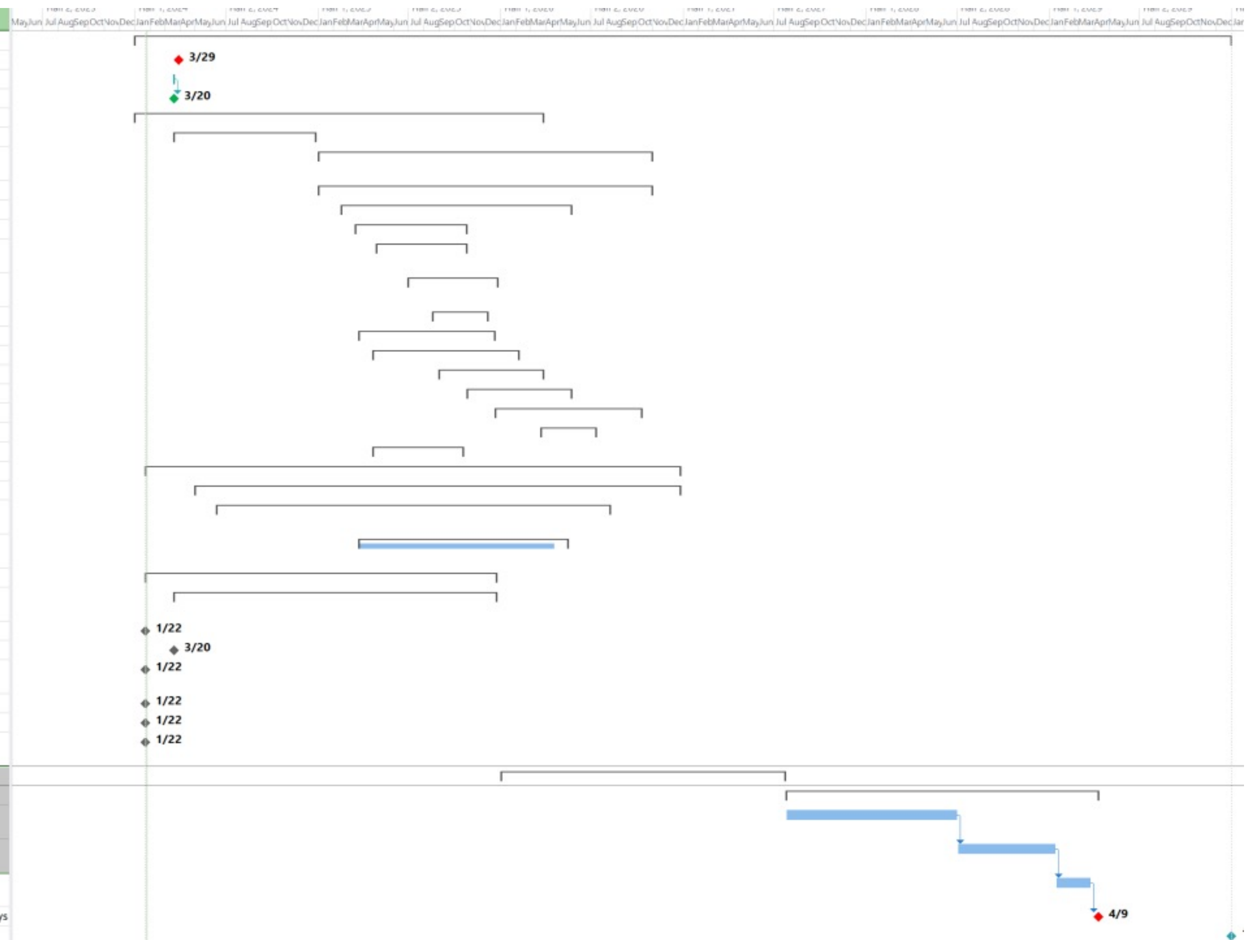
Top Level WaterFEL Cost

WATERFEL Item		Qty	Unit Cost	Total Cost	Cost + Taxes
			US$	US$	CAD$
Accelerator Total				$913,549	$1,237,133
Magnets Total				$600,341	$812,986
Magnet Power Supplies				$181,714	$246,078
RF Systems				$2,386,023	$3,231,167
Ancillary Systems Total				$829,383	$1,123,156
Beamline Systems Total				$245,000	$331,781
Undulator Total				$1,344,914	$1,821,291
Optical Total				$1,008,585	$1,365,832
Labor, Travel & Shipping Total				$766,553	$1,038,071
Pulse Radiolysis Beamline				$0	$0
PROJECTED MACHINE COST				$8,276,062	$11,207,494
CONTINGENCY	@	11.25%		$931,057	$1,260,843
WATERFEL PROJECT COST ESTIMATE WITH CONTINGENCY				$9,207,119	$12,468,337
SCOTT HOPKINS COST ESTIMATE AFTER TAXES & BEFORE BUY-INS					$12,465,081
Inflation since 2010		41.10%			
Inflation since 2015		29.81%			
Inflation Since 2018		22.50%			
Inflation Since 2019		20.30%			
Inflation Since 2020		18.90%			
Canada Taxes		3.41%			
$/€		1.08841			
CAD$/US$		0.73844			

- Contingency at 11.25% is light for this early in the project
- May need more projected manpower
- Modulator higher & RF structure ROM quote lower than amount budgeted – adjusted by removing radiolysis beamline & Kentec pulser
- Need to develop additional savings without compromising project goals to increase the starting contingency

Top Level WaterFEL WBS

	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		WATER FEL	1565 days?	M 1/1/24	M 12/31/29	
2		Project Begins - Cost Certified	0 days	F 3/29/24	F 3/29/24	
3		Kickoff Workshop at Triumf	1 day	T 3/19/24	T 3/19/24	
4		Key Design Decisions Made	0 days	W 3/20/24	W 3/20/24	3
5		Facility	585 days	M 1/1/24	F 3/27/26	
19		System Design	203 days	W 3/20/24	F 12/27/24	
22		Accelerator System Procurements	477 days	T 1/2/25	F 10/30/26	
23		RF Structures	477 days	T 1/2/25	F 10/30/26	
31		Magnets	330 days	M 2/17/25	F 5/22/26	
38		Magnet Power Supplies	160 days	M 3/17/25	F 10/24/25	
43		Controls, Networking, CPUs & VME	130 days	M 4/28/25	F 10/24/25	
46		Timing Devices & Diagnostic Boards	130 days	M 6/30/25	F 12/26/25	
49		Racks	80 days	M 8/18/25	F 12/5/25	
51		Beamline Support Structures	195 days	M 3/24/25	F 12/19/25	
53		S-Band Waveguide	210 days	M 4/21/25	F 2/6/26	
56		Vacuum Components	150 days	M 9/1/25	F 3/27/26	
59		Beamline Components	150 days	M 10/27/25	F 5/22/26	
62		Diagnostics	210 days	M 12/22/25	F 10/9/26	
65		Chillers	80 days	M 3/23/26	F 7/10/26	
68		Beam dumps	130 days	M 4/21/25	F 10/17/25	
71		Optical Transport Procurement	765 days?	M 1/22/24	F 12/25/26	
72		Undulator Procurement	693 days	W 5/1/24	F 12/25/26	
78		Optical Chambers Procurement	562 days	T 6/13/24	F 8/7/26	
82		Optical Transport Procurement	300 days	M 3/24/25	F 5/15/26	
87		Auxilliary Systems	502 days?	M 1/22/24	T 12/23/25	
88		High-Power 3 GHz Modulators	460 days	W 3/20/24	T 12/23/25	
92		1 GHz Gun HV Power Supply	0 days	M 1/22/24	M 1/22/24	
94		1 GHz SHB Supply	0 days?	W 3/20/24	W 3/20/24	
96		500 MHz Solid State Kicker Amp	0 days	M 1/22/24	M 1/22/24	
98		25+ MHz Pulse Picker	0 days	M 1/22/24	M 1/22/24	
100		1 GHz PreAmplifiers	0 days	M 1/22/24	M 1/22/24	
102		Bipolar Relay Box for TDK & Delta PS	0 days	M 1/22/24	M 1/22/24	
104		Installation	405 days	F 1/2/26	F 7/23/27	
113		Commissioning	446 days	M 7/26/27	M 4/9/29	
114		MIR Commissioning Placeholder	245 days	M 7/26/27	F 6/30/28	112
115		FIR Commissioning Placeholder	140 days	M 7/3/28	F 1/12/29	114
116		2-Color Commissioning Placeholder	50 days	M 1/15/29	F 3/23/29	115
117		User Operations Begin	0 days	M 4/9/29	M 4/9/29	116FS+11 days
118		Project Complete	0 days	M 12/31/29	M 12/31/29	



- Not particularly worried about the schedule
- May not get the early beneficial occupancy indicated but installation & commissioning are much longer than we really anticipate

What Else Might We Repurpose or Change

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