FRITZ-HABER-INSTITUT
MAX-PLANCK-GESELLSCHAFT

FHI FEL:
A two-color dual-oscillator infrared free-electron laser

Wieland Schöllkopf

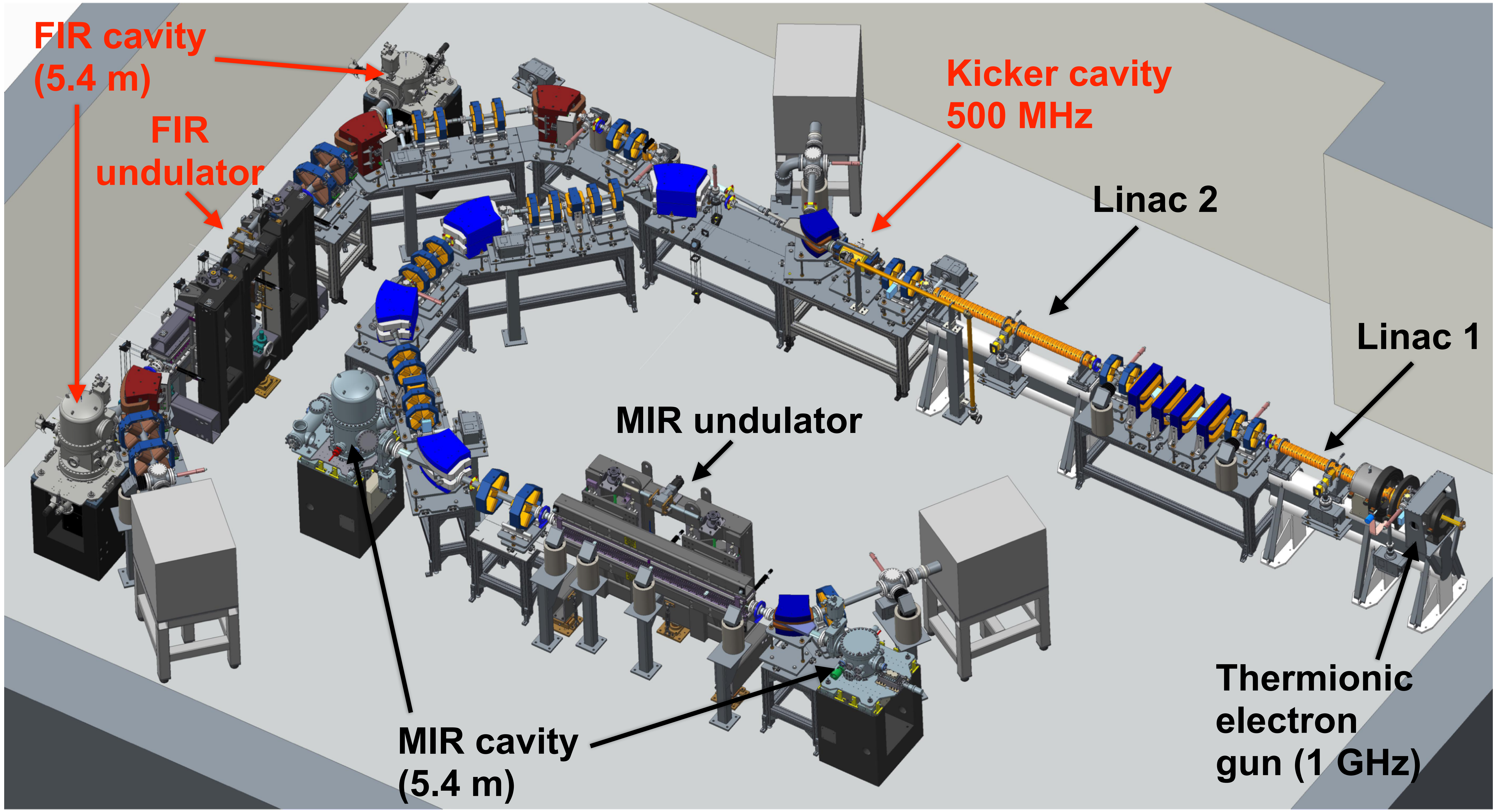
FRITZ-HABER-INSTITUT
MAX-PLANCK-GESELLSCHAFT

- Mid-IR FEL at FHI (since 2013)
- New Far-IR FEL branch (2023)
- 2-color operation of MIR and FIR
- First user applications (2025)

Wieland Schöllkopf

FHI FEL: a dual-oscillator two-color FEL

Commissioning: 2012 - MIR (2.8 - 60 µm) / 2023 - FIR (4.5 - 175 µm)
- Kicker cavity to permit synchronous operation of both FEL's: 2-color mode

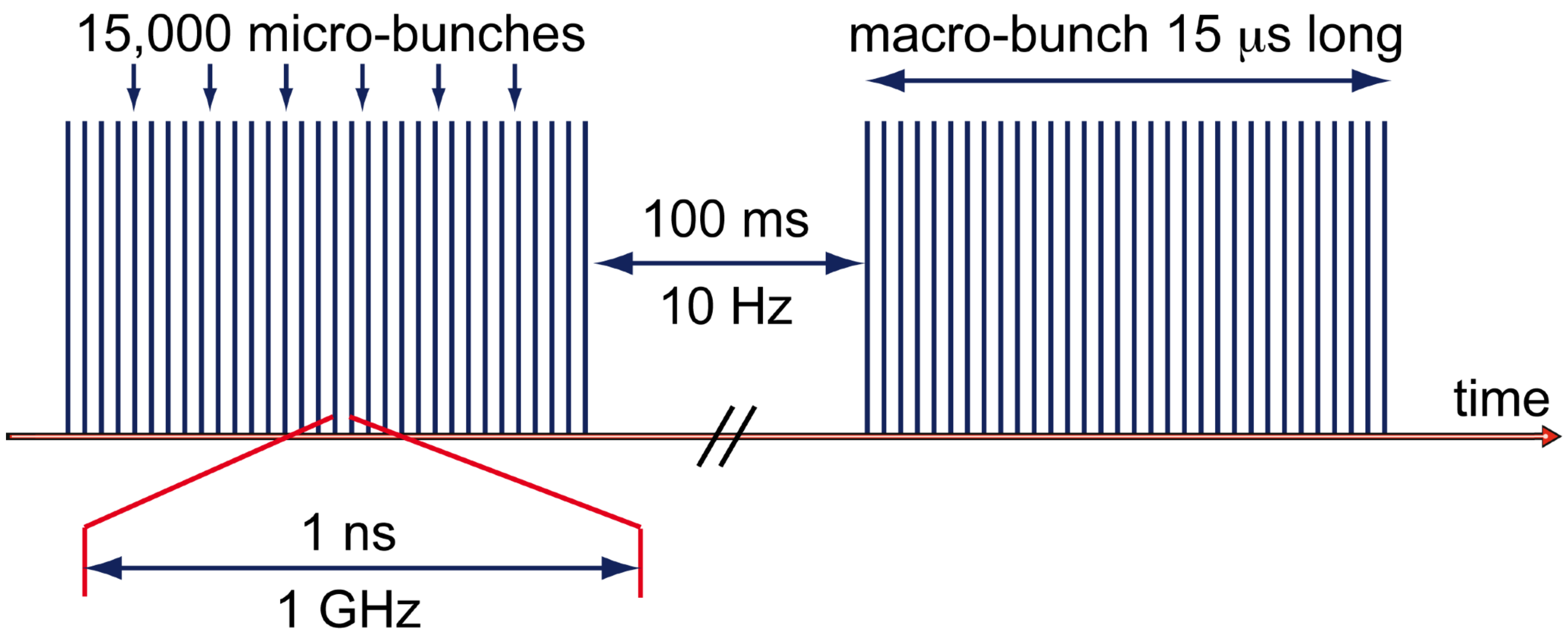


Specs of electron linear accelerator

<u>Normal-conducting S-band accelerator (AES, Inc.):</u>

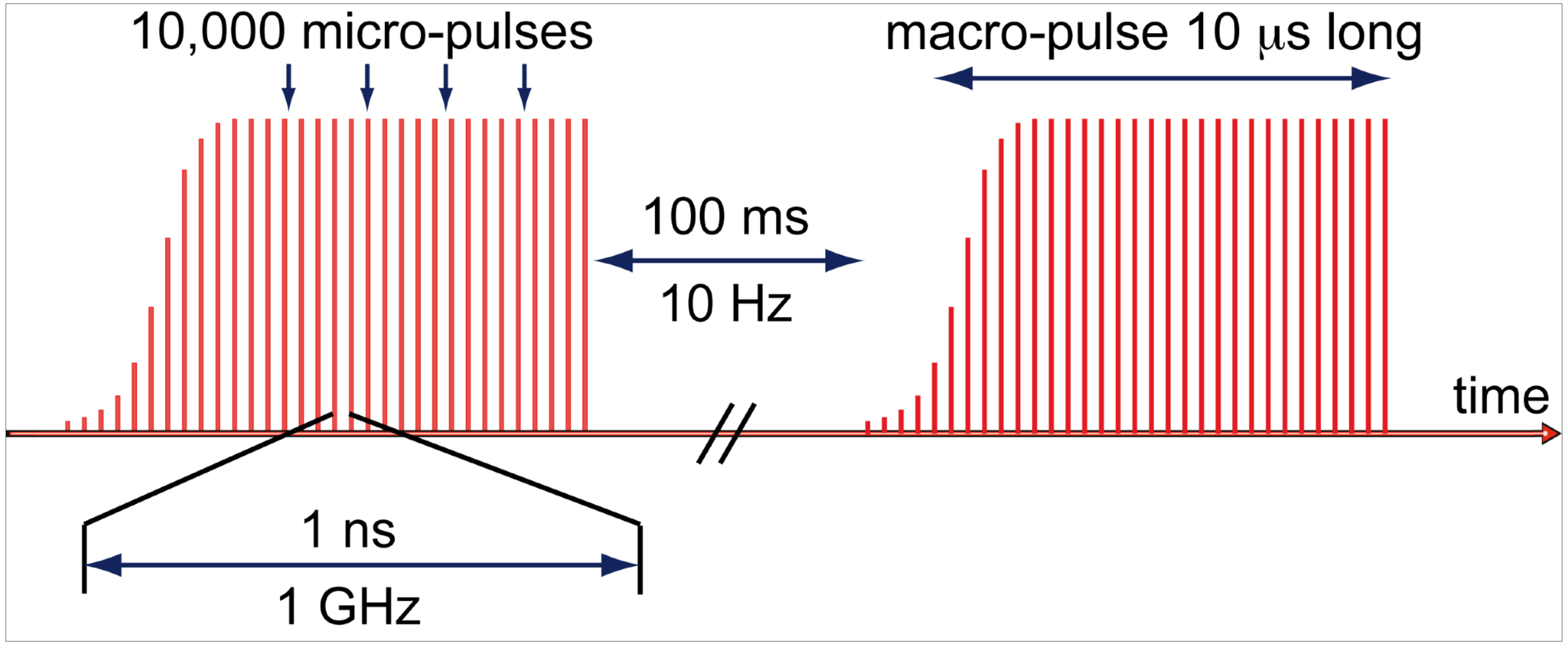
microwave:	3 GHz, 15 MW
electron energy:	15 - 50 MeV
bunch charge:	> 200 pC (1.25 10^9 electrons)
bunch length:	1 - 5 ps
bunch rep. rate:	1 GHz (or 55.5 MHz)
macro-bunch length:	up to 15 μs
macro-bunch rep. rate:	10 Hz

Time structure of electron bunch trains



Specs of FHI FEL IR radiation

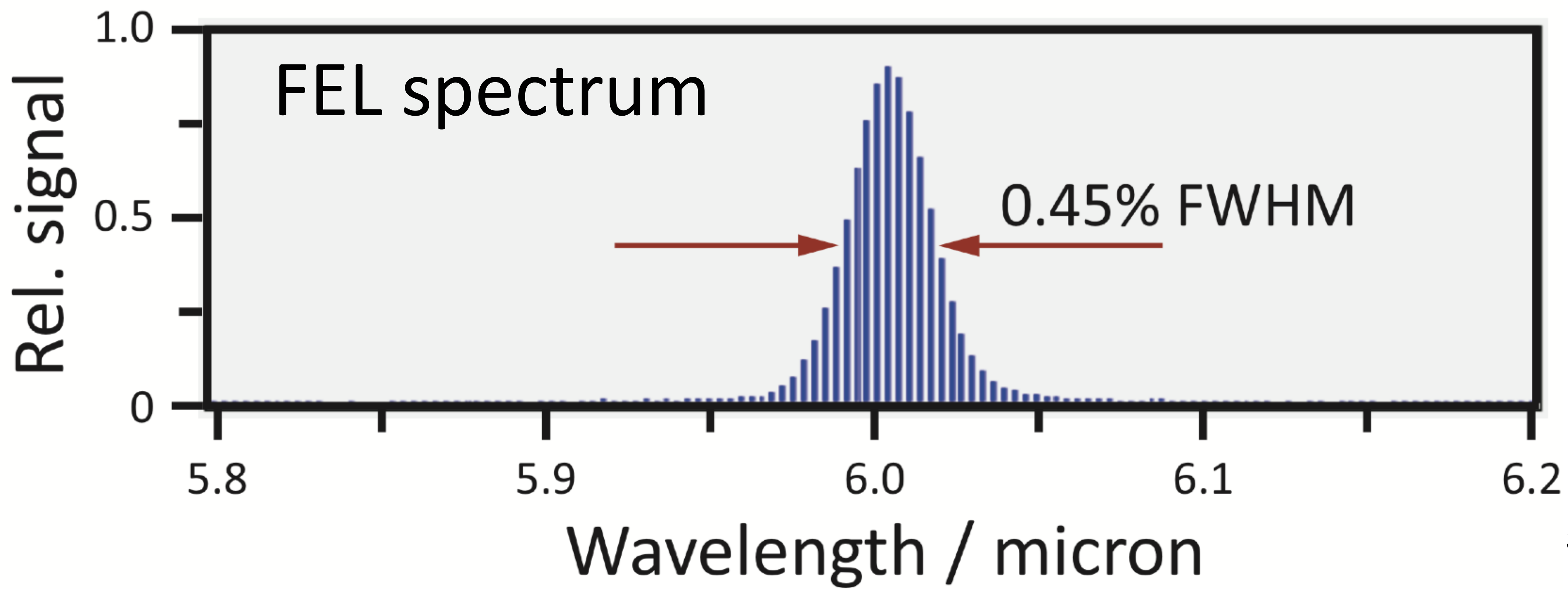
Time structure of IR output: micro-pulses and macro-pulses



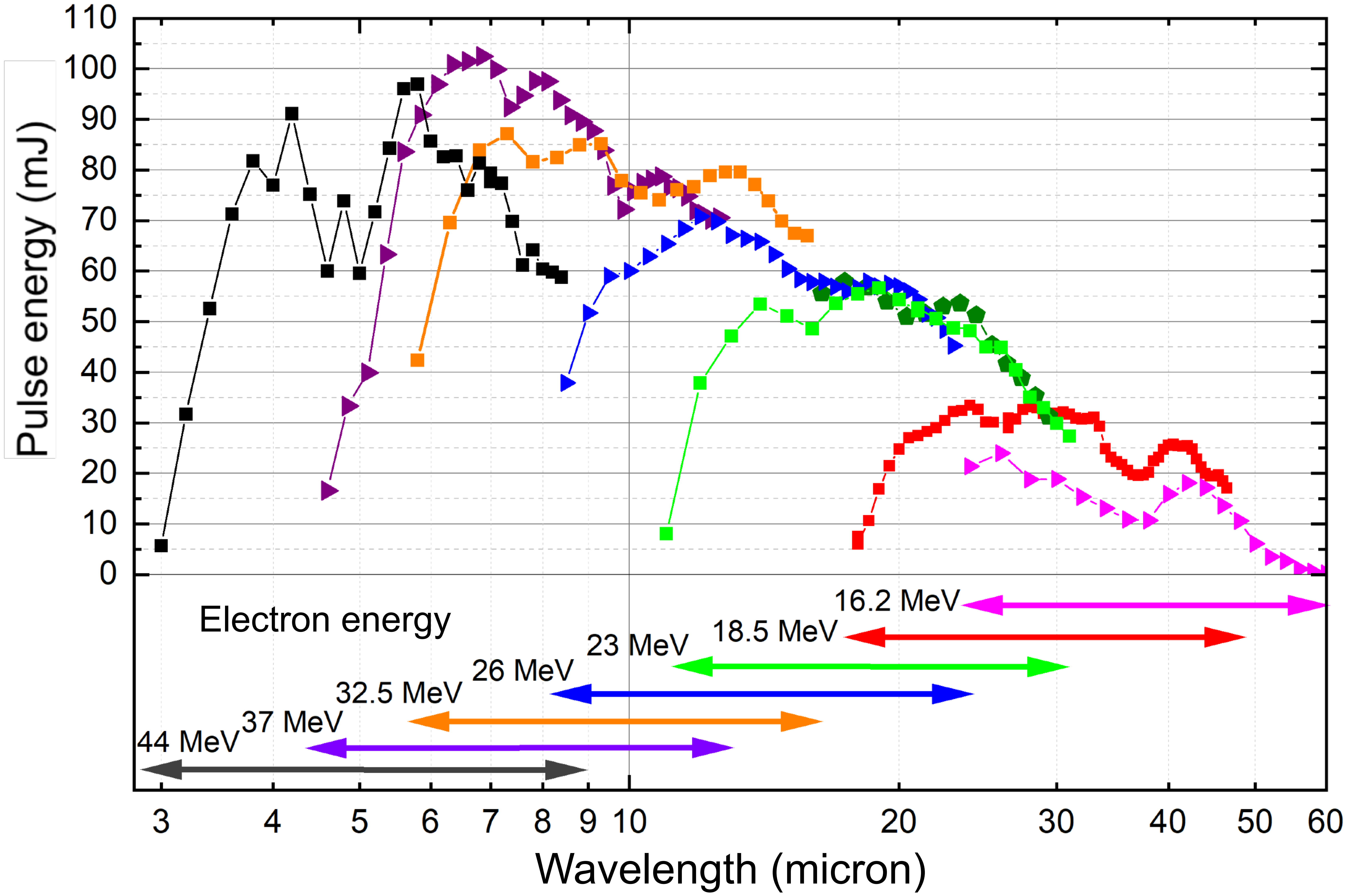
Micro-pulse: ≈ 10 μJ
≈ 0.3 … 5 ps

Macro-pulse: ≈ 100 mJ
≈ 10 μs

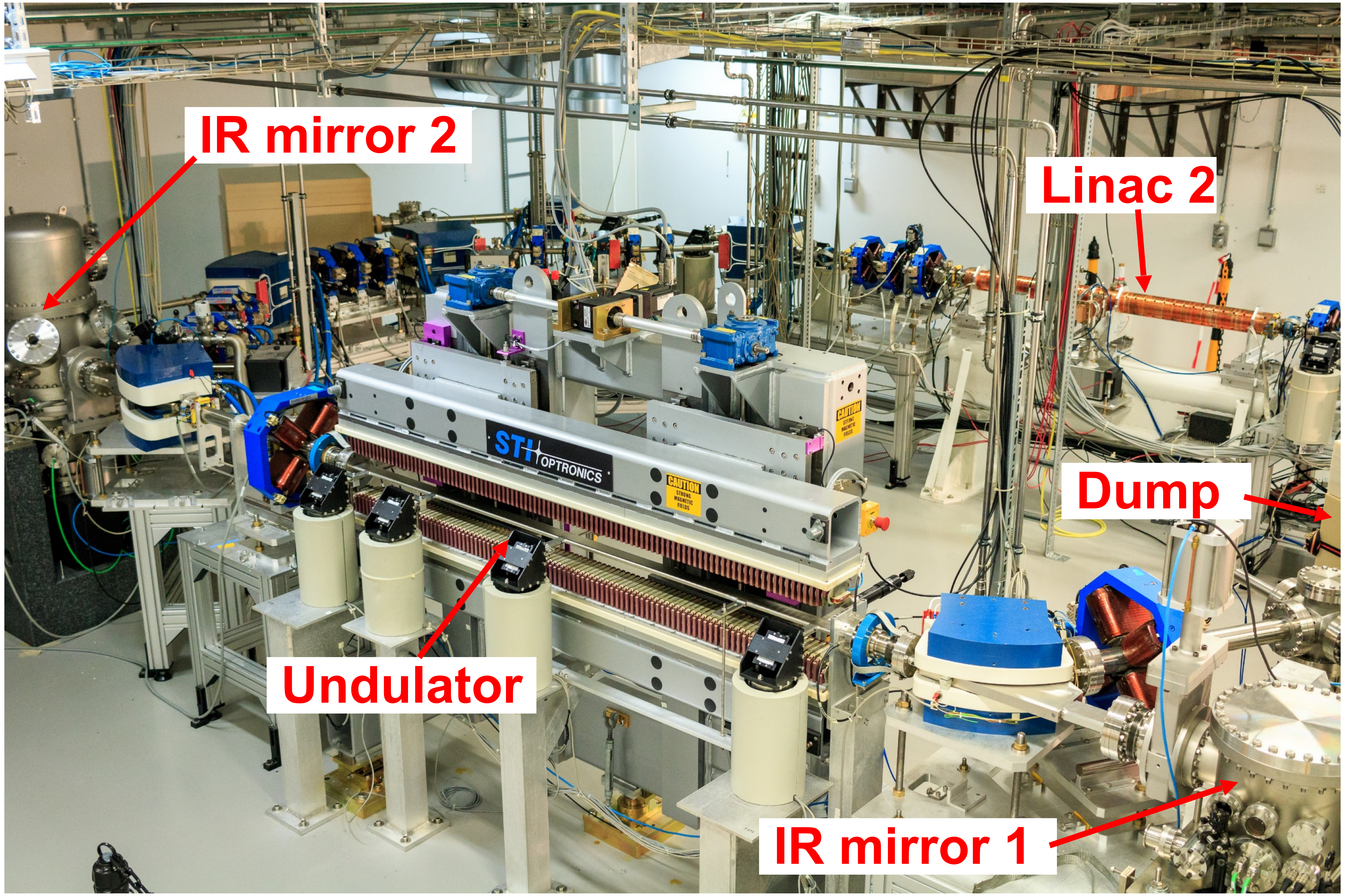
Spectral width: ≈ 0.3 – 5%
relative (FT-limited)



Macro-pulse energies at narrow bandwidth (0.3 – 0.7%)



Photograph of the FHI FEL



Two-color upgrade

Aim 1: Extension of wavelength range to **far-IR** (~ 200 μm / 50 cm^{-1}):
2nd undulator & cavity

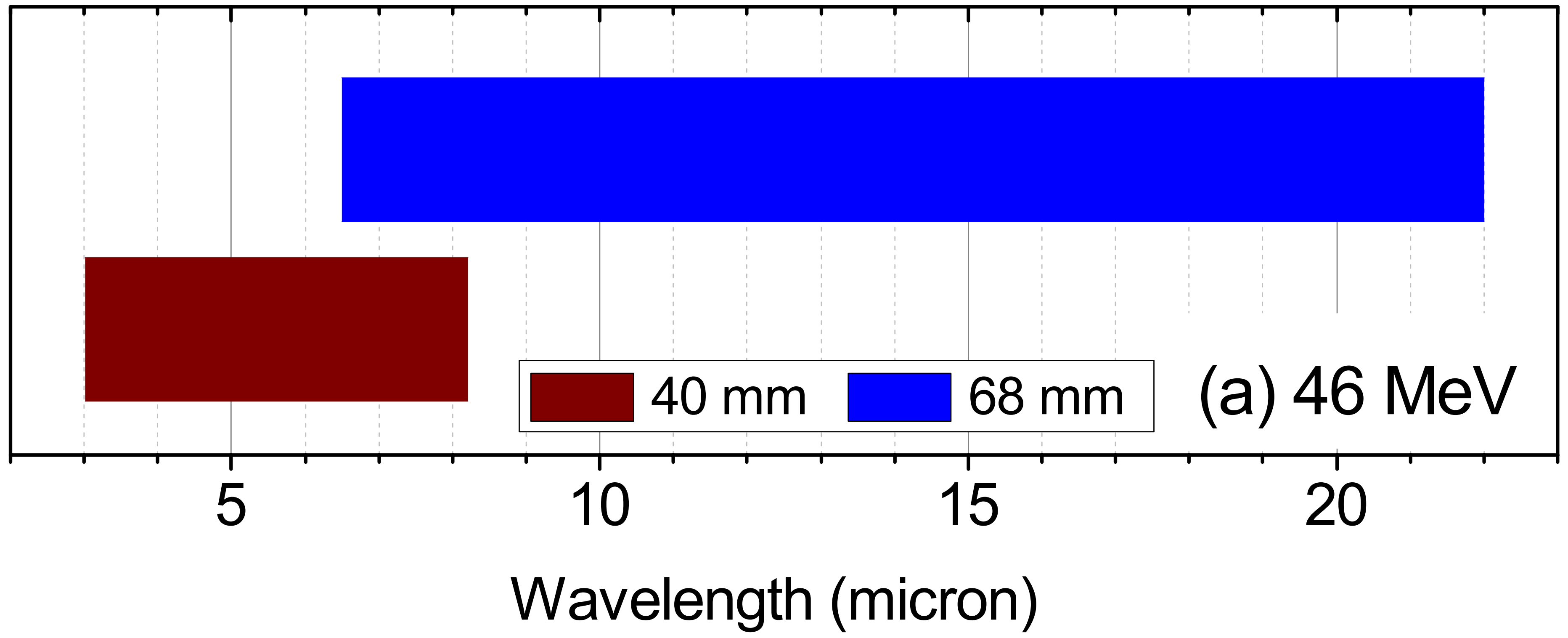
Aim 2: Synchronous operation of mid-IR and far-IR:
2-color FEL for novel experiments;
MIR/FIR pump-probe, 2D-IR, non-linear chi(3), …

Aim 3: For any given electron energy the undulator gap scan ranges overlap.

Far-IR wavelength range defined by **2nd undulator's** period λ_U.

$$\lambda = \frac{\lambda_U}{2\gamma^2}(1 + K^2)$$

- MIR undulator: **40 mm period**
- New FIR undulator: **68 mm period**



Far-IR/THz FEL branch commissioned in 2023

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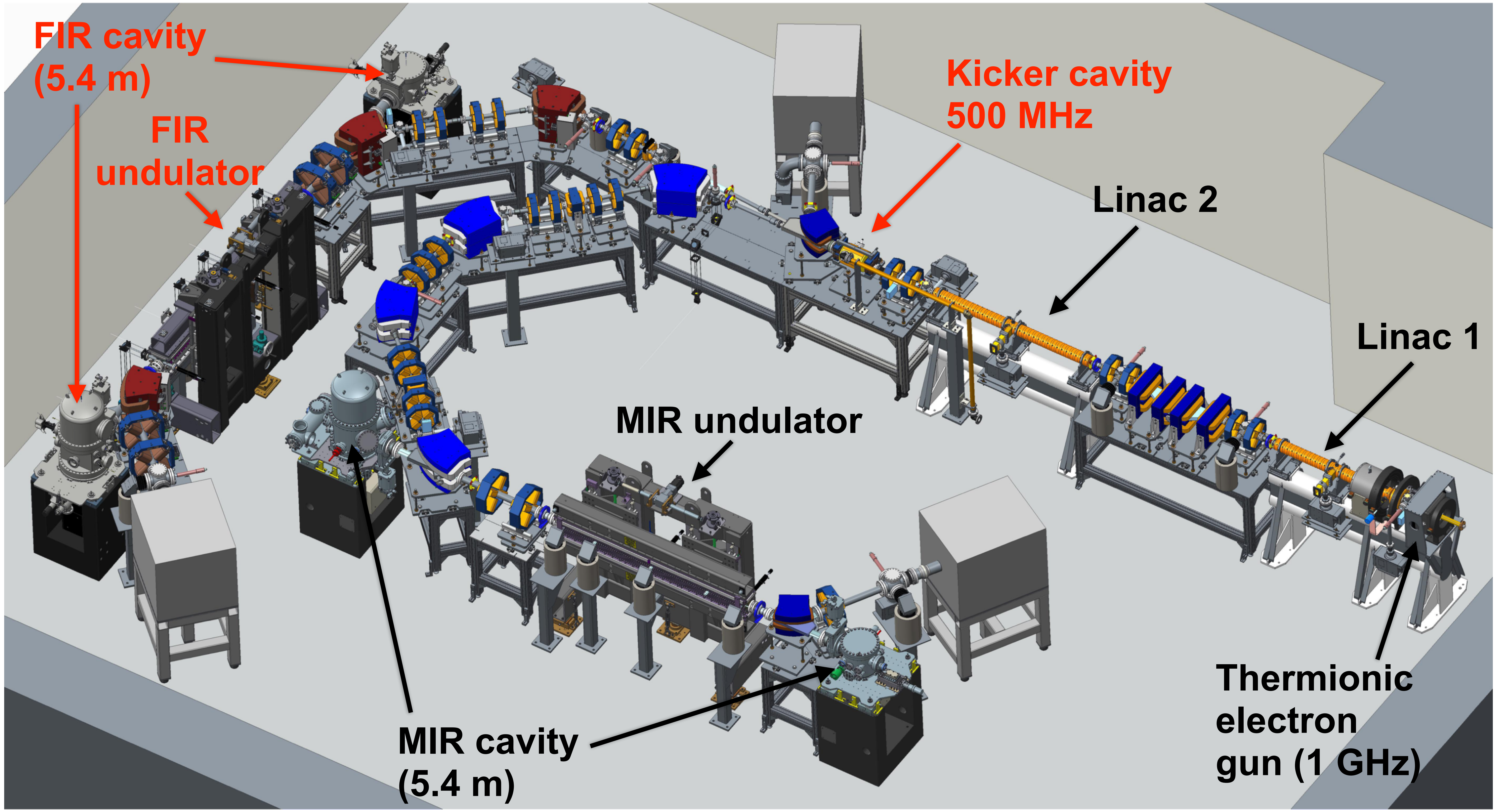
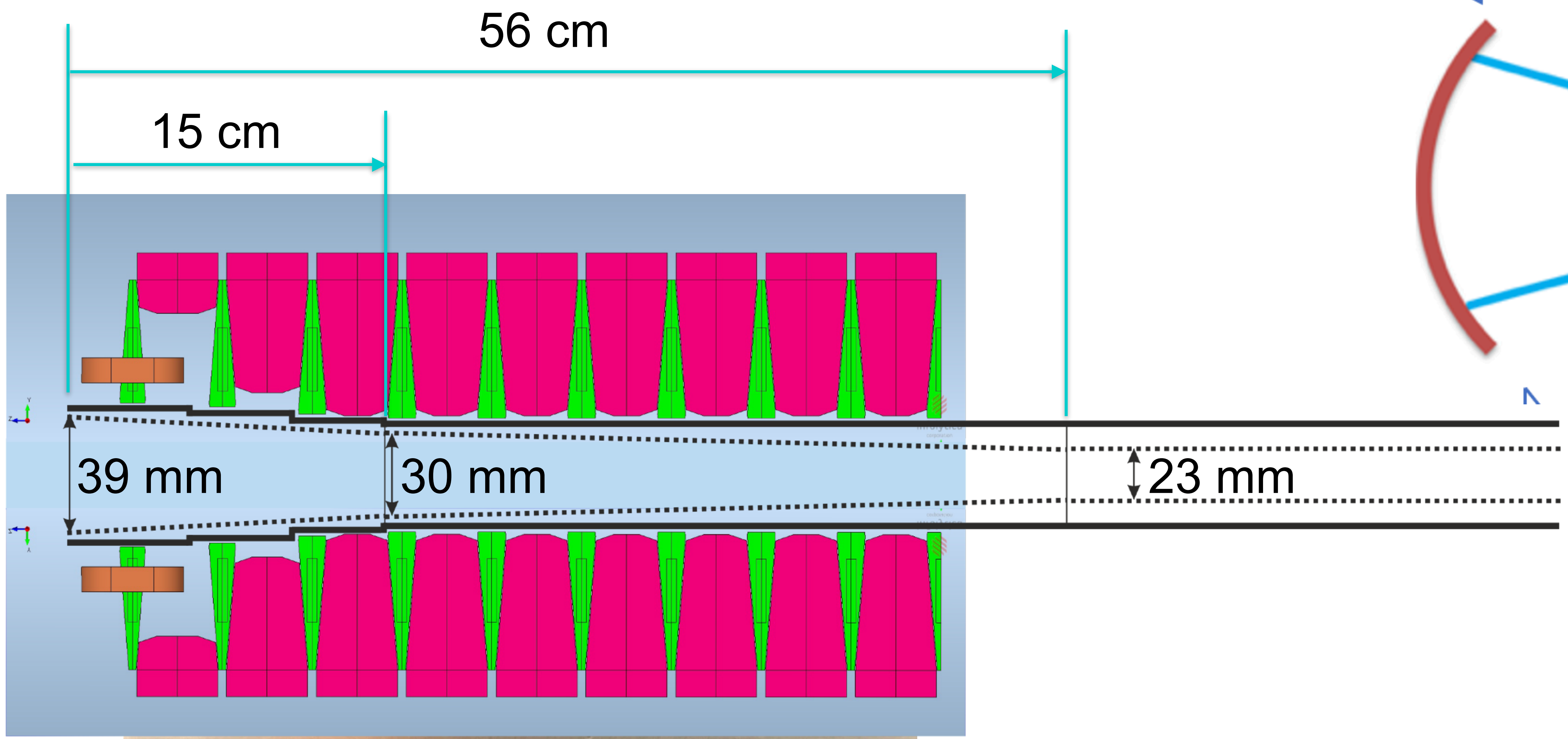
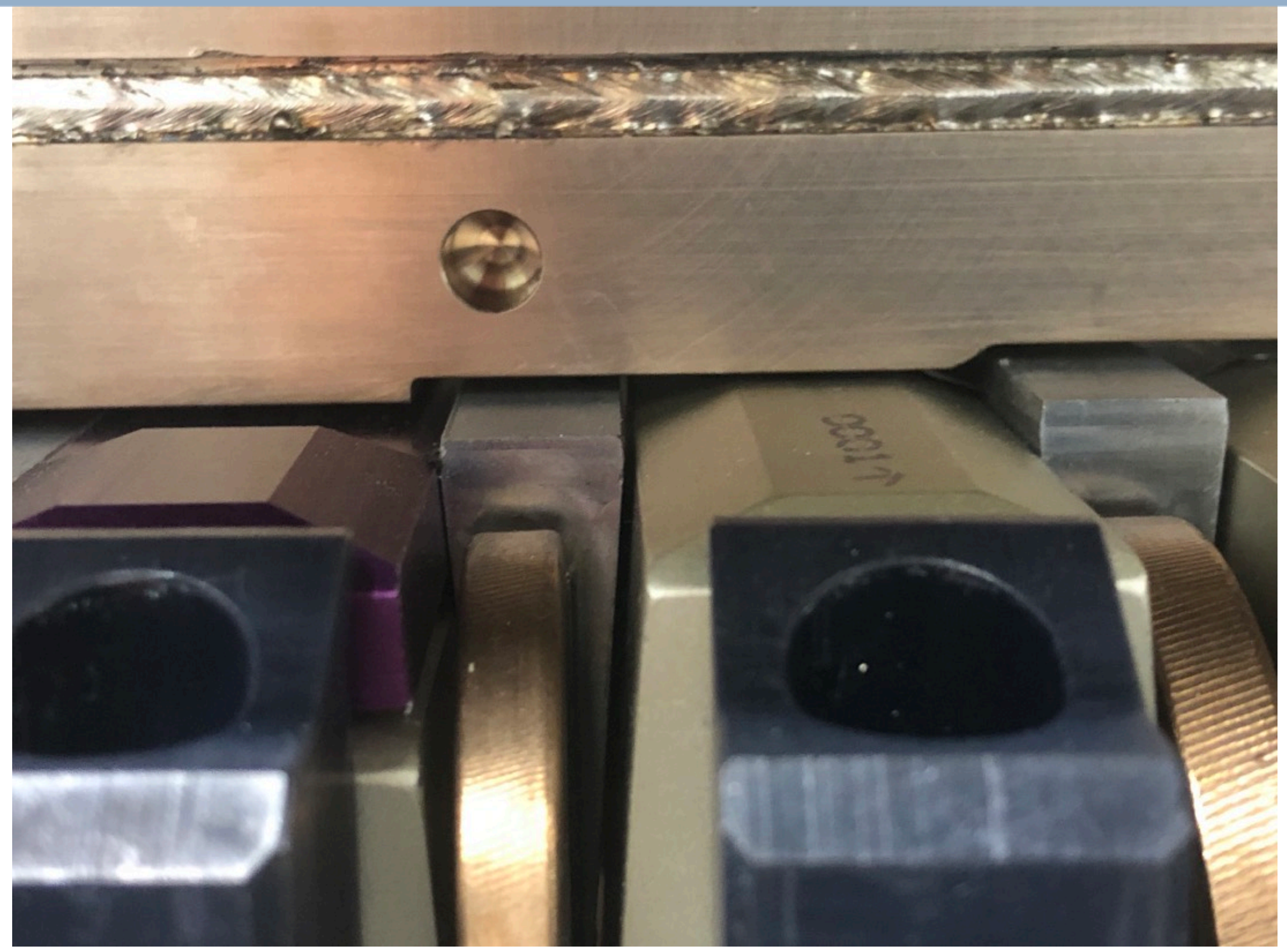
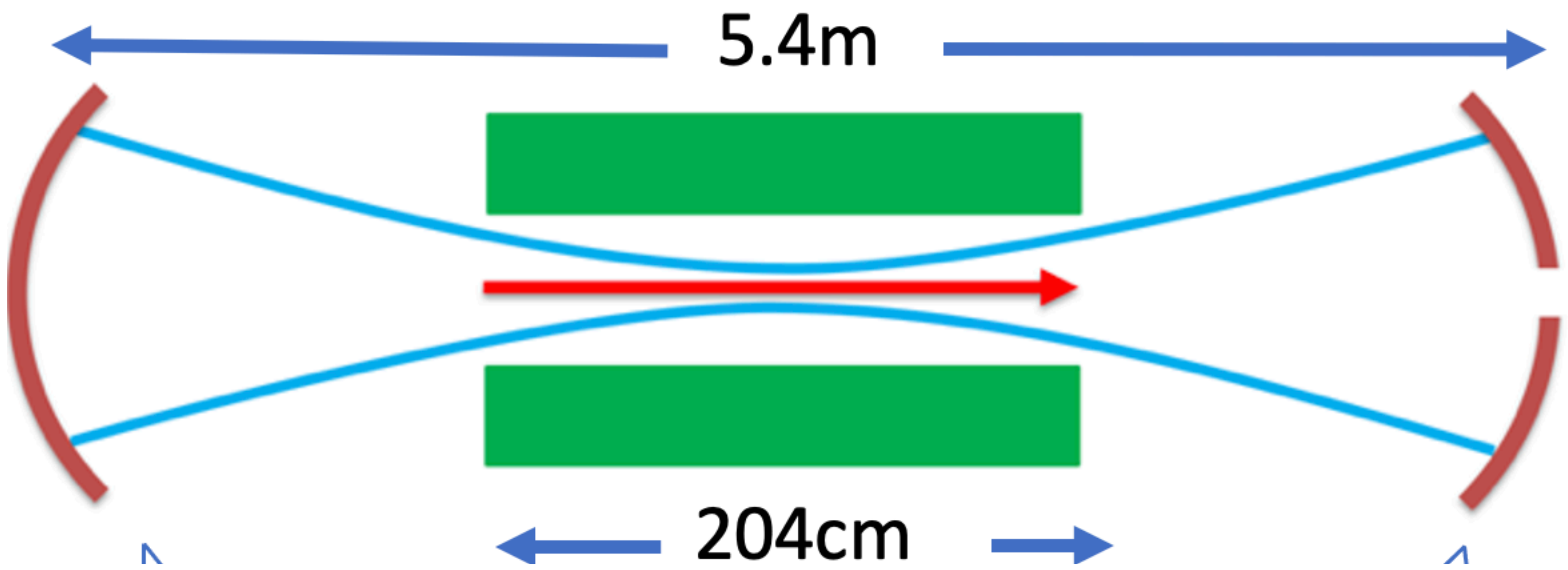


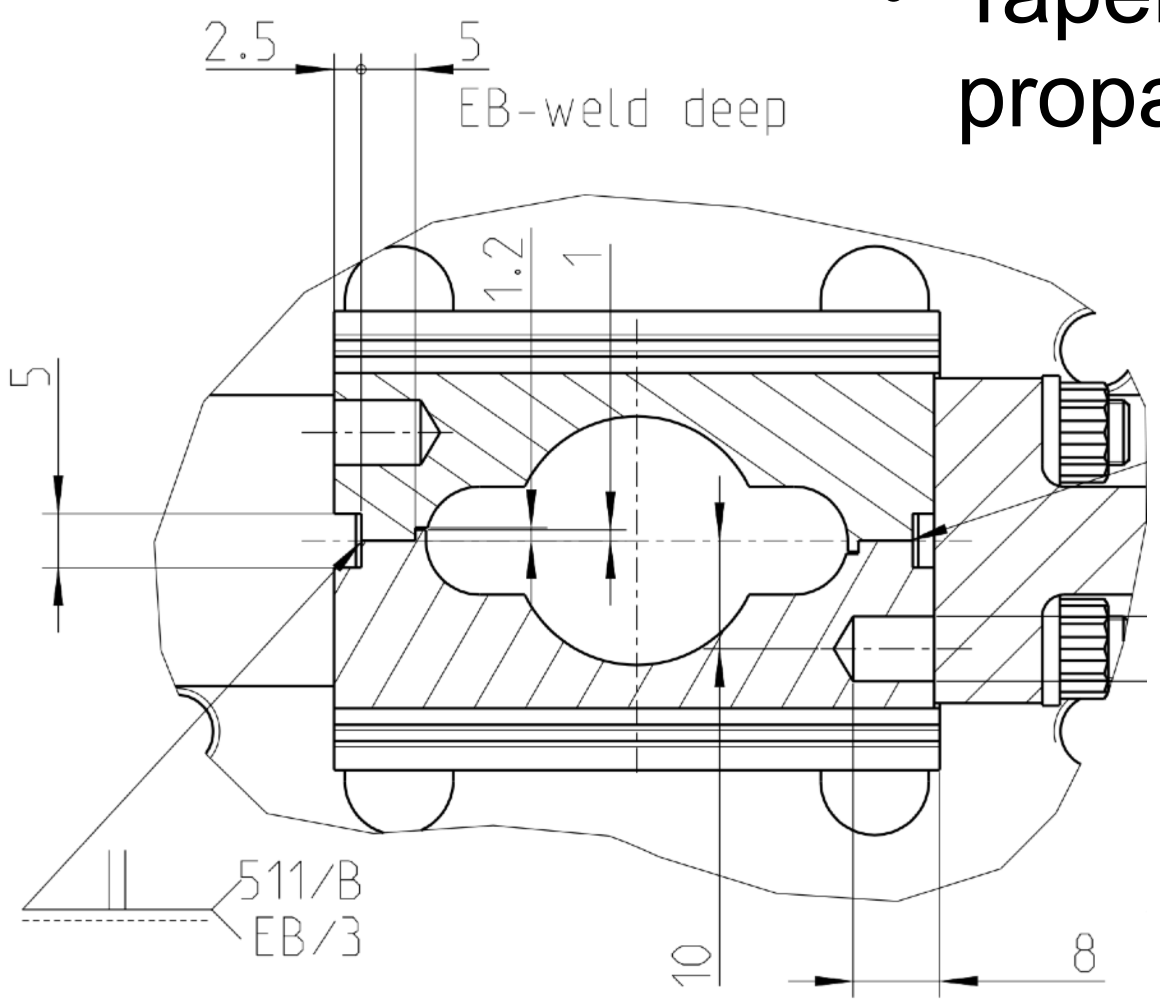
FIR oscillator design







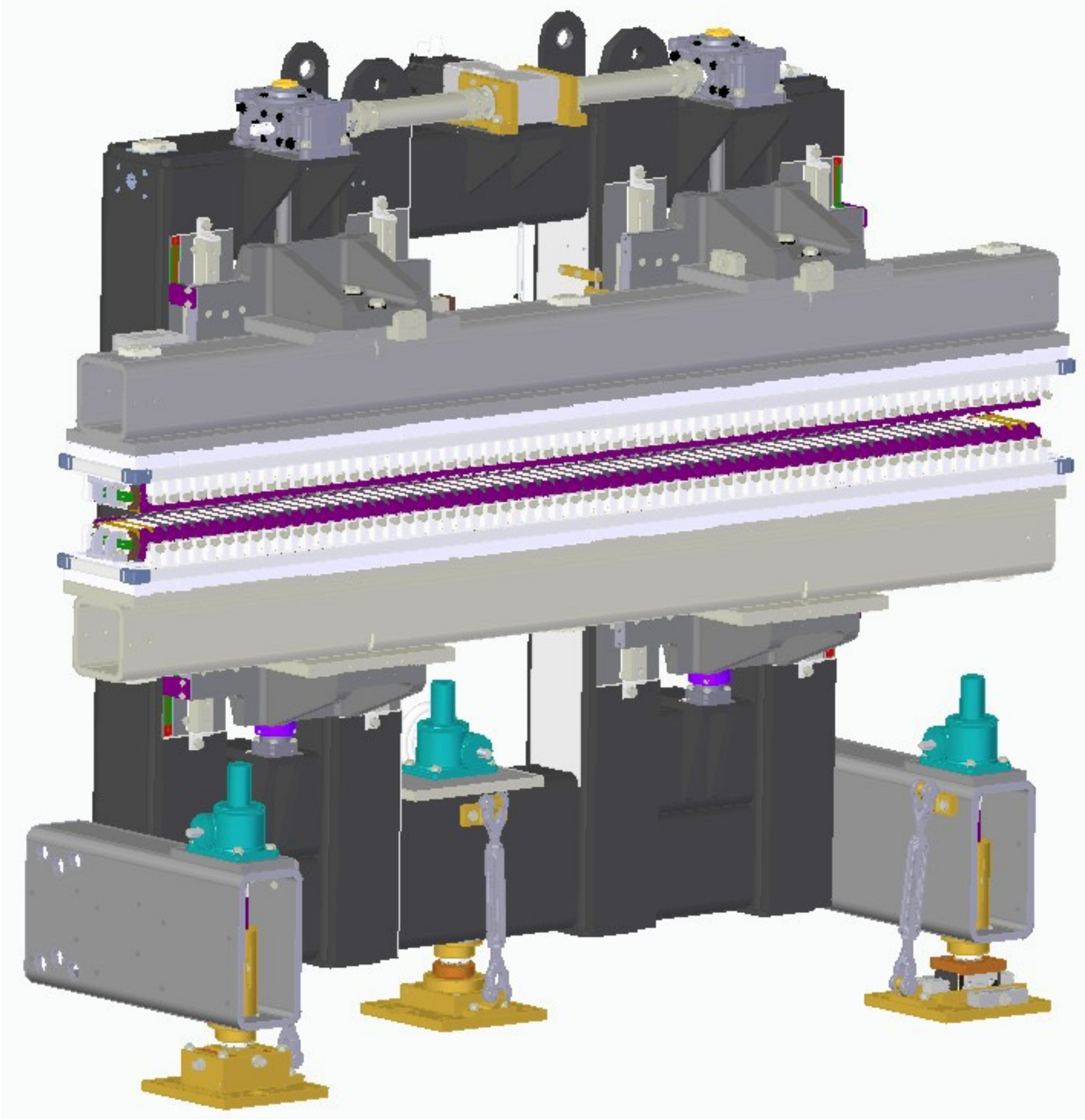
- Short Rayleigh range and short undulator design proposed by Bill Colson.
- Need for large vacuum chamber and large min. undulator gap
- Tapered design to permit as much free-space propagation of optical mode as possible



Central cross section
23 mm high
40 mm wide

designed by John Rathke
fabricated by FMB

FIR Undulator



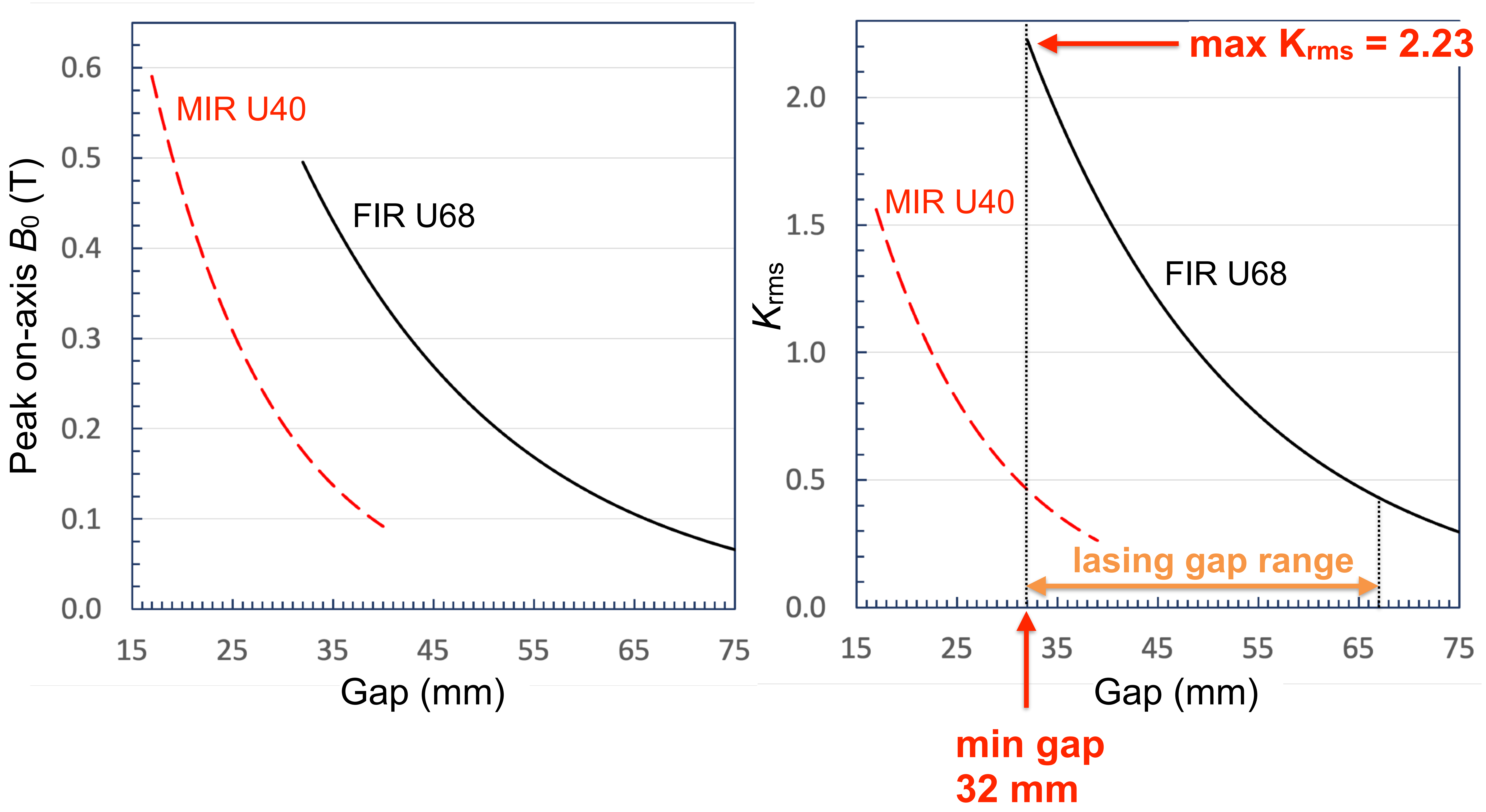
- Type: hybrid magnet
- Period: λ_U = 68 mm
- Length: 2.2 m
- No. of periods: 33
- K_{rms} = 2.2 at min. gap 32 mm

- Radiation hard design
- NdFeB (Vacodym 983-DTP, grain boundary diffusion)
- Wedged pole geometry
- Design: Steve Gottschalk

- Assembled at FHI (in parallel with another λ_U = 40 mm undulator built by FELIX)
- Characterization by 7-m-granite Hall probe scanner at FHI

FIR Undulator

Gap dependence of B_0 peak field and K for MIR and FIR undulators



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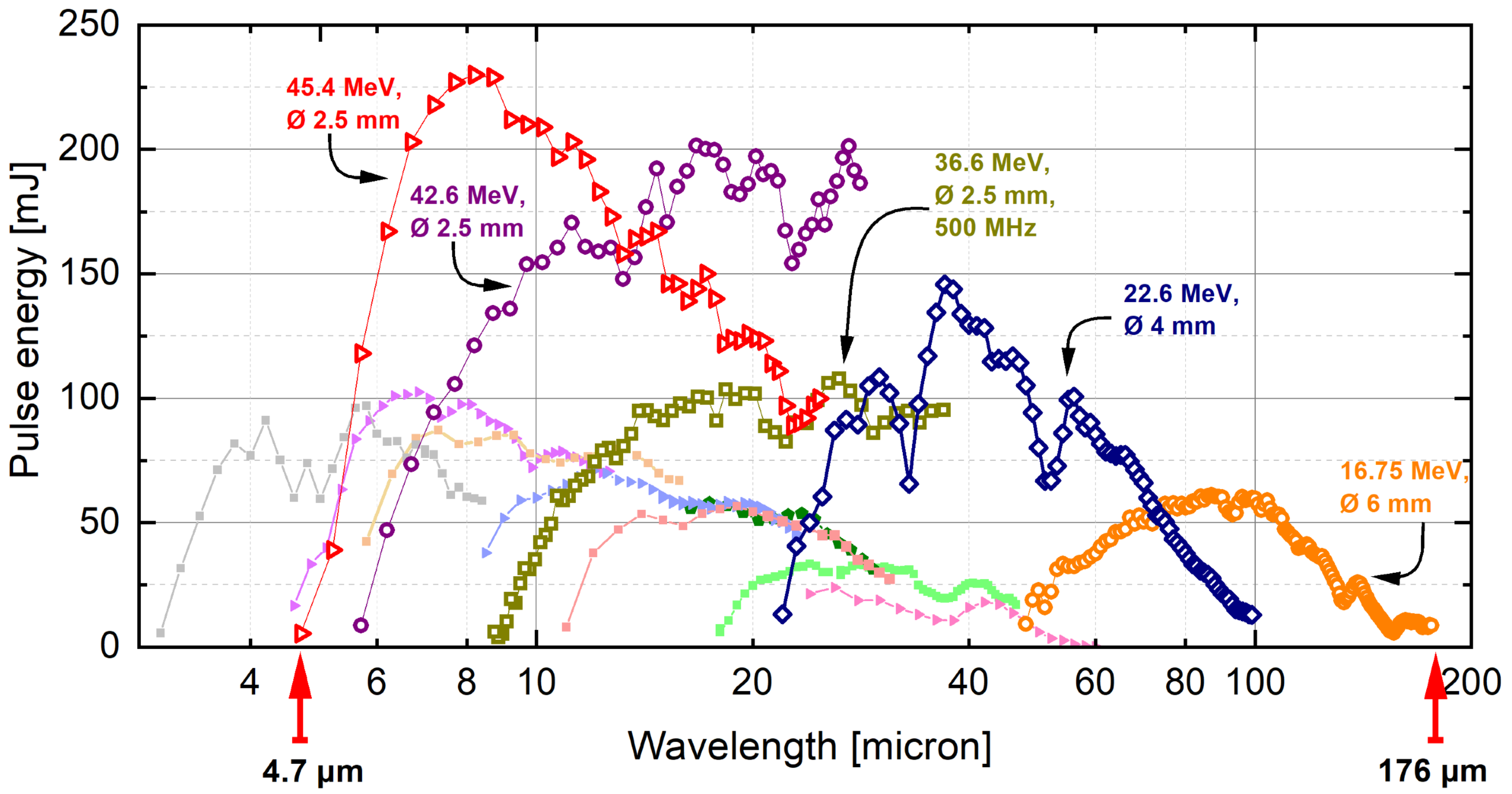
Macro-pulse energies of FIR FEL

- Undulator gap scans at 5 electron energies from 16.7 to 45.4 MeV
- Outcoupling-hole diameters: 2.5 mm, 4 mm, 6 mm
- More power than MIR FEL (partly due to short Rayleigh-range design as indicated by simulations by Bill Colson)



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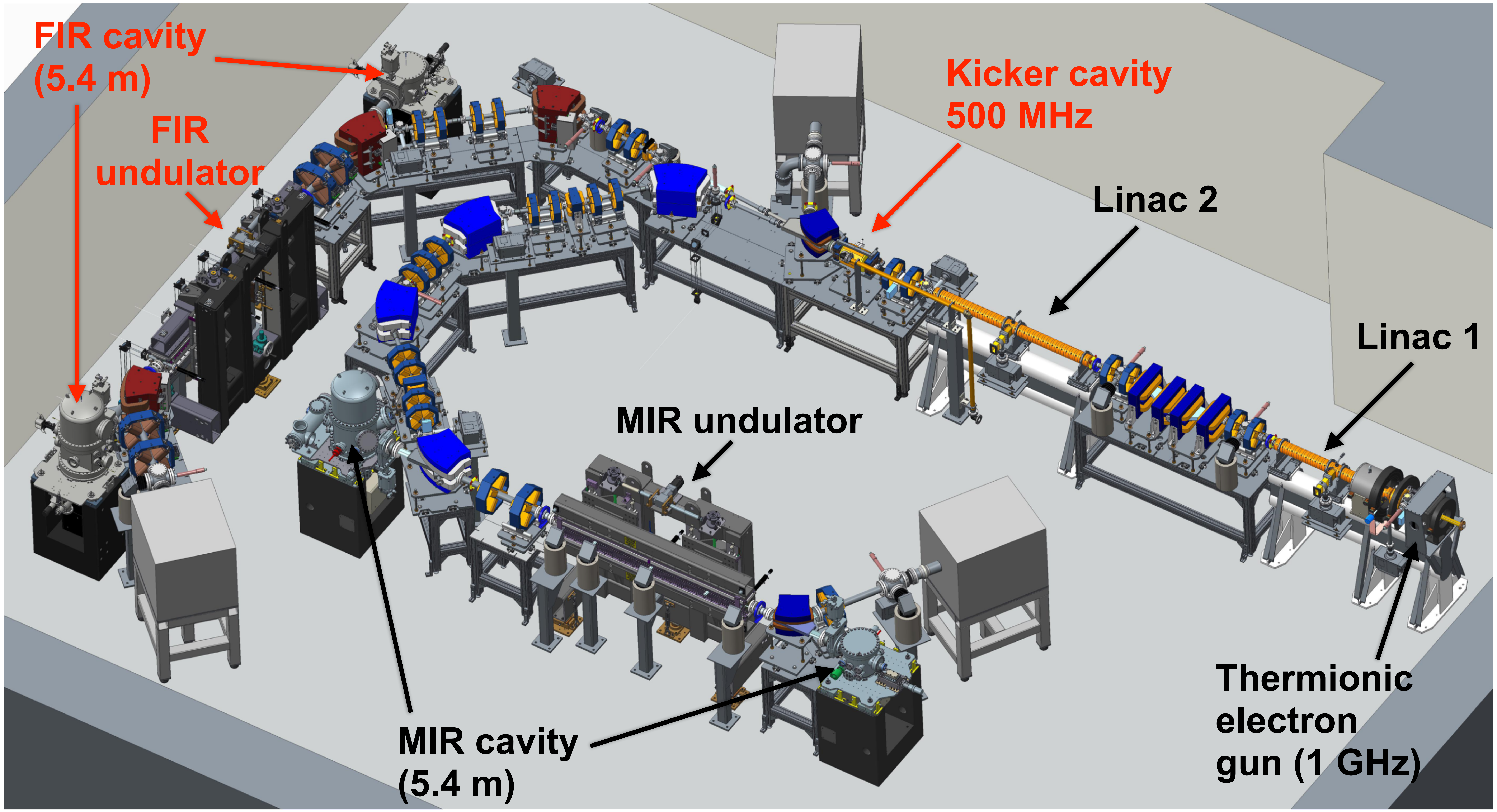
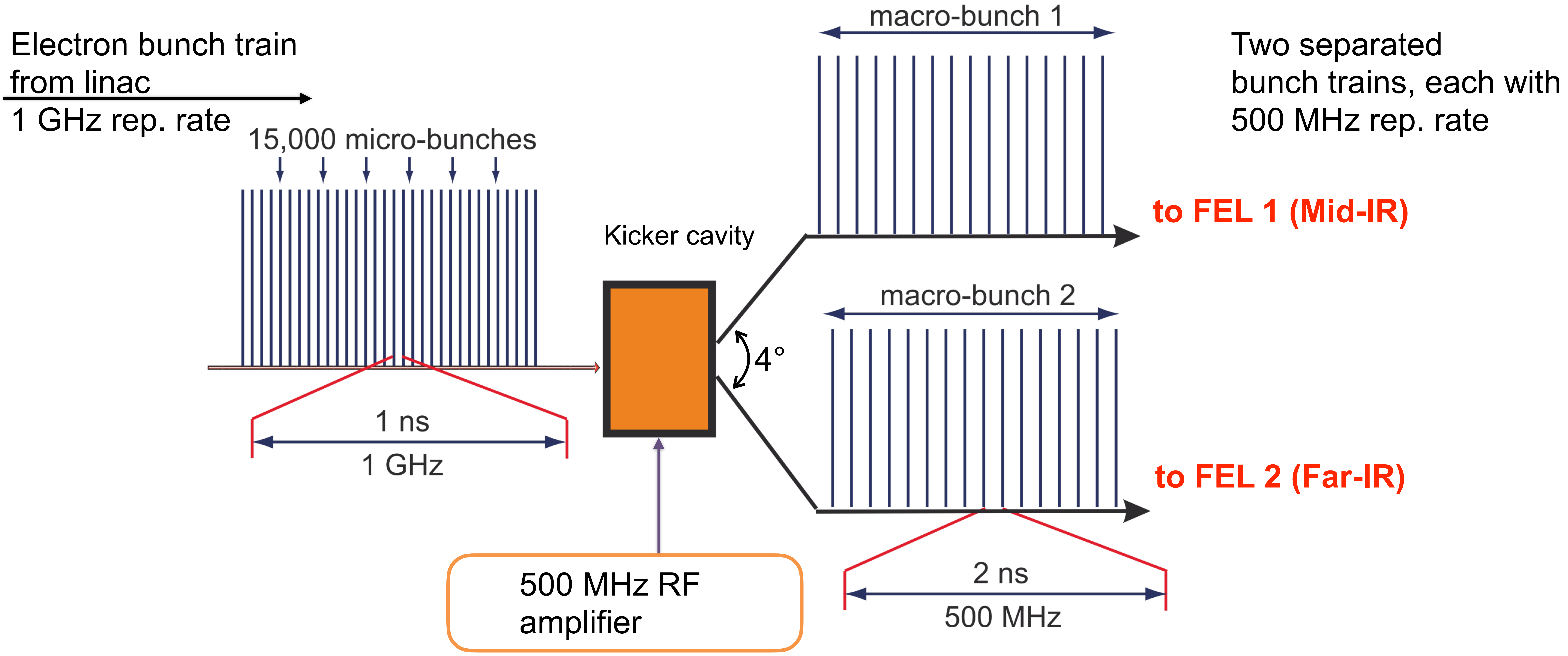
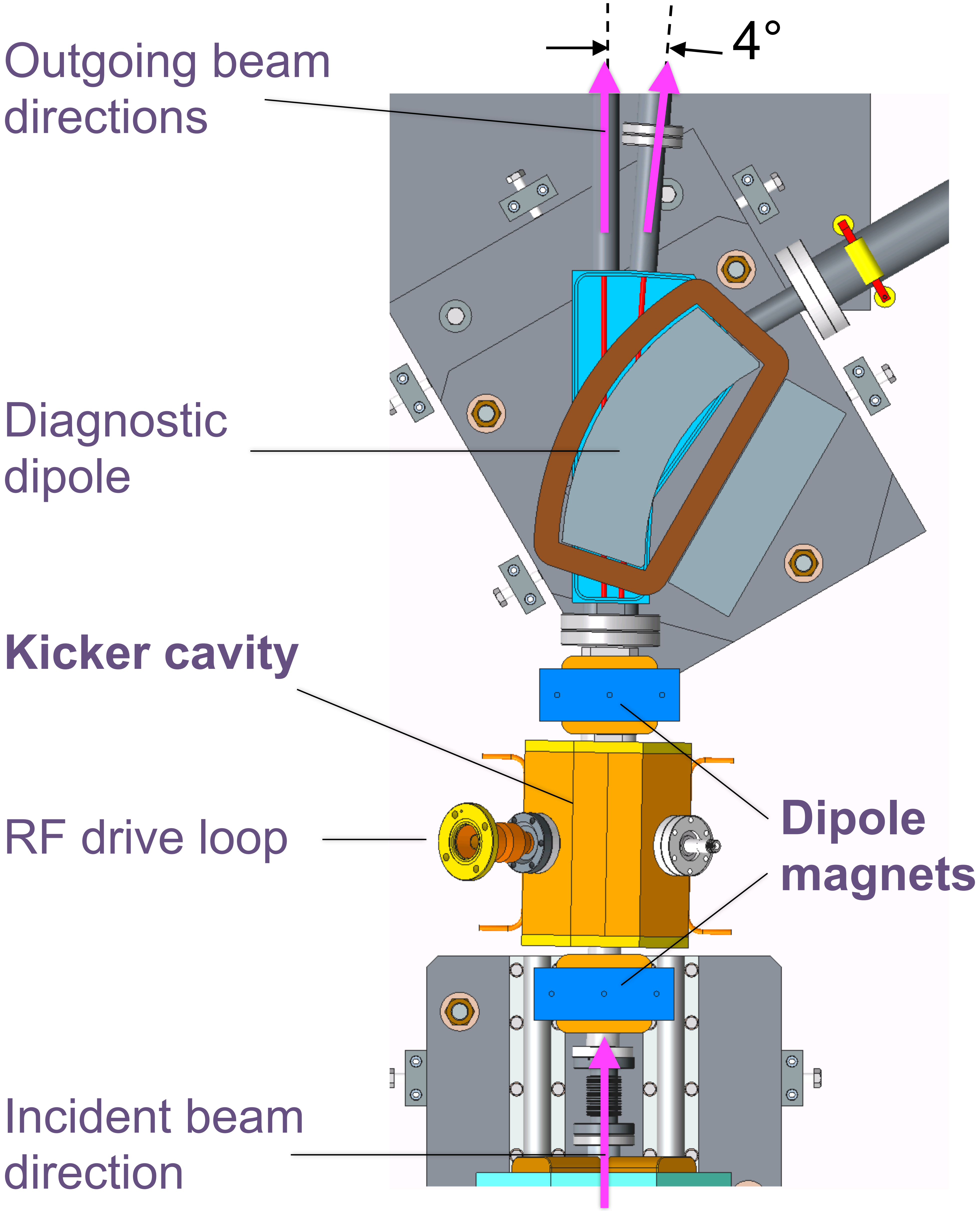


Beam Splitting by 500 MHz Kicker Cavity



500 MHz Kicker Cavity



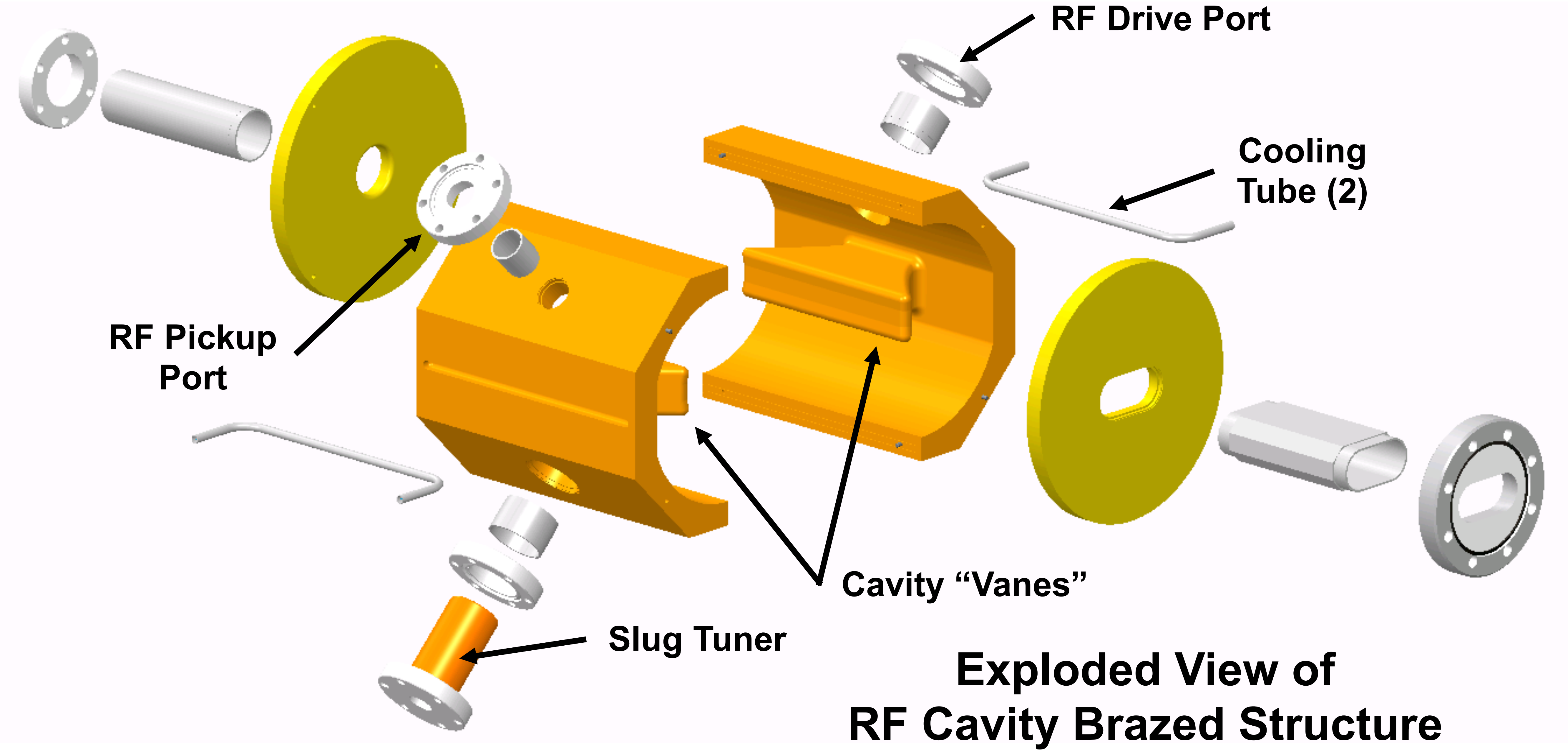
Incoming electron bunch train:
repetition rate 1 GHz (or 111.1 MHz)

Modes of operation:

(i) cavity off, dipoles off: All beam to FEL 1
(ii) cavity off, dipoles on 2°: All beam to FEL 2
(iii) cavity on, dipoles on 1°: Two 500 MHz bunch trains (or 55.5 MHz) separated by 4°

→ two users at the same time
→ allows 2-color experiments
→ unique FEL setup

500 MHz Kicker Cavity



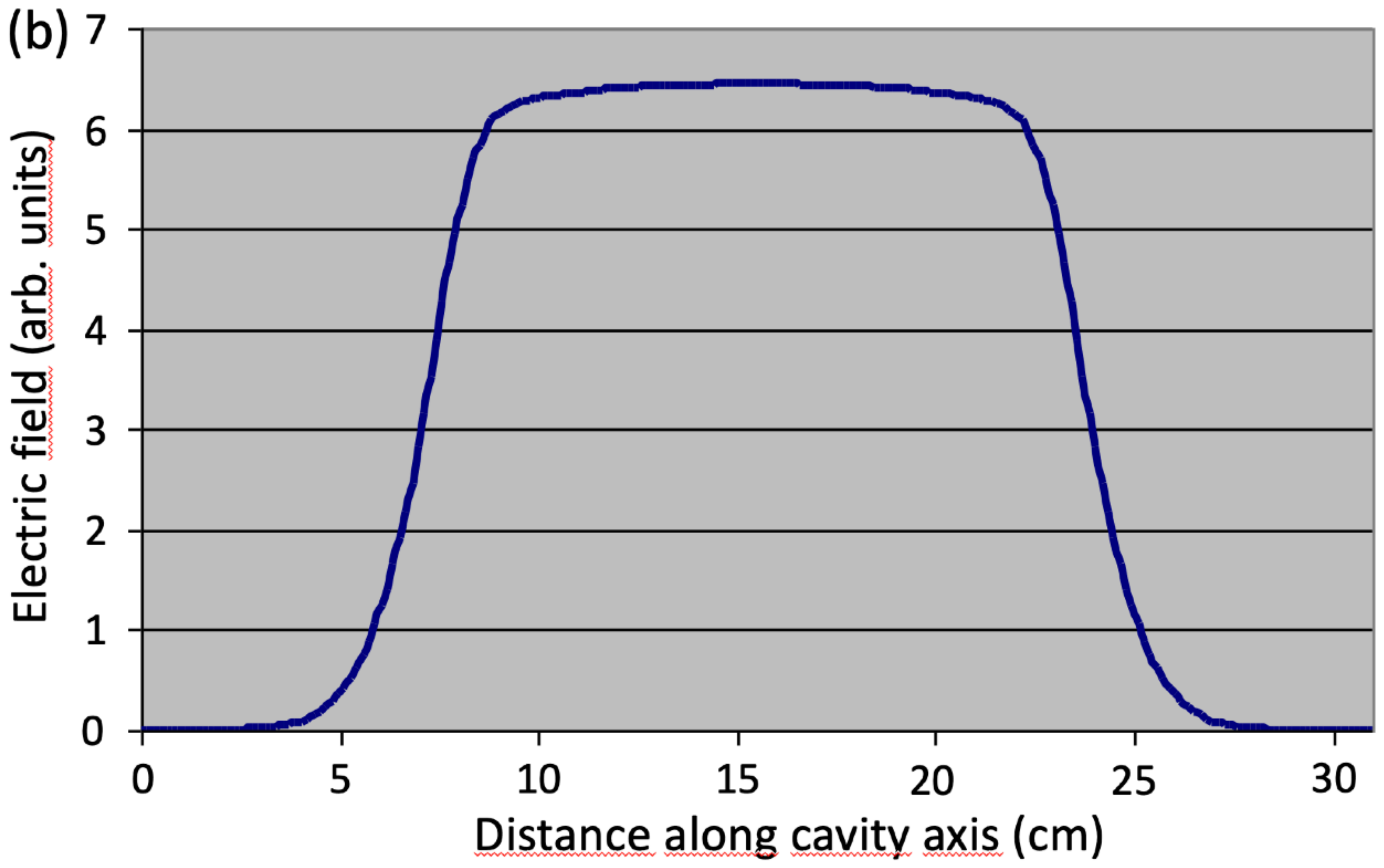
Exploded View of
RF Cavity Brazed Structure

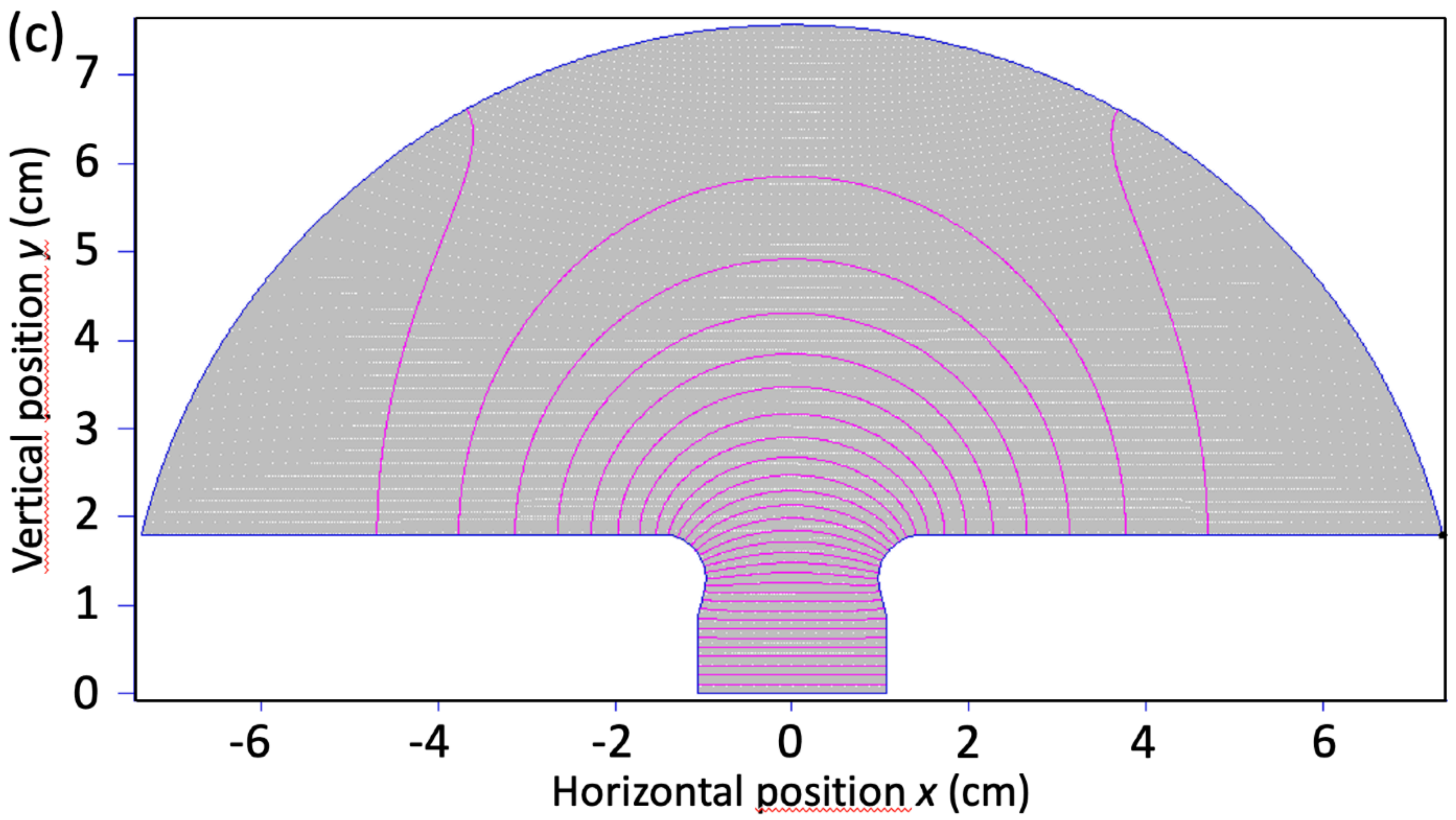
RF amplifier

- solid state technology
- 500 MHz
- 56 kW
- pulsed 10 Hz
- 40 μs pulses
- built by Jema France

Max. peak electric field on axis:

11.5 MV/m



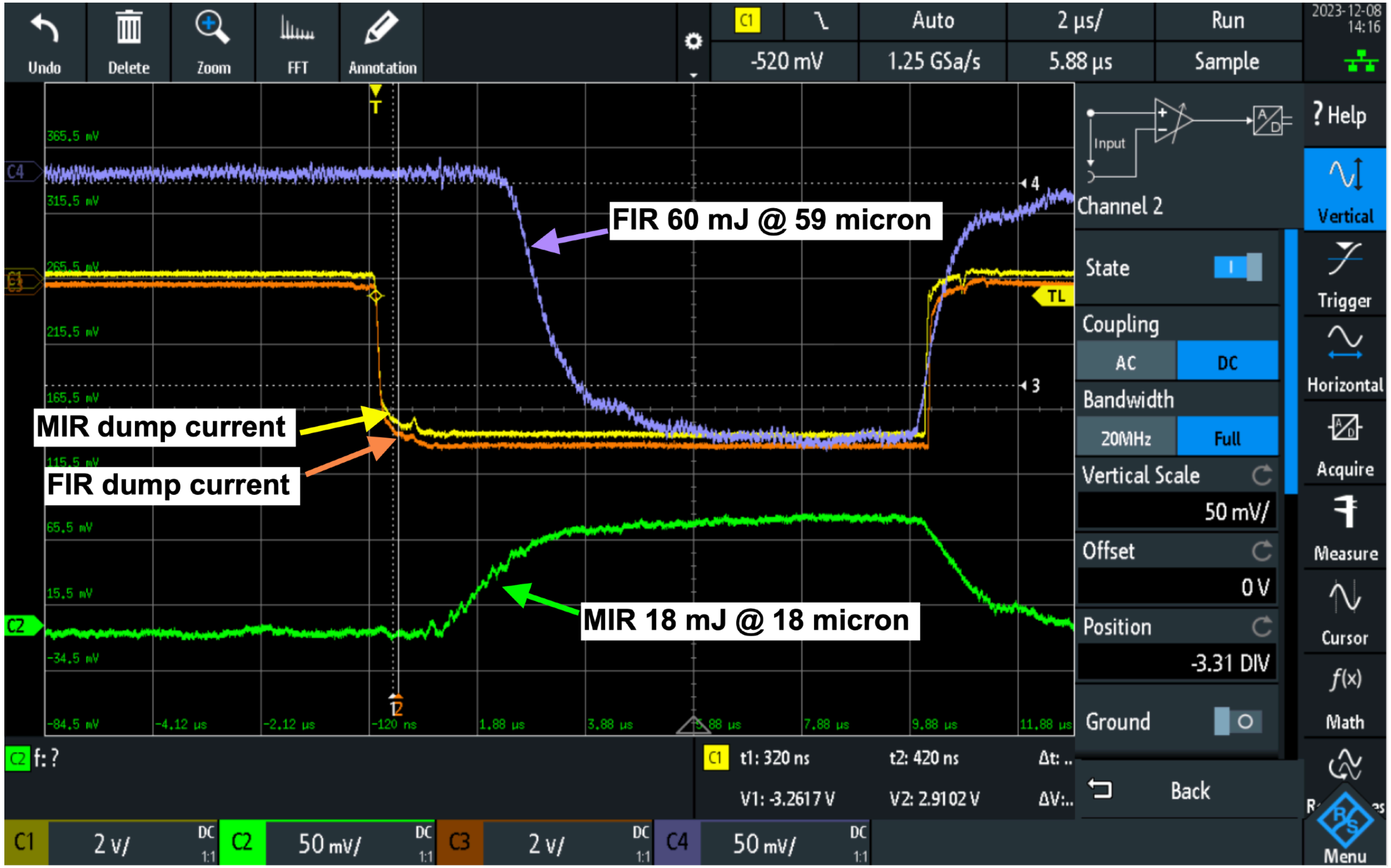


Wall losses 36 W
Q = 9838

Design by **John Rathke, Tom Schultheiss, Lloyd Young,** manufactured by RI GmbH

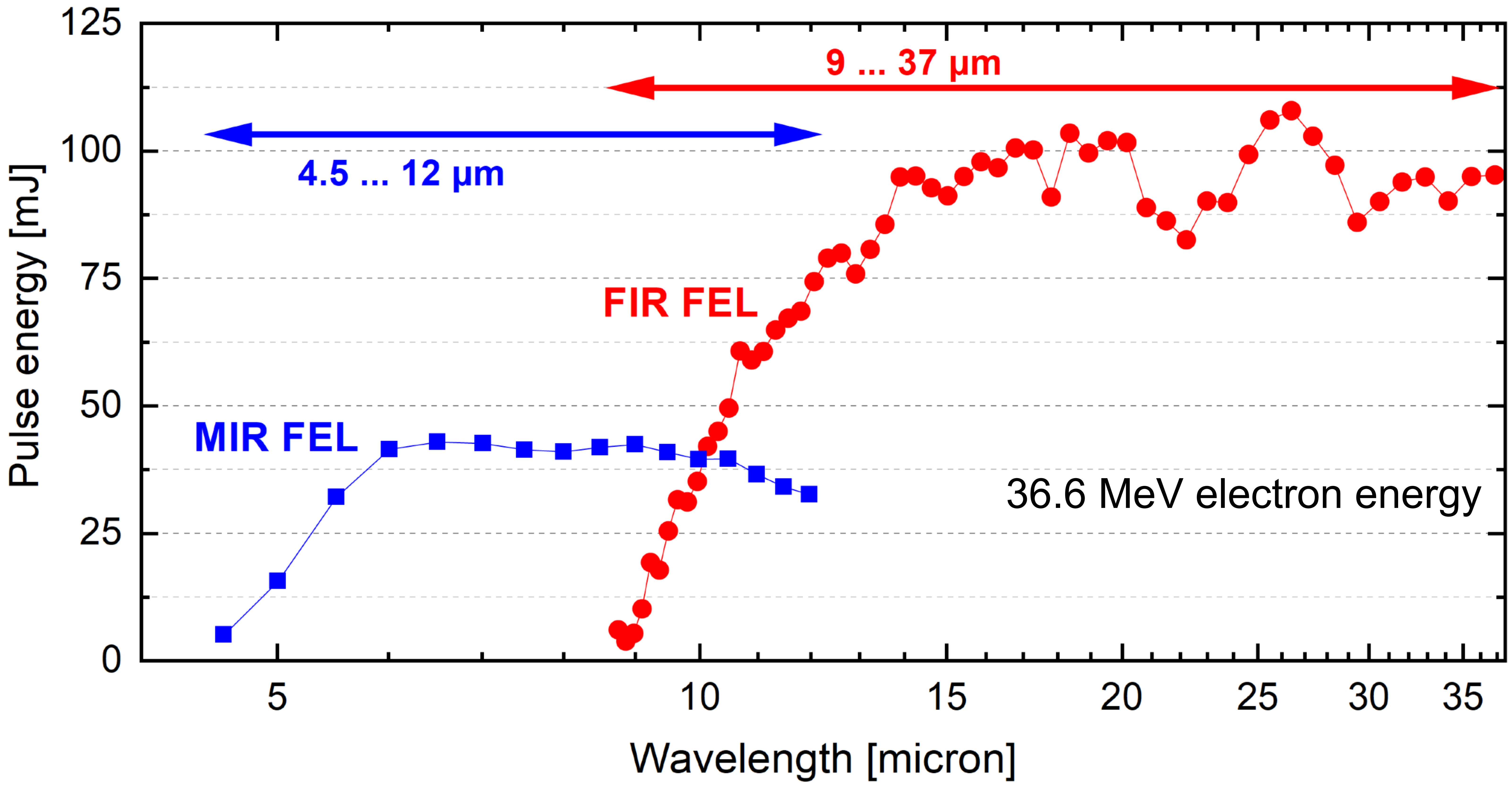
2-color operation

Oscilloscope screenshot at 22.6 MeV electron energy:
electron macro-bunches and radiation macro-pulses



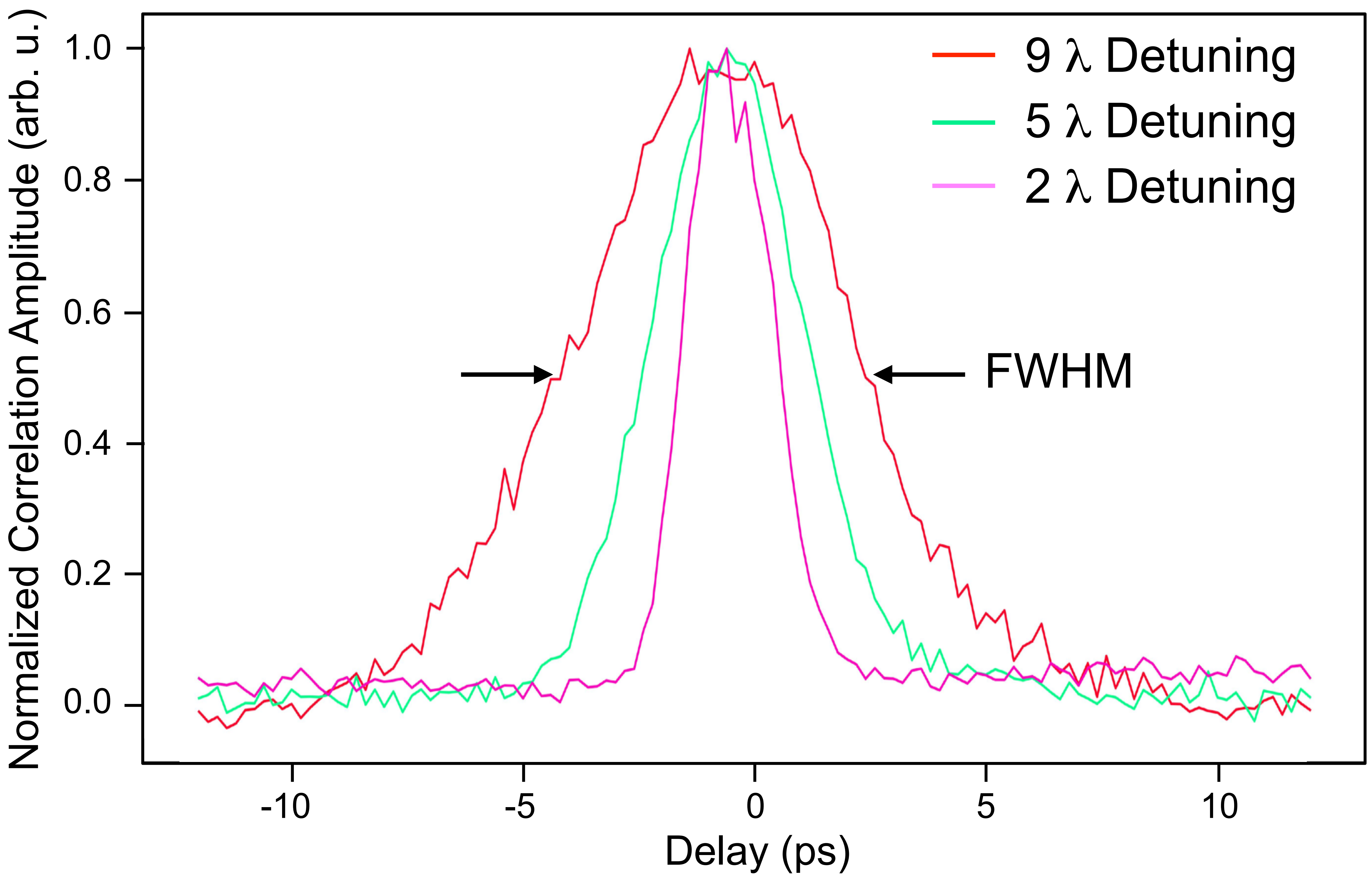
Two-color lasing power curves

- Simultaneous lasing of MIR and FIR FEL
- 500 MHz micro-pulse rep. rate in each FEL
- Independent scanning of λ_{FIR} and λ_{MIR}, no interference effects
- Wide continuous range of wavelengths: λ_{FIR} / λ_{MIR} = **0.75 … 7.5**



MIR and FIR are synchronized

- Cross-correlation measurement
- Overlap MIR and FIR pulses on non-linear material (GaSe)
- Detect sum-frequency-generation (SFG) signal as function of delay of one of the pulses
- Repeat for various FEL cavity lengths detuning



FWHM of cross-correlation signals for 3 cavity length detunings (both MIR and FIR)

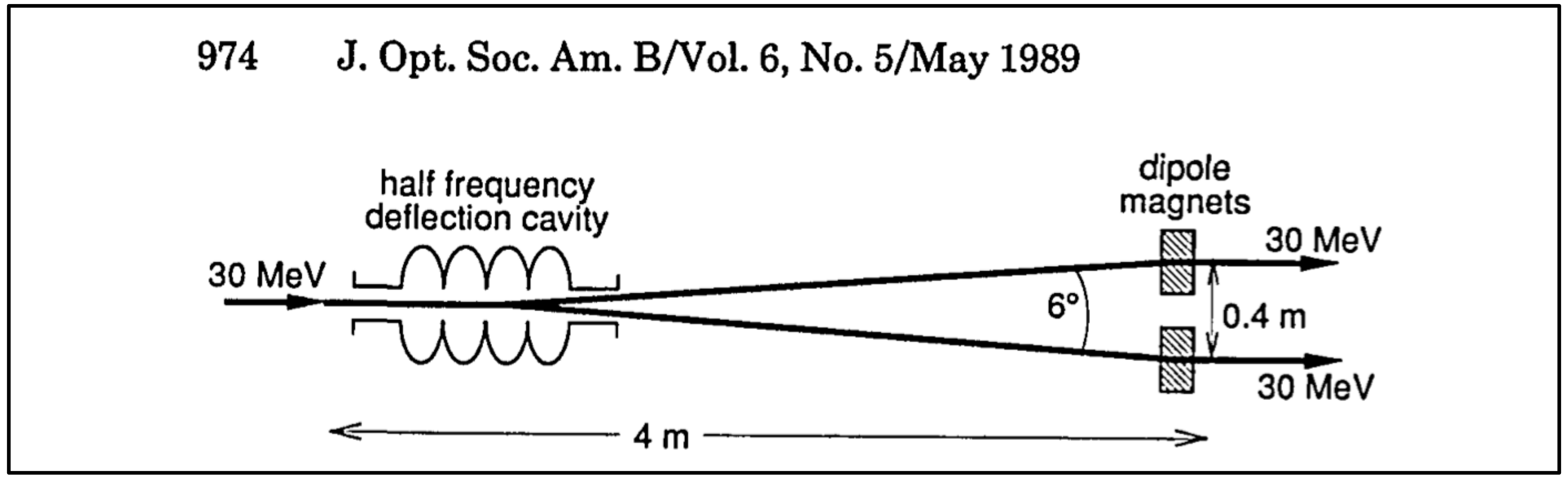
6.5 ps at 9 λ
3.0 ps at 5 λ
2.2 ps at 2 λ

- MIR and FIR FEL pulses are highly synchronized
- Upper limit for the relative jitter of both FEL's: sub ps

Akash Behera, América Torres-Boy, Alex Paarmann et al.

Previous two-color oscillator FEL’s

<u>Approach 1:</u> Split electron bunch train in two by side deflecting cavity (kicker cavity)



Proposal: H.A. Schwettman and T.I. Smith *J. Opt. Soc. Am. B* **6**, 973 (1989)

<u>Approach 2:</u> Single cavity with step-tapered (segmented) undulator
Pioneering work at ***CLIO***, demonstrated 30 years ago:

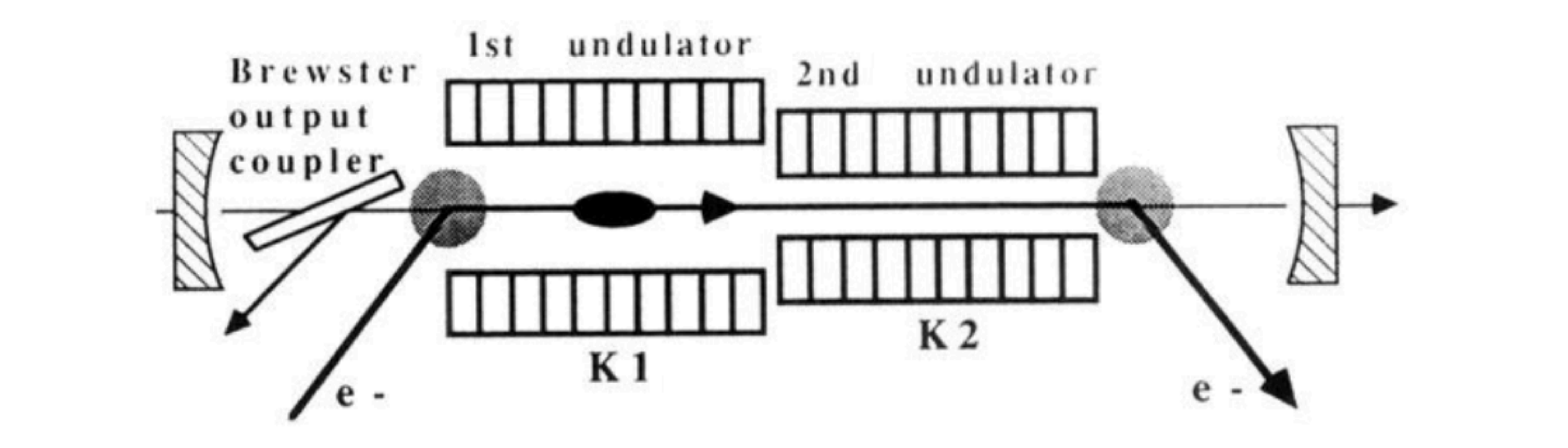


FIG. 1. Two-color free electron laser layout. K_1 and K_2 refer to the upstream and downstream undulators, respectively.

D.A. Jaroszynski, R. Prazeres, F. Glotin, and J.M. Ortega *Phys. Rev. Lett.* **72**, 2387 (1994); *Nucl. Instr. and Meth. A* **358** 224 (1995)
R. Prazeres, F. Glotin, C. Insa, D.A. Jaroszynski, and J.M. Ortega, *Nucl. Instr. and Meth. A* **407** 464 (1998)

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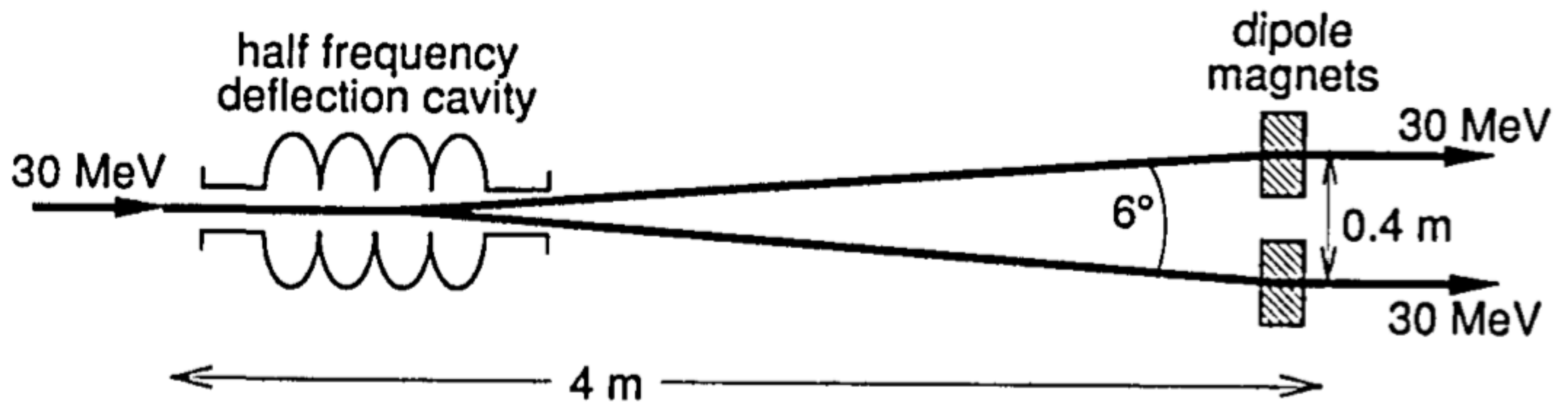
974 J. Opt. Soc. Am. B/Vol. 6, No. 5/May 1989



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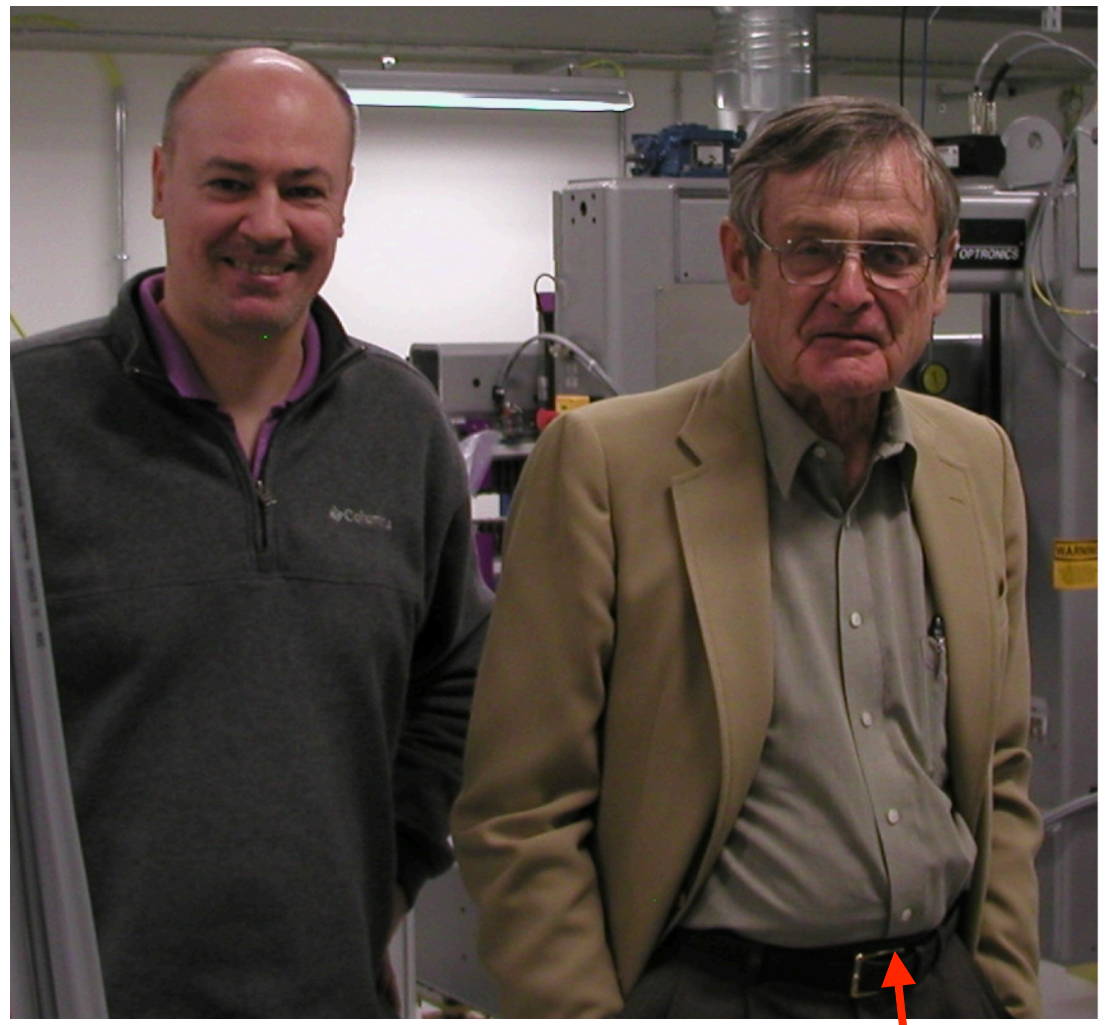

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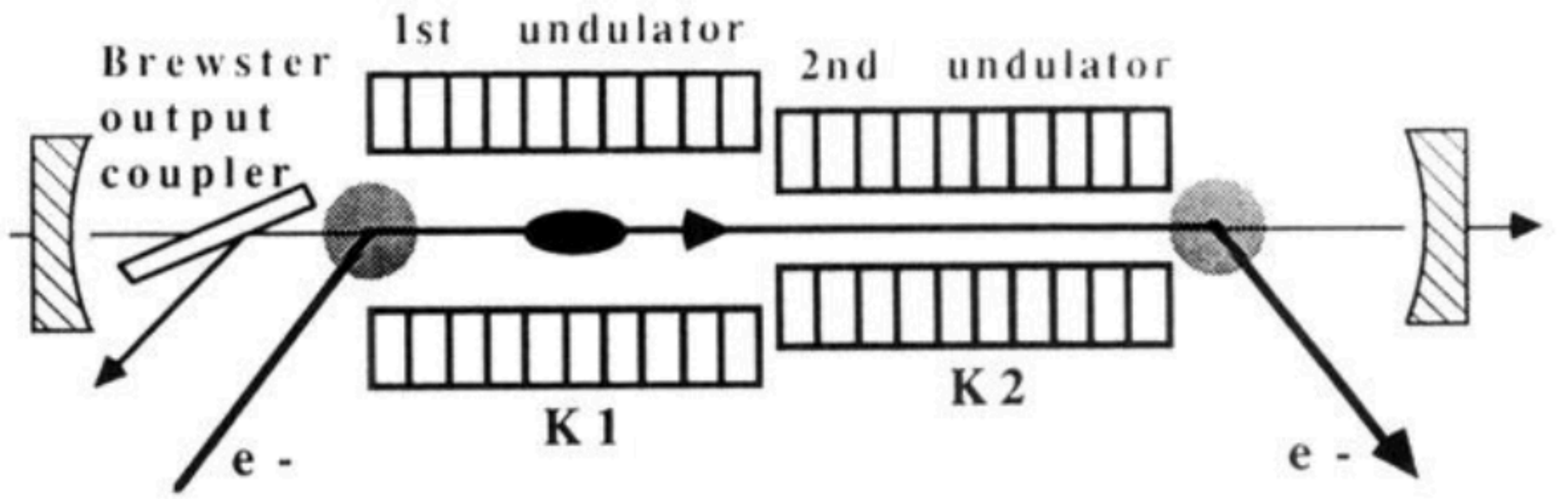

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First Operation of a Free-Electron Laser*

D. A. G. Deacon,† L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith
High Energy Physics Laboratory, Stanford University, Stanford, California 94305
(Received 17 February 1977)

A free-electron laser oscillator has been operated above threshold at a wavelength of 3.4 μm.

D.A. Jaroszynski, R. Prazeres, F. Glotin, and J.M. Ortega *Phys. Rev. Lett.* **72**, 2387 (1994); *Nucl. Instr. and Meth. A* **358** 224 (1995)
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1st user applications of two-color FEL

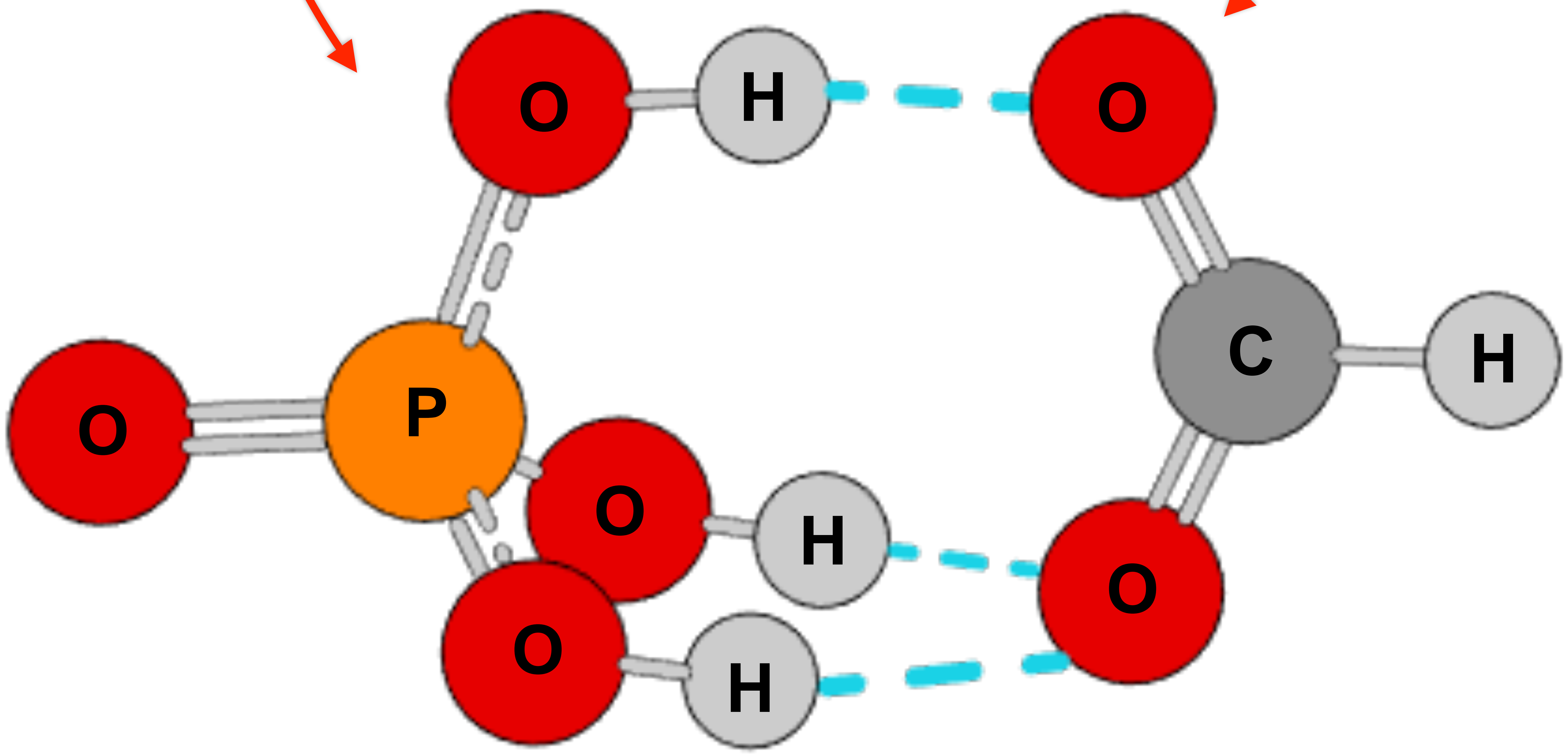
Vibrational spectra of (deuterated) Phosphoric Acid Formate

H_3PO_4 — HCO_2^-

D_3PO_4 — HCO_2^-

H_2DPO_4 — HCO_2^-

Multiphoton action spectroscopy at 0.4 K in He nano-droplets



3 hydrogen bonds

América Torres-Boy, Gert von Helden, Gerard Meijer et al.

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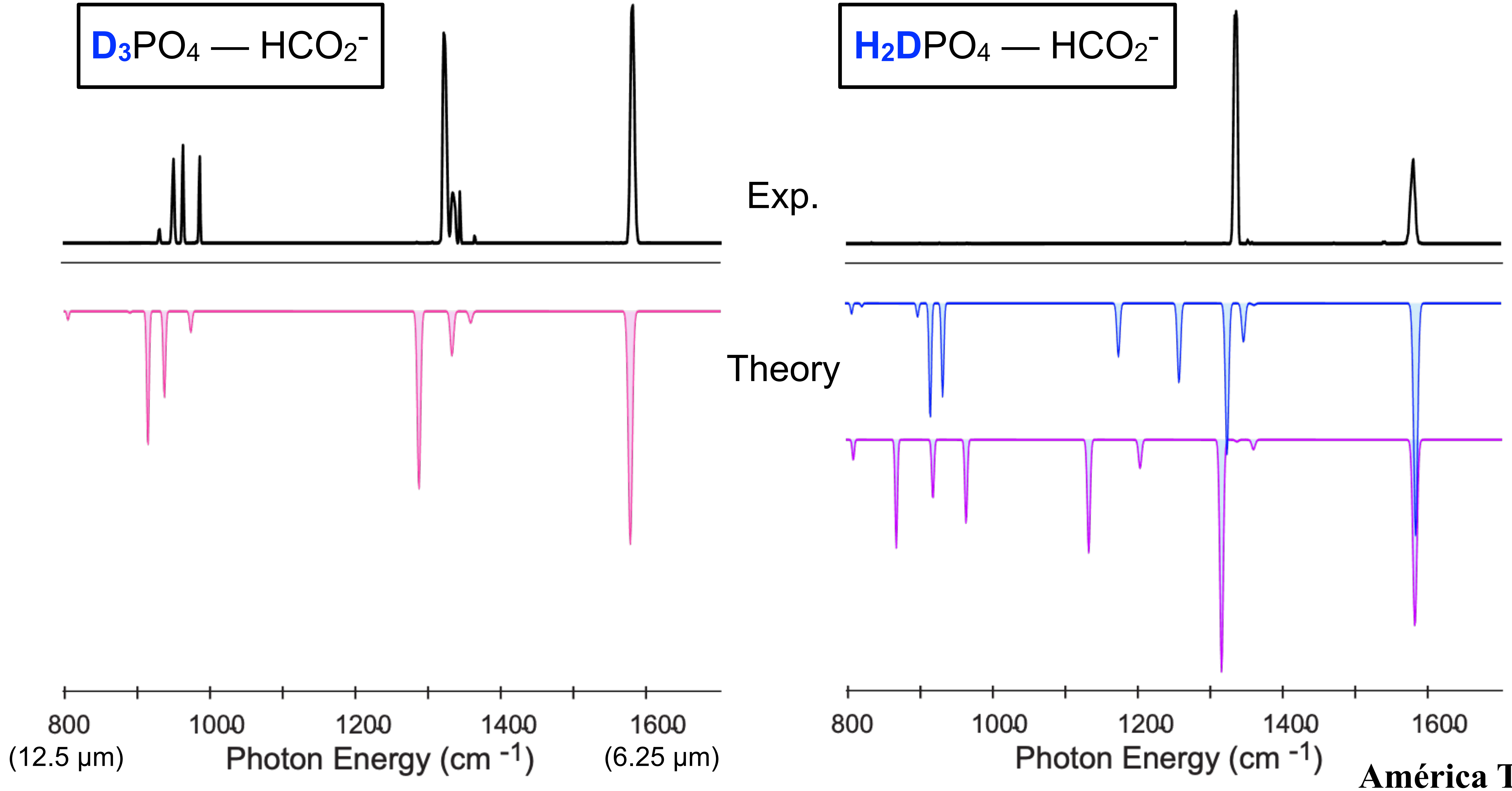

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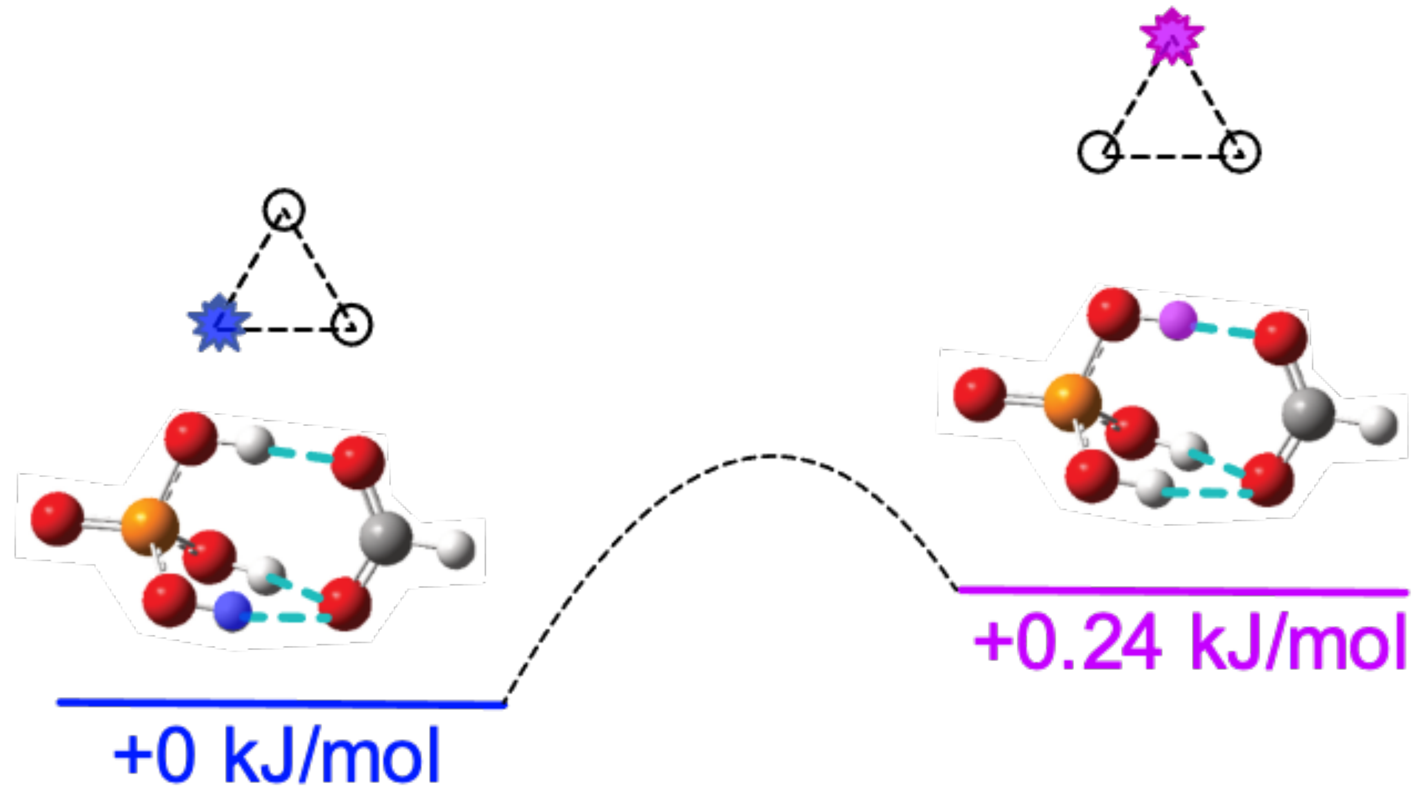
Two "isotopomers" of H_2DPO_4 — HCO_2^-



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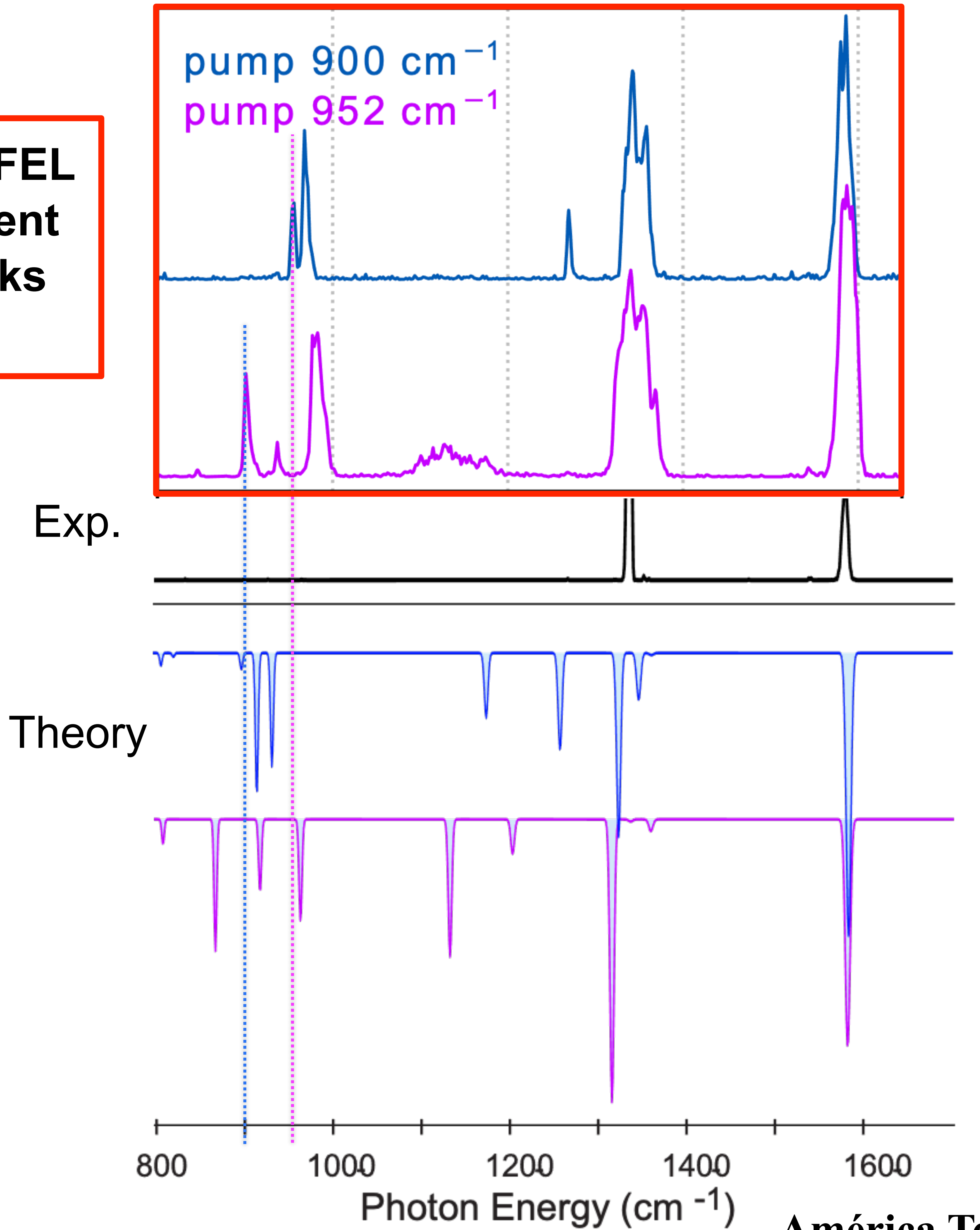
H_2D PO_4 — HCO_2^-

Two-color FEL measurement makes peaks visible



Two-color mode

MIR FEL: scan

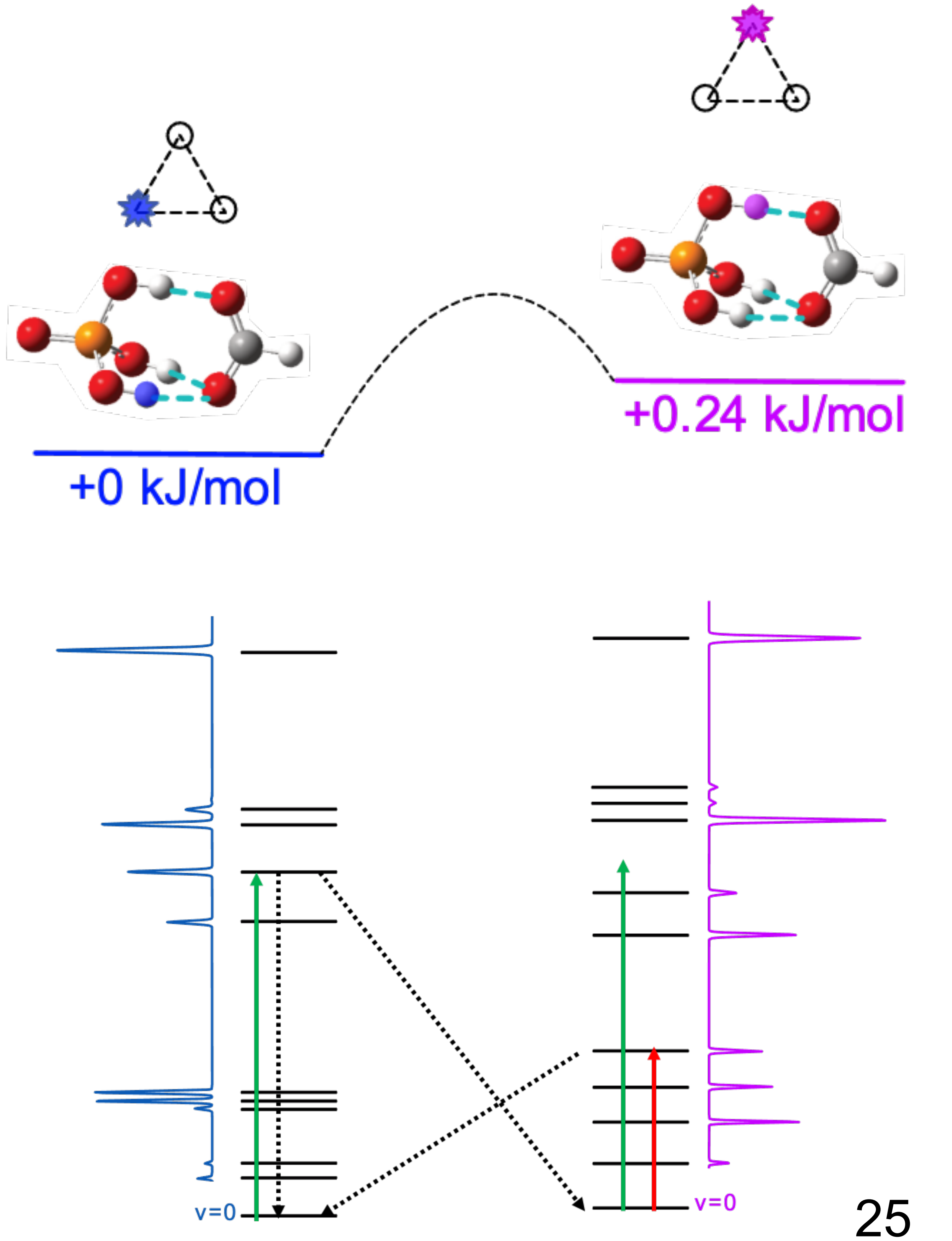
FIR FEL: pump

„re-pumper“ after de-excitation to the other isotopomer

Insight into interconversion dynamics

Multiphoton action spectroscopy at 0.4 K in He nano-droplets

Two “isotopomers“ of H_2DPO_4 — HCO_2^-



América Torres-Boy, Gert von Helden, Gerard Meijer et al.

Summary & Conclusions

- FHI FEL operational since 2013 in the mid-IR (~3 to 50 μm)
- 6 FHI user groups and their collaborators; >110 publications as of today

- **Two-color upgrade 2023:**
  - 2nd FEL for far-IR from 4.5 to 175 micron
  - Two-color dual-oscillator operation established,
    - enabled by 500 MHz side-deflecting cavity
    - no interference between MIR and FIR lasing
    - wide continuous tuning range $\lambda_{FIR} / \lambda_{MIR} = 0.75 \ldots 7.5$
  - Two-color operation also in reduced pulse-repetition rate mode
  - Novel user experiments (pump-probe, SFG, …) in two-color mode now possible at FHI

Acknowledgment

FHI Berlin:

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Gert von Helden,

Heinz Junkes (IT),

William Kirstädter (IT),

Sebastian Kray (MP),

K.P. Vogelgesang (MP),

Alex Paarmann (PC),

Martin Wolf (PC),

Frank Kubitz + Team (FWT),

FHI ELAB,

FHI FEL user groups, …..

Consultants to FHI:

Alan Todd (formerly AES Inc.),

John Rathke (formerly AES Inc.),

Tom Schultheiss (formerly AES Inc.),

Lloyd Young (formerly LANL),

Steve Gottschalk (formerly STI Optronics),

Dave Dowell (formerly SLAC),

Bill Colson (formerly NPS)

FELIX (Nijmegen, NL): Lex van der Meer,
Arjan van Vliet

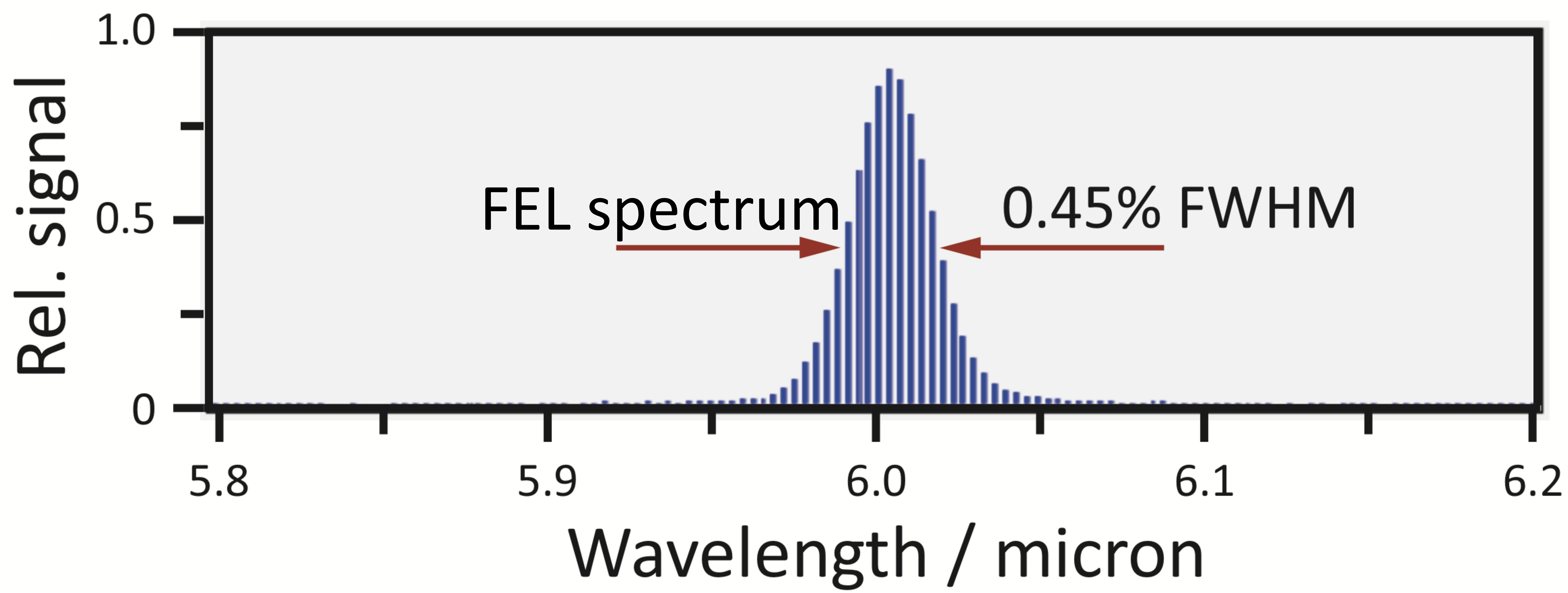
FELBE (HZDR Rossendorf): Ulf Lehnert

BESSY (Berlin): Johannes Bahrdt, Klaus Ott

The End

FHI FEL Spectrum

Line spectrum measured with grating spectrometer (Acton, 75 g / mm)



- Typically 0.3 ... 0.7% FWHM for IR spectroscopic experiments
- IR pulses as short as ~ 0.5 ps at correspondingly wider spectral width also possible

Reduced Repetition Rate Mode

Number of IR pulses in a FEL cavity when kicker is OFF (100% to one FEL)				
Division Factor n	Gun Rep. Rate	Pulse separation		No. of pulses
	[MHz]	[m]	[ns]	5.4
1	1000	0.3	1	36.00
2	500	0.6	2	18.00
3	333.333	0.9	3	12.00
4	250	1.2	4	9.00
6	166.667	1.8	6	6.00
9	111.111	2.7	9	4.00
12	83.3333	3.6	12	3.00
18	55.5556	5.4	18	2.00
36	27.7778	10.8	36	1.0

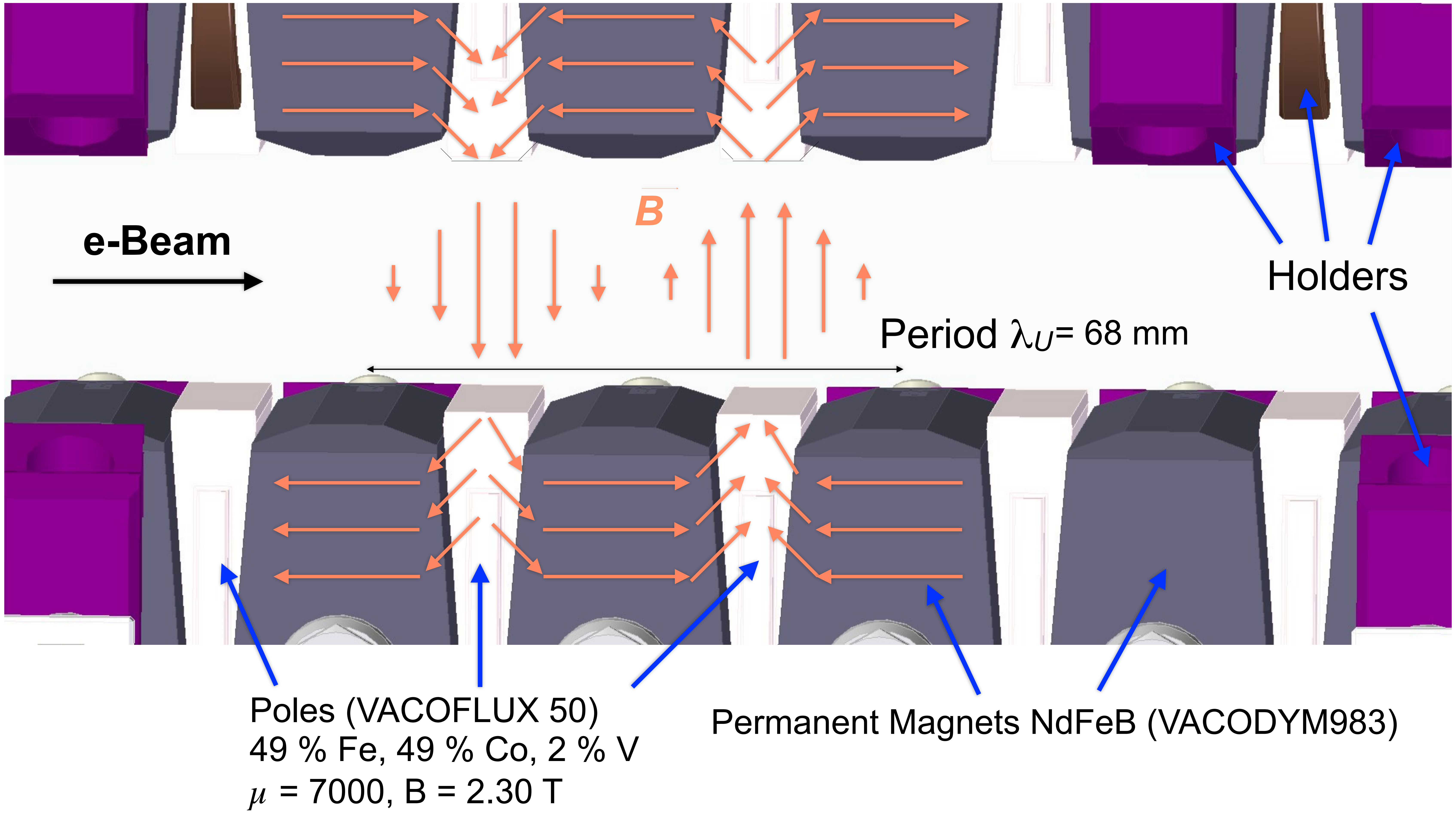
Cavity length: 5.4 m
Cavity round-trip time: 36 ns

Standard mode of FHI FEL
(1 GHz sine wave from RF amplifier)

Two-color mode possible

Reduced rep-rate mode of FHI FEL
(High-voltage gun pulser)

Hybrid magnet undulator FHI & FELIX



Wedged-pole design by Steve Gottschalk:
1. strong field & 2. radiation hard