Commissioning of CW FEL Amplifier for Coherent Electron Cooler (CeC)

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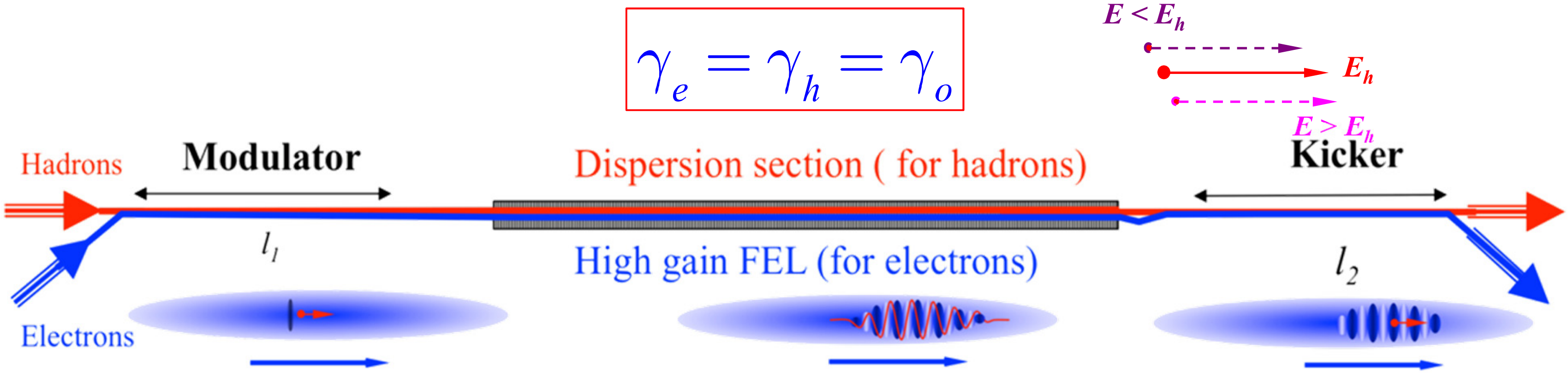
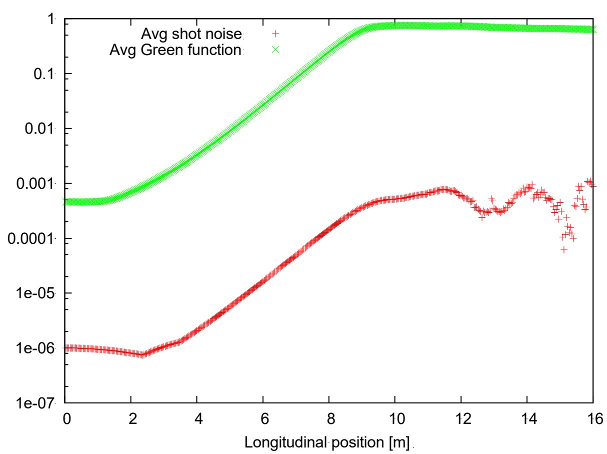
Key difference of FEL CeC amplifier

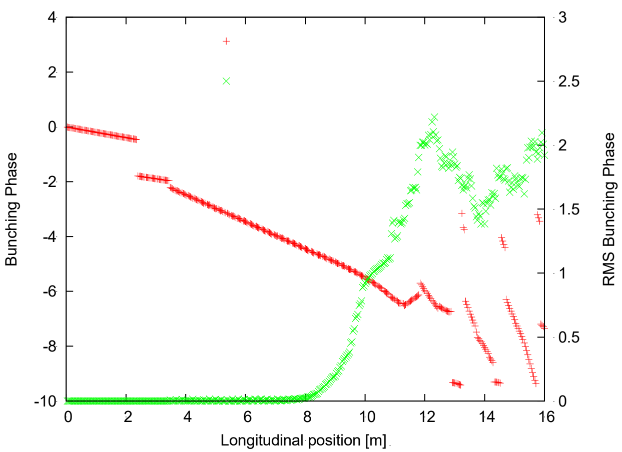


- In our case it had to be a **low a_w FEL** to match FEL group-velocity with hadron velocity

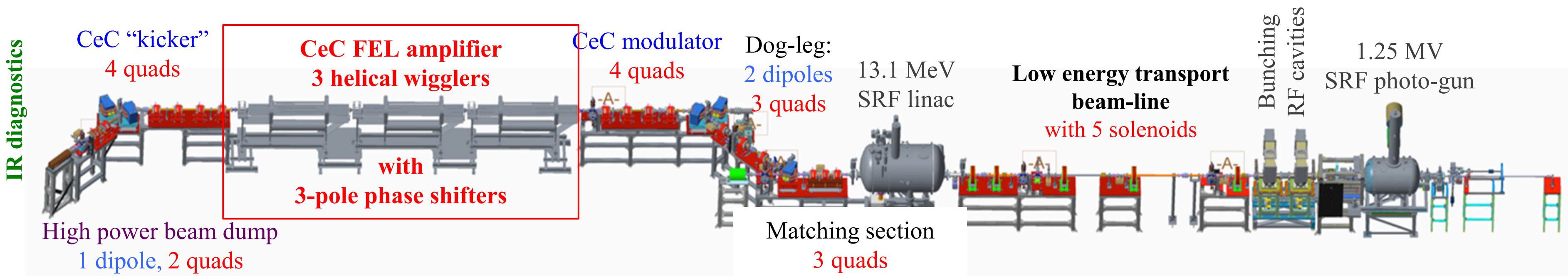
$$v_{group} = v_{z,e}\cdot(1-\alpha)+\alpha\cdot c \cong v_o + c\left(\alpha - a_w^2(1-\alpha)\right)\gamma_o^{-2} \geq v_o;\quad a_w^2 \leq \frac{\alpha}{1-\alpha};\qquad \alpha_{3D} < \alpha_{1D} = \frac{1}{3}$$

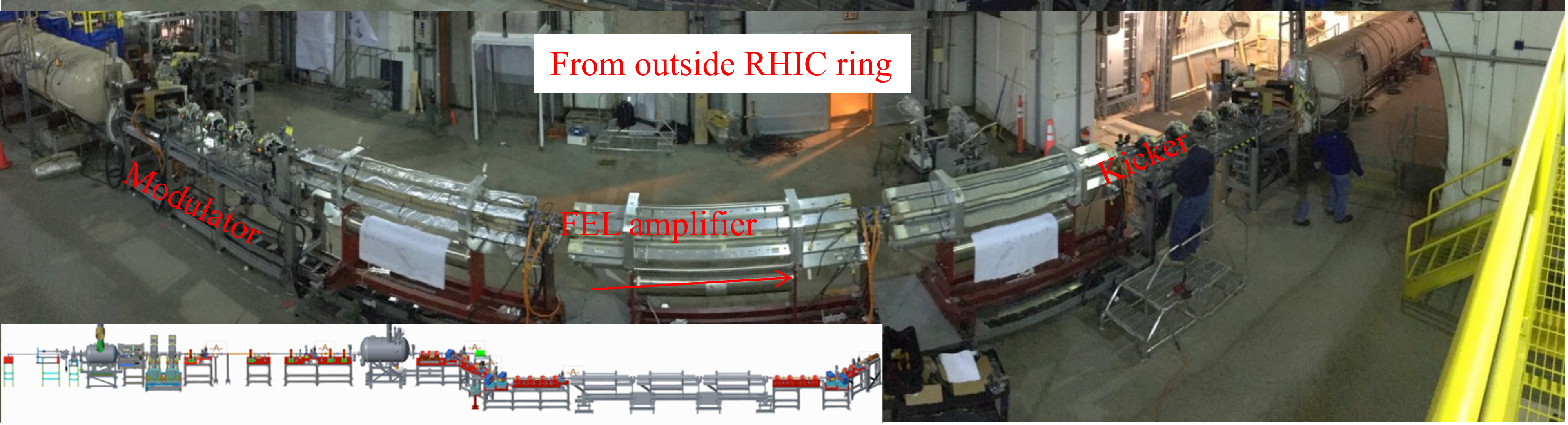
- FEL serves as a **BROAD-BAND LINER CeC** amplifier: **SATURATION IS BAD!**

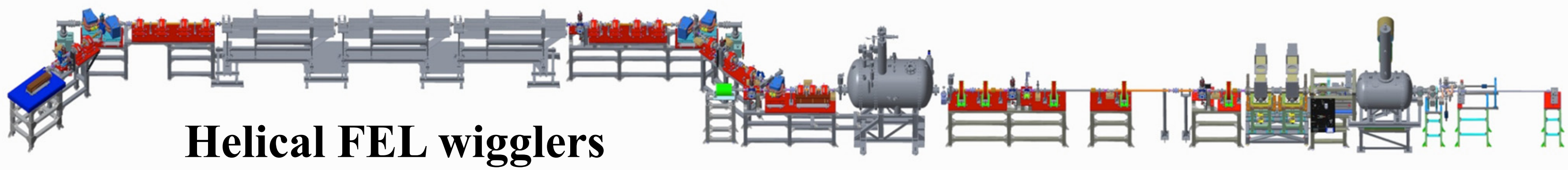




CeC experiment at RHIC

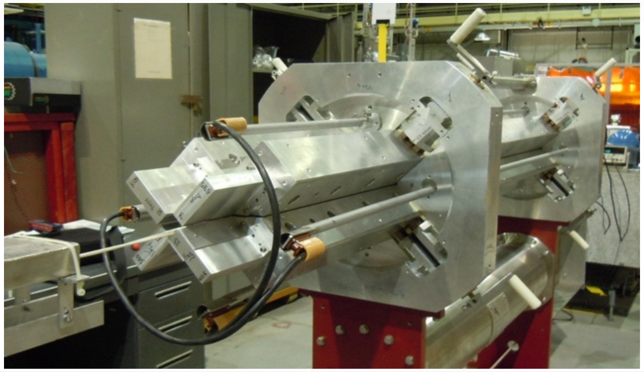




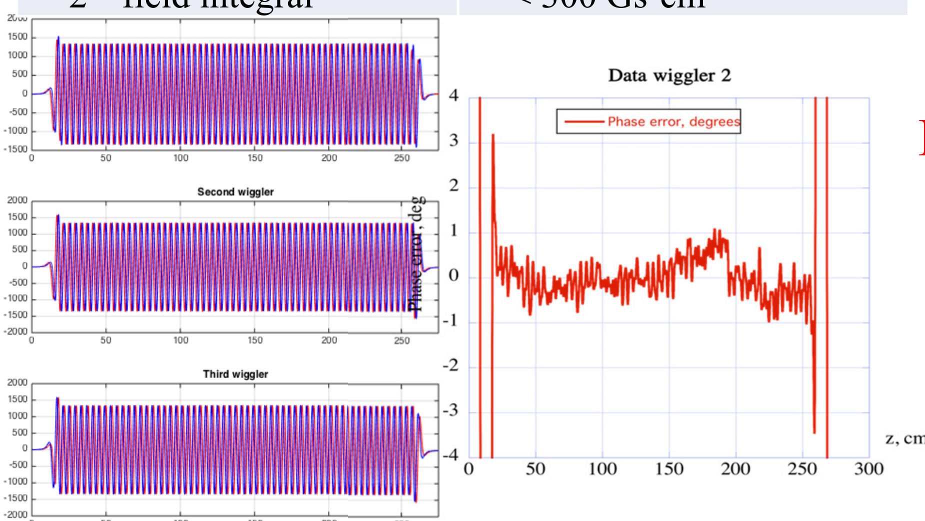


Helical FEL wigglers

CeC SRF accelerator



Parameter	Value
Wiggler parameter, a_w	**0.5 +0.05/-0.1**
Wiggler gap, mm	**32**
Wiggler period, mm	**40**
RMS FEL Phase Error	< 1° (3° peak-to-peak)
1^{st} field integral	< 30 Gs·cm
2^{nd} field integral	< 300 Gs·cm^2



Parameter	
Species in RHIC	Au^{+79} 26.5 GeV/u
Electron energy	**14.56 MeV**
Charge per electron bunch	0.1- 10.7 nC
Peak current	50 -100A
Bunch duration, psec	12
Normalized beam emittance	**0.15 - 5 mm mrad**
FEL wavelength	**31 μm**
Repetition rate	78.17 kHz
CW beam	150 μA

Record performer 1.25 MV CW SRF gun

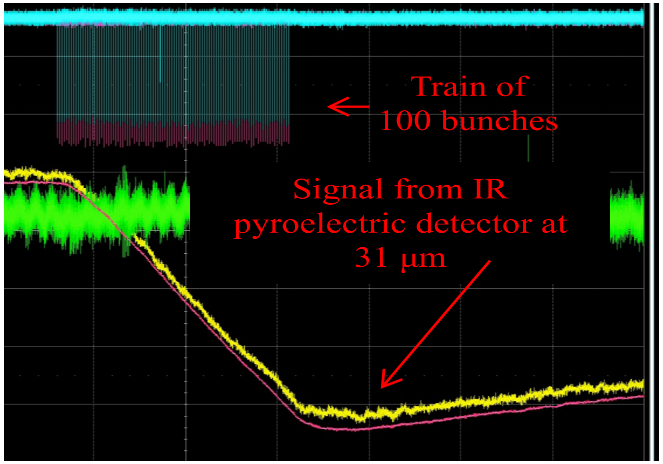
suitable for CW X-ray FELs

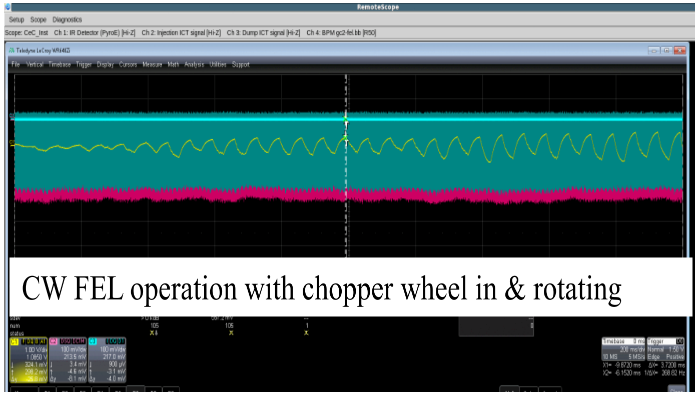
100 pC ε_{norm} = 0.15 mm mrad

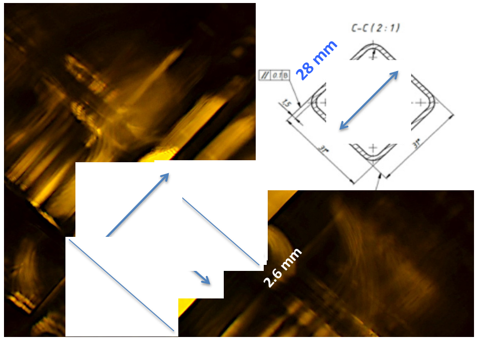
600 pC ε_{norm} = 0.35 mm mrad

Instead of Conclusions

- FEL amplification was demonstrated in April 2018 – it was easy and took two days
- Few more days to confirm that we do not saturate the FEL
- Typical peak current was between 50 A and 70 A with measure peak power was 20±5 kW with 50 A peak current
- FEL studies were not a priority – it was a tool for Coherent electron Cooling experiment
- Small gap of FEL wigglers (28 mm diamond) is incompatible with RHIC operating at low (few GeV/u) ions – FEL system is removed last year and conserved
- Coherent electron Cooling experiment continues with a new broad-band – a Plasma Cascade micro-bunching Amplifier



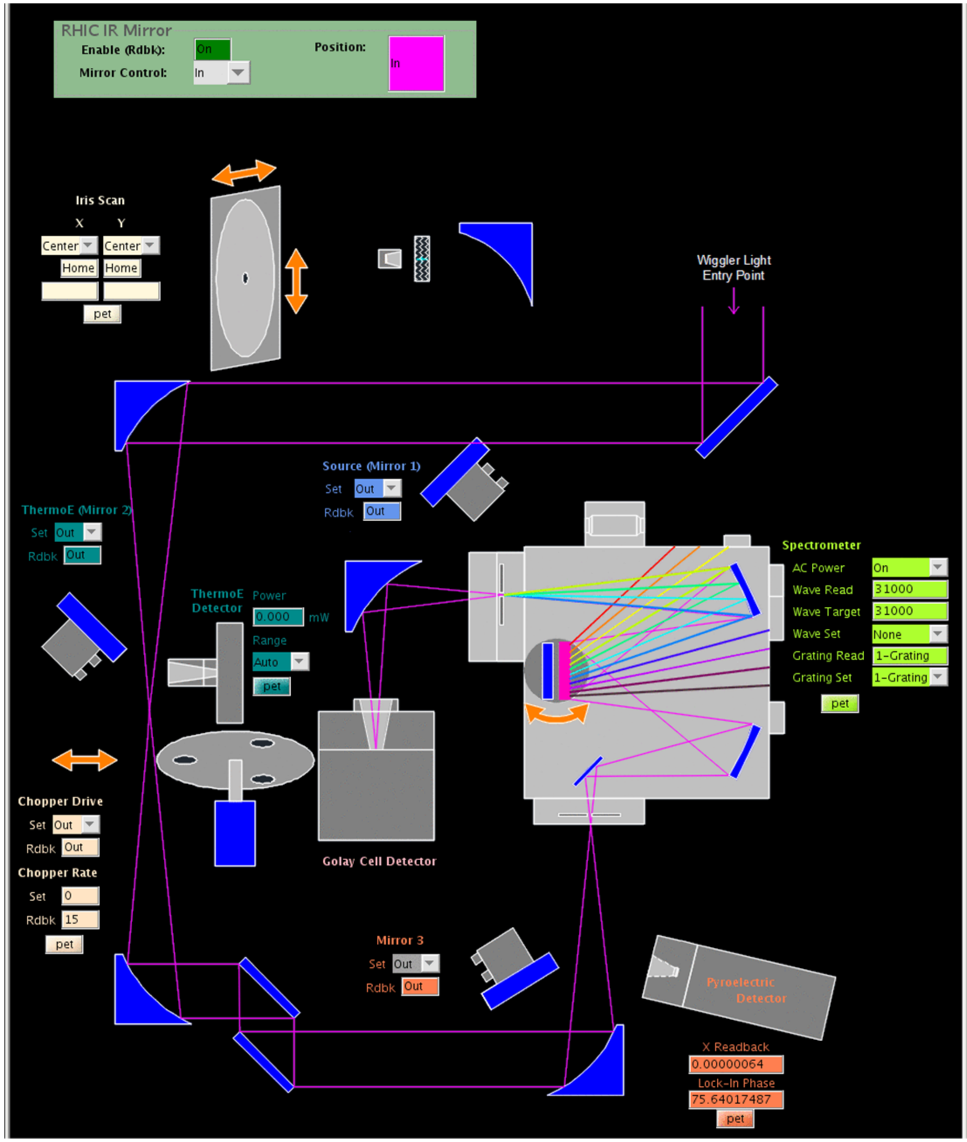




… it takes a village to build such system

… never can get all of your photos…

IR diagnostics



Golay cell: GC-1D optoacoustic detector

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CALIBRATION DATA

The calibration data are summarized in the table below:

Detector GC-1D	No. GC00060	
Power supply unit GC-PS/1	No. PS08005	
Window material	diamond	
Aperture of entrance cone	11 mm	
Aperture of entrance window	6 mm	
Reference frequency	5 Hz	10 Hz
Calibration power	1.17×10^{-6} W	1.17×10^{-6} W
Noise output at reference frequency	1.28×10^{-5} V/Hz$^{1/2}$	7.58×10^{-6} V/Hz$^{1/2}$
Optical responsivity at reference frequency	1.22×10^{5} V/W	1.01×10^{5} V/W
Response rate T_R (see Fig. 10)	38 ms	38 ms
Noise-equivalent power at reference frequency	1.05×10^{-10} W/Hz$^{1/2}$	7.52×10^{-11} W/Hz$^{1/2}$
Detectivity (D*) at entrance cone aperture	9.53×10^{9} cmHz$^{1/2}$/W	1.27×10^{10} cmHz$^{1/2}$/W
Detectivity (D*) at entrance window aperture	4.01×10^{9} cmHz$^{1/2}$/W	5.77×10^{9} cmHz$^{1/2}$/W

Pyroelectric detector

gentec-eo

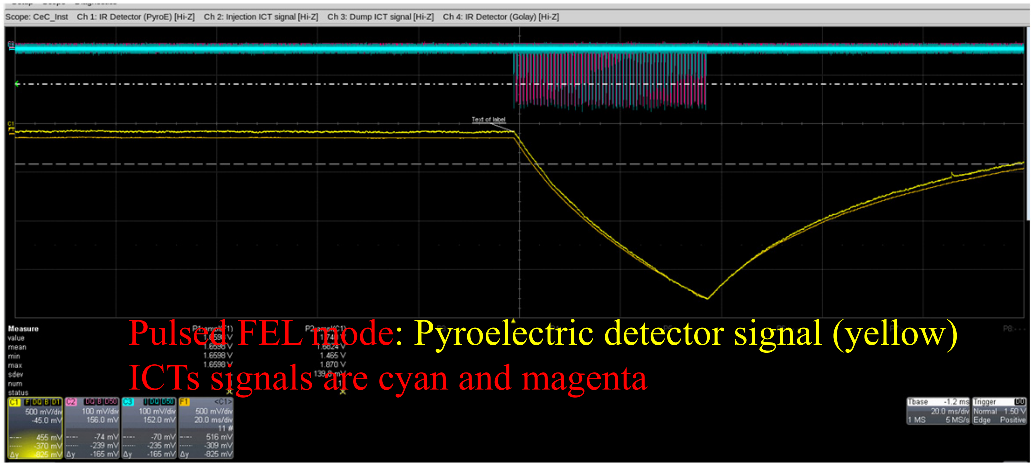
CERTIFICATE OF CALIBRATIC

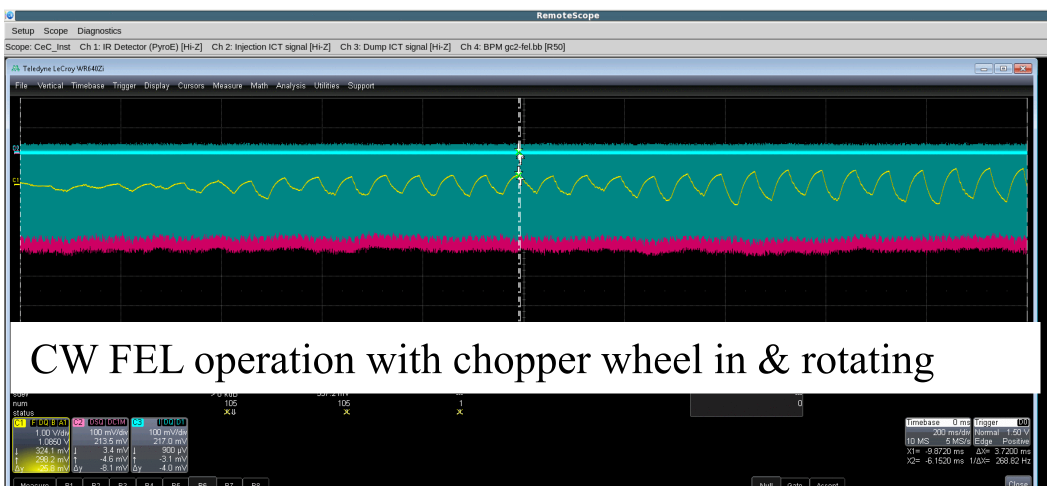
Certificate # : 506449-171103
Model Number: THz5I-BL-BNC
Head Serial Number: 506449
Cal. Procedure: 100-1025
Customer Name:
Instrument ID:
Date of Calibration: November 3, 2017
Calibration Due Date: *

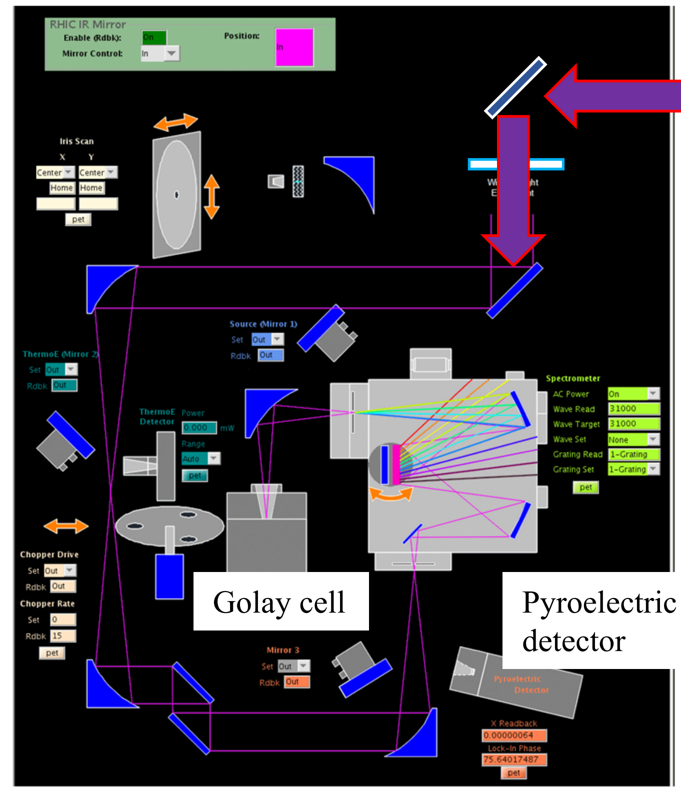
Calibration Data

Calibration								
Meaurement Parameter	Sensitivity		Into Load	Power	Rep.Rate	Ambient Temp.	Relative Humidity	**Beam Ø**
@ 633 nm	V/W	%	Ω	**uw**	Hz	°C	%	**mm**
Rv (P to P)	2.12E+05	± 2.1	NA	8.2	5	21	33	1
Rv (RMS)	6.91E+04	± 2.1	NA	8.2	5	21	33	1
					Hz	°C	%	**mm**
Vn (RMS) @ 1 Hz BW	1.30E-04	± NA	NA	NA	5	21	33	NA
	W/Hz$^{1/2}$				Hz	°C	%	**mm**
NEP (P to P)	6.10E-10	NA	NA	NA	5	21	33	NA
NEP (RMS)	1.90E-09	± NA	NA	NA	5	21	33	NA

FEL amplifier and Infrared Diagnostics were fully operational



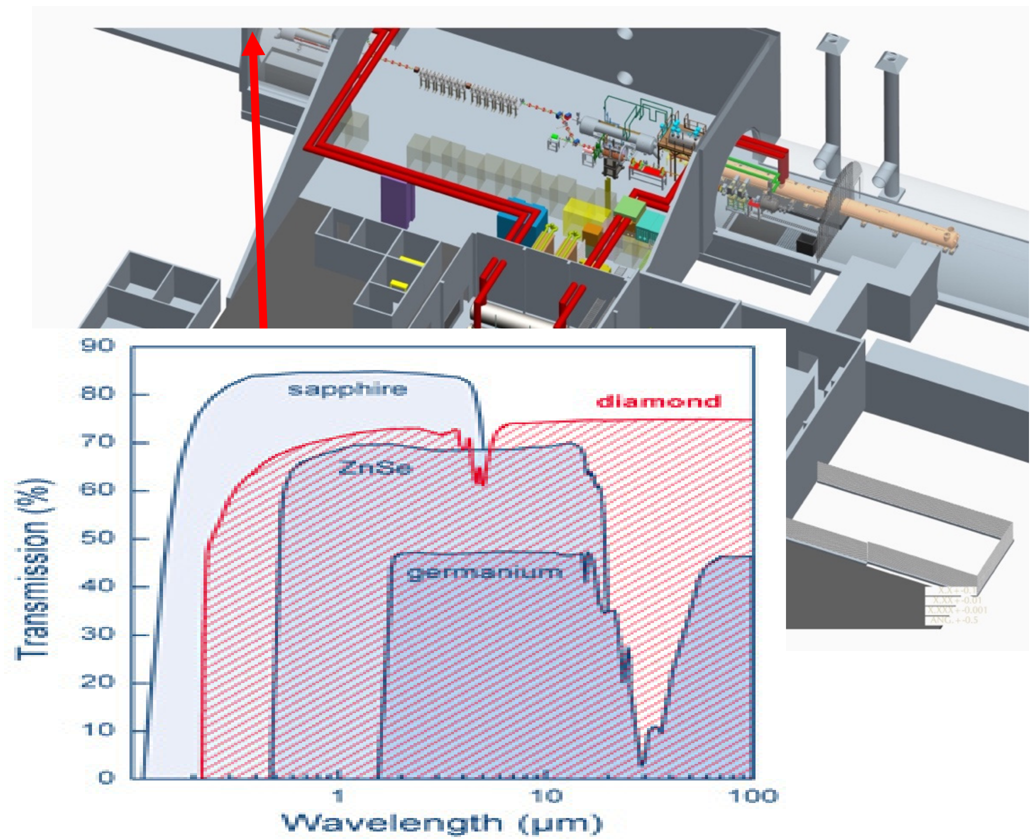




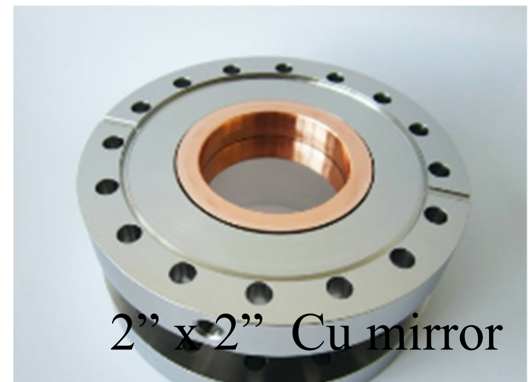
IR diagnostics controls

IR Diagnostics for 30 μm

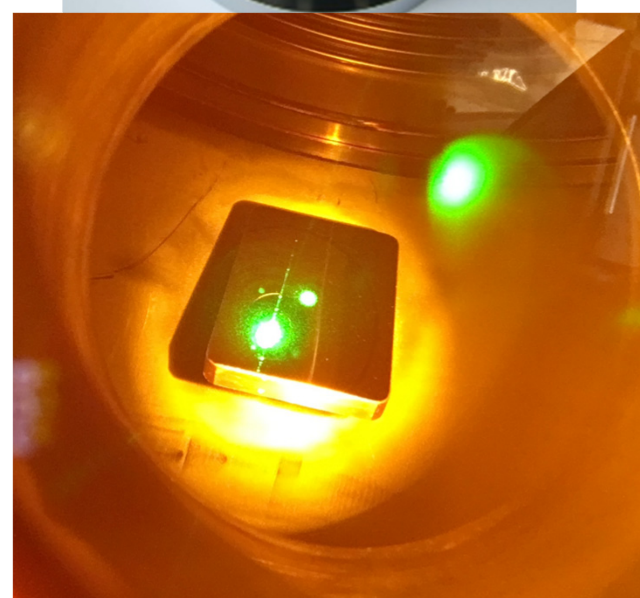
- New CVD diamond window was installed
- IR diagnostics detector system was upgraded to be sensitive at 30 μm



SVD diamond window

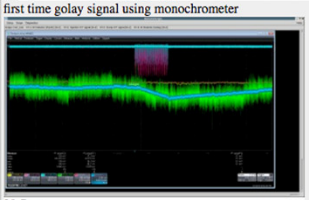


2'' x 2'' Cu mirror



Jun 01 20:50 cp yjing [31 edits]

first time golay signal using monochrometer



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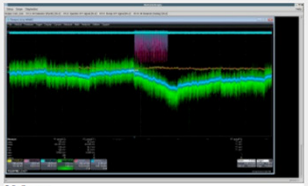

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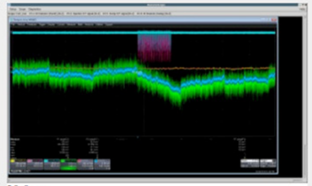

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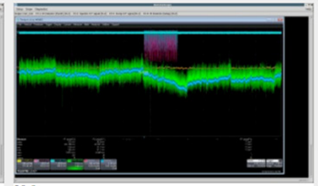

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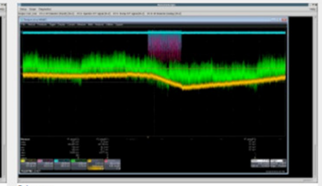

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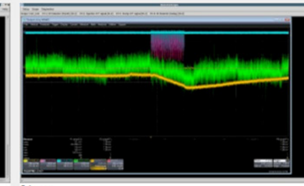

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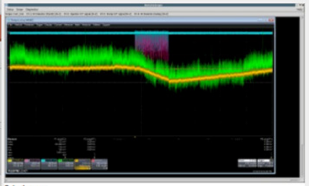

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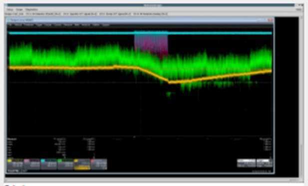

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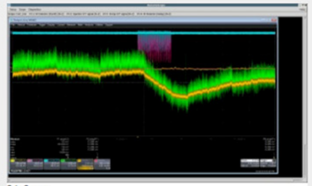

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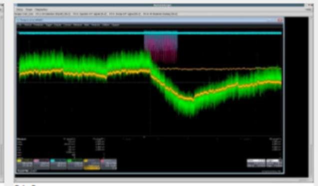

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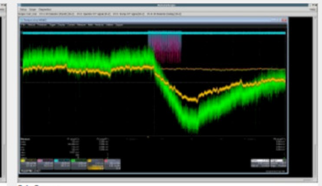

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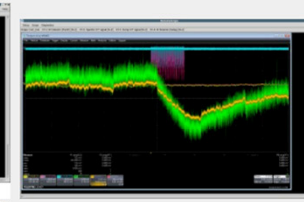

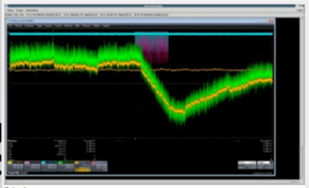

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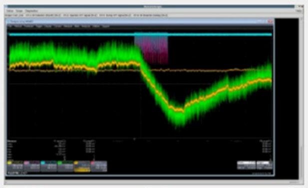

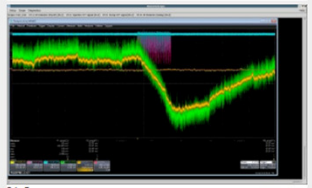

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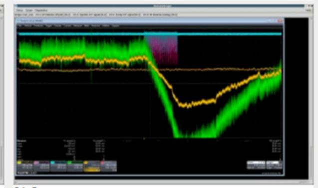

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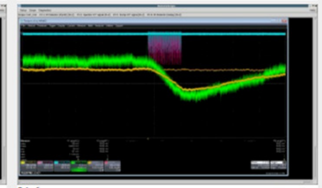

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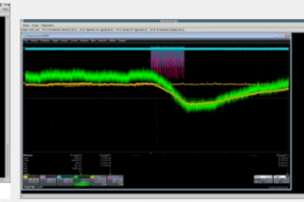

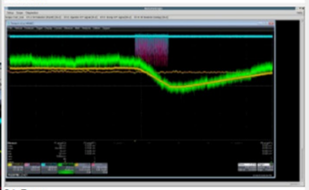

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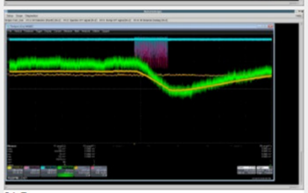

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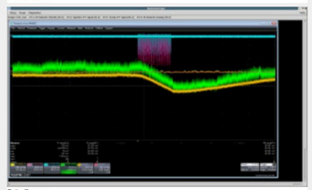

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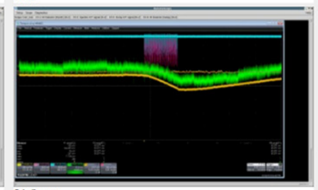

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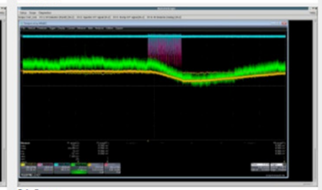

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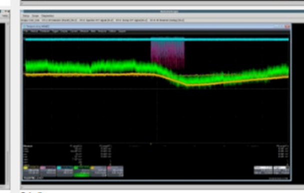

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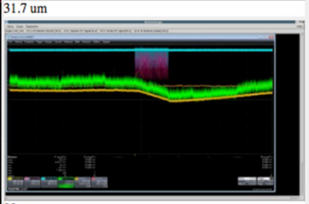

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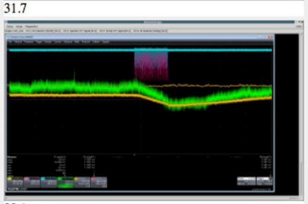

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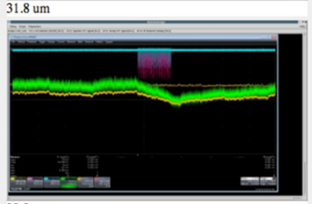

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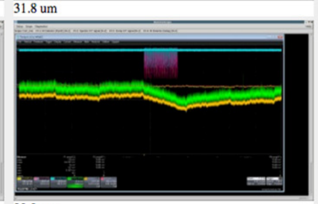

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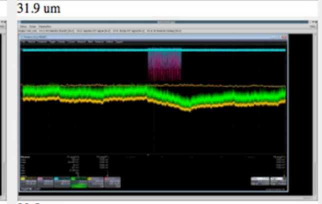

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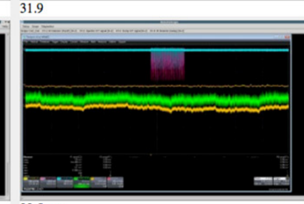

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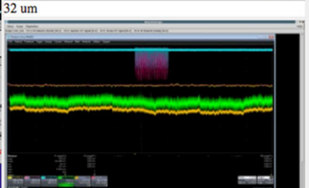

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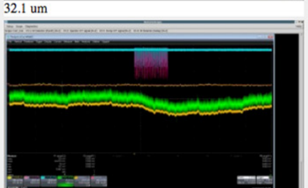

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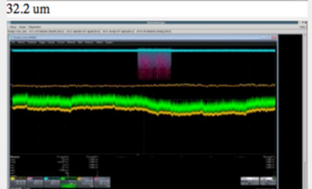

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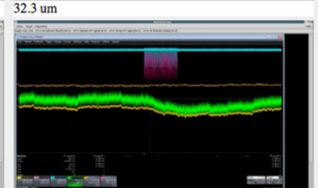

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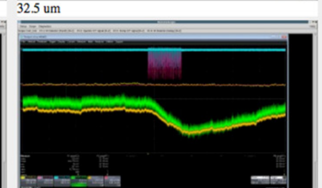

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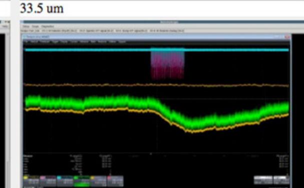

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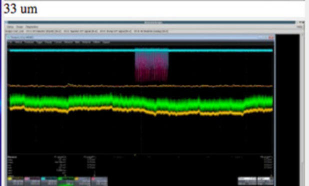

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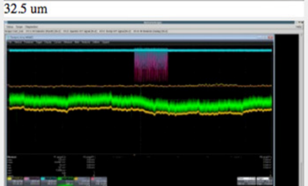

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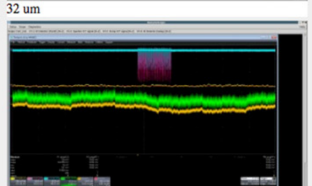

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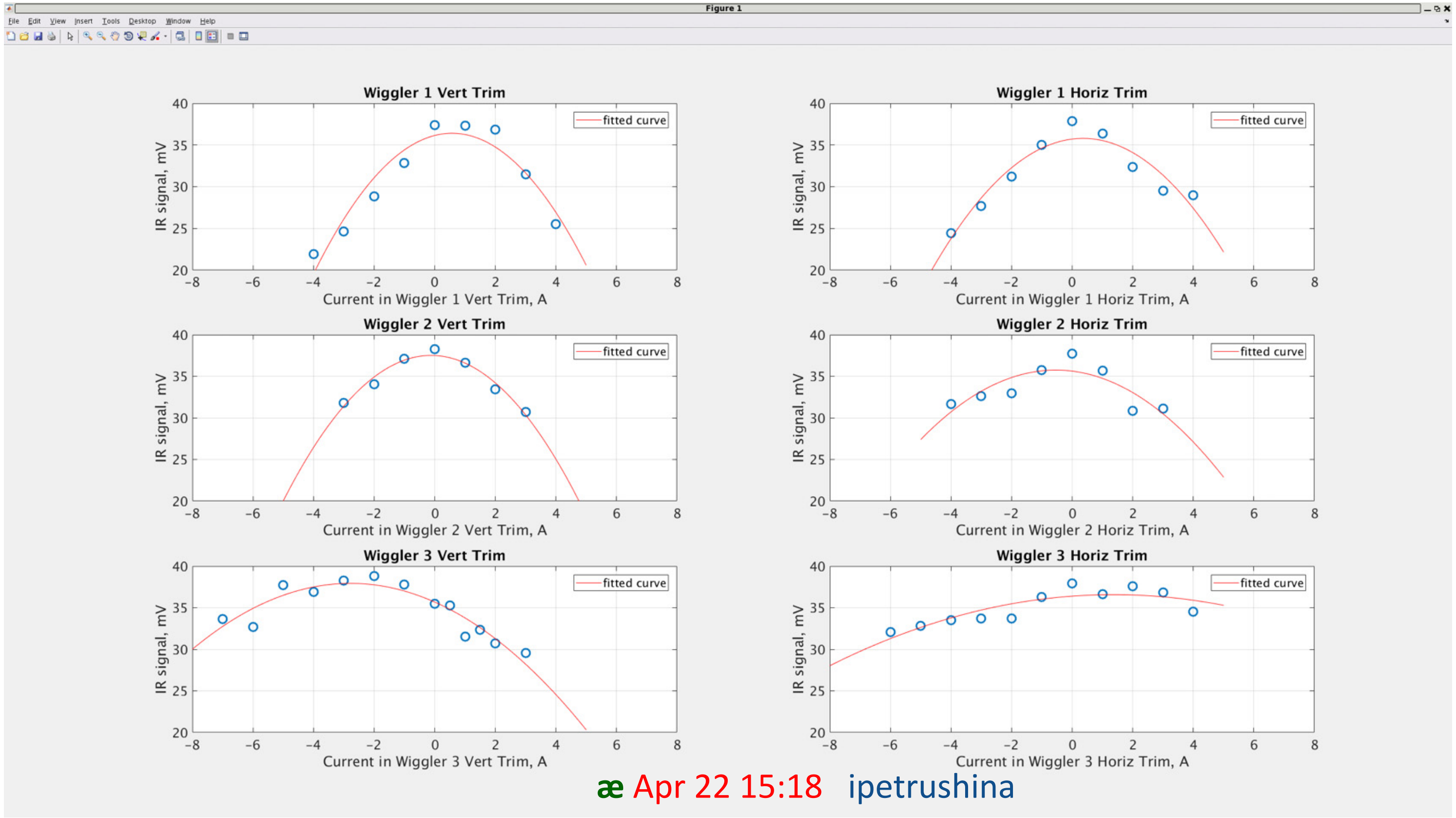
FEL power gain estimation

- Charge - 0.7 nC
- Peak current – 50 A
- Measured peak power – 20±5 kW
- Wiggler period - 4 cm
- a_w =0.5
- N_w=180
- FWHM FEL bandwidth 1.6%
- Spontaneous radiation peak power 1.9 W
- FEL Saturation ~ 30 MW

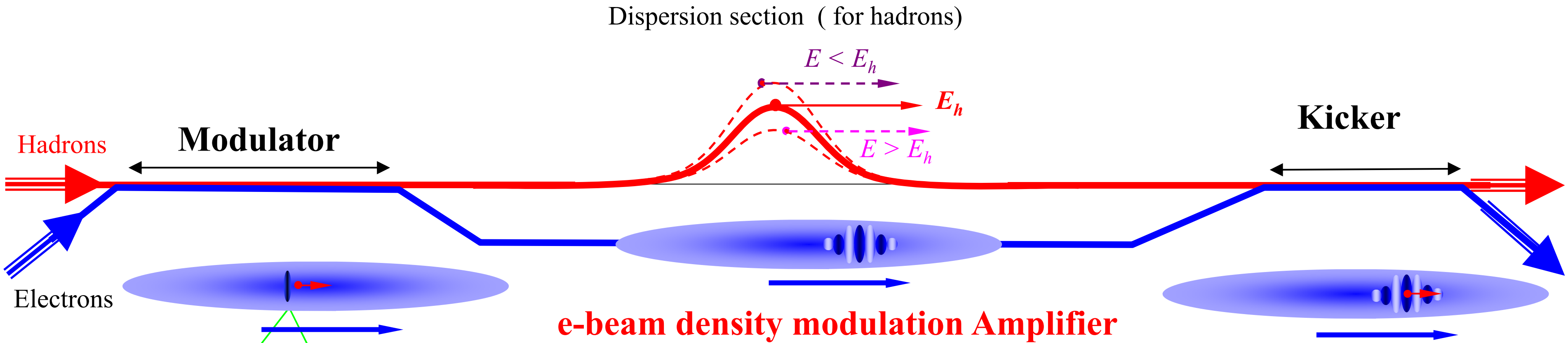
- FEL gain
- With natural shot noise – $(7\pm2)\cdot10^5$
- With 200-400-fold stronger noise in e-beam
- $(2\pm1)\cdot10^3$

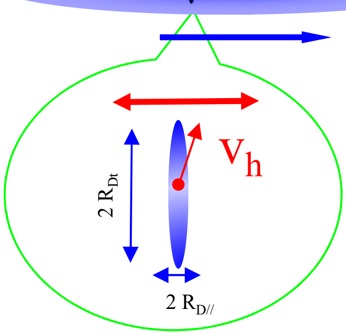
FEL signal dependence on wiggler trims settings

These dependencies are consistent with expectations: Wiggler 1 trims affect trajectory in two wigglers downstream. Wiggler 2 trims – only trajectory in the third wiggler, and wiggler 3 trims only trajectory in the kicker and the last dipole.

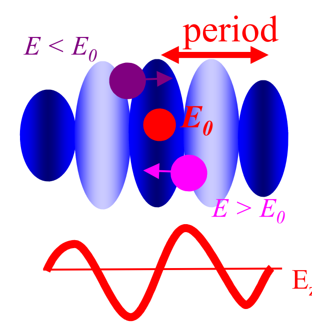


What is a CeC?
It is a stochastic cooling at optical frequencies





- All proposed CeC systems are based on the same basic scheme
- In the modulator, electron beam picks-up density modulation ("imprint") from individual ions
- This modulation is amplified in a broad-band high frequency amplifier (instability)
- In a kicker, ion's momentum is corrected by electric field induced in the electron beam
- Important feature of an amplifier– its frequency bandwidth
- CeC with two amplifiers: FEL and PCA does not require separation of the electron and hadron beams



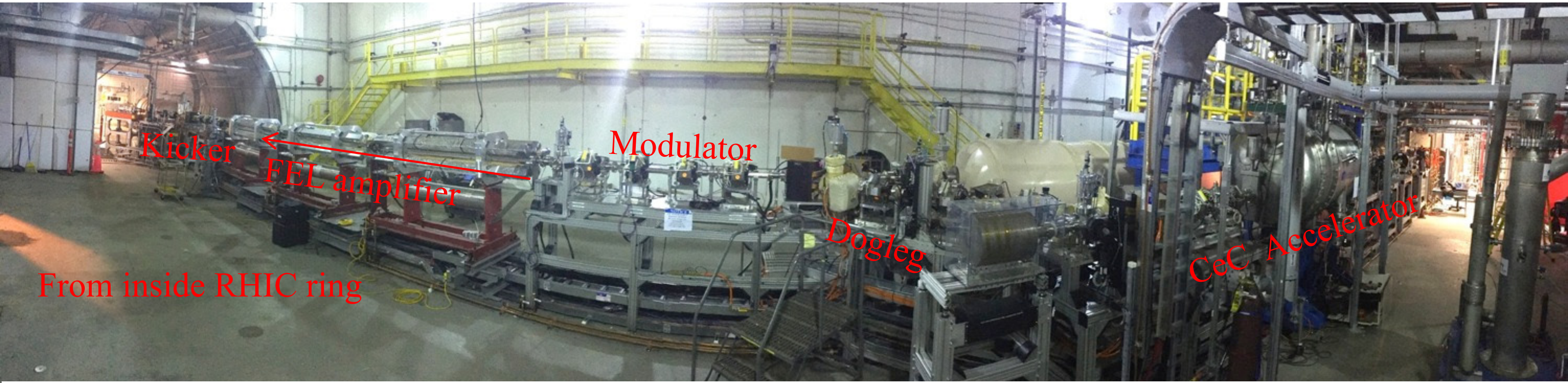
While idea of coherent electron cooling was invented by Ya. Derbenev in 1981 (!) the role of our original 2007 paper "*Free Electron Lasers and High-energy Electron Cooling*" (later shrinked into a PRL 102, 114801 2009) was to define the theoretical framework of estimating and calculating the cooling rate in such systems. We included two amplifiers in our original paper: a high-gain FEL and a single-stage micro-bunching amplifier. In 2013 D. Ratner developed the idea of multi-stage micro-bunching amplifier in his original PRL 111, 084802 (2013)

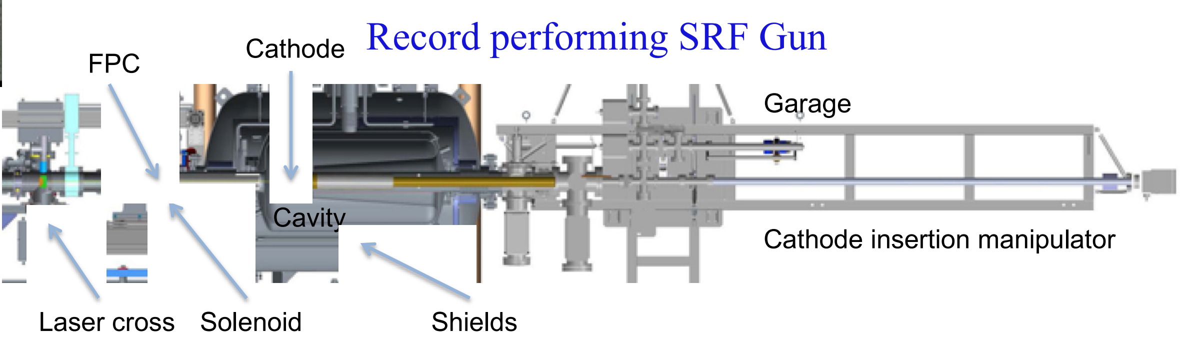

PRL **102**, 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

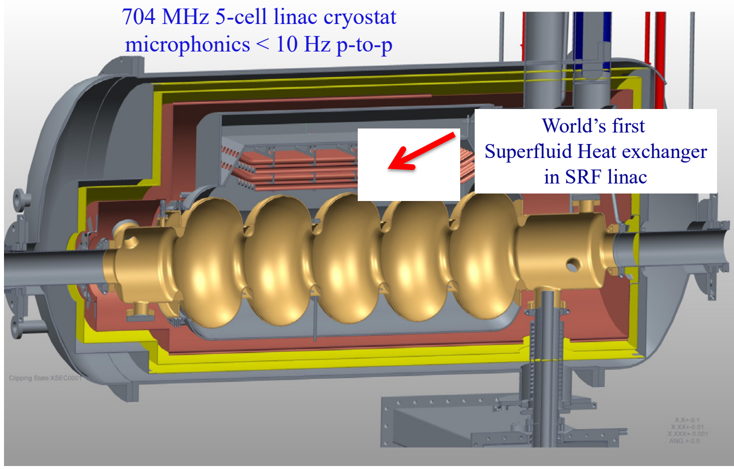
Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]

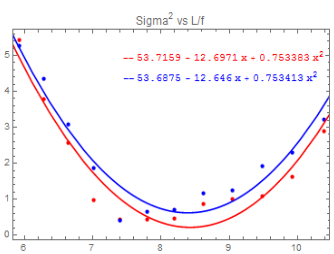
State of the art CeC system







- Quarter-wave SRF photo-electron gun
- 4 K operating temperature
- CsK_2Sb Cathode operating for months
- Up to 10.7 nC charge per bunch
- Record low normalized emittance of 0.32 mm mrad at 0.5 nC



- and many more innovations in accelerator physics and technology