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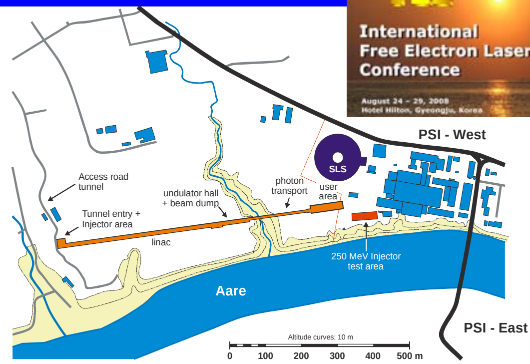
International Free Electron Laser Conference



Low Thermal Emittance Measurements at the Low Emittance Gun (LEG) Test Facility for the PSI-XFEL Project

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PSI XFEL-2008-18

Outline

- ☐ Short Introduction to PSI and the PSI-XFEL Project
- ☐ Low Emittance Gun (LEG) Test Facility for the PSI-XFEL Project
- ☐ Methods to measure a low Thermal Emittance which is closer to theoretically expected one
- ☐ Thermal Emittance Measurements with Two different Cathodes
- ☐ Summary & Acknowledgements

PSI & Test Facilities for PSI-XFEL Project

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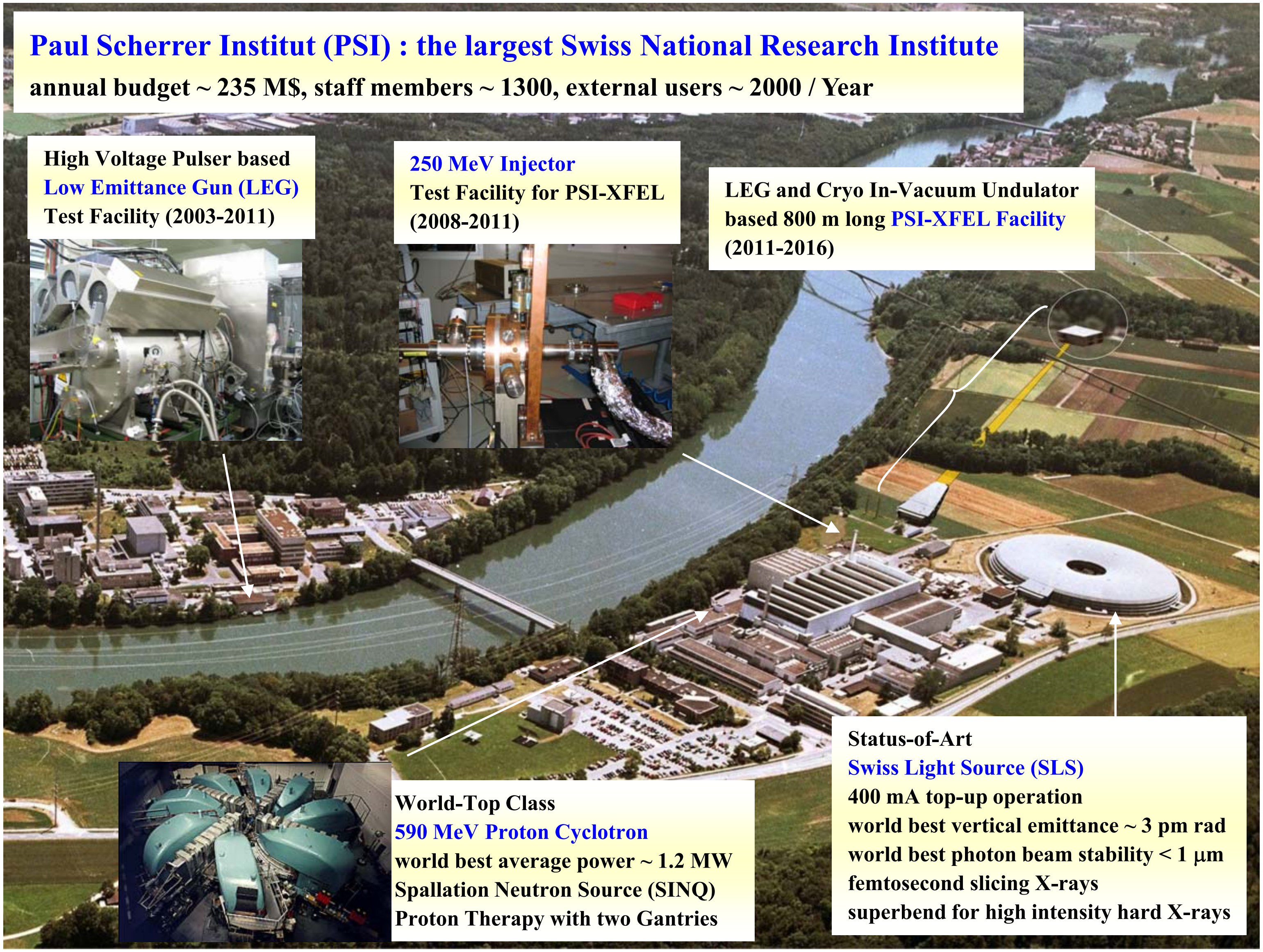

Paul Scherrer Institut (PSI) : the largest Swiss National Research Institute

annual budget ~ 235 M$, staff members ~ 1300, external users ~ 2000 / Year

High Voltage Pulser based
Low Emittance Gun (LEG)
Test Facility (2003-2011)

250 MeV Injector
Test Facility for PSI-XFEL
(2008-2011)

LEG and Cryo In-Vacuum Undulator
based 800 m long PSI-XFEL Facility
(2011-2016)

World-Top Class
590 MeV Proton Cyclotron
world best average power ~ 1.2 MW
Spallation Neutron Source (SINQ)
Proton Therapy with two Gantries

Status-of-Art
Swiss Light Source (SLS)
400 mA top-up operation
world best vertical emittance ~ 3 pm rad
world best photon beam stability < 1 μm
femtosecond slicing X-rays
superbend for high intensity hard X-rays

Operating LEG Test Facility for PSI-XFEL

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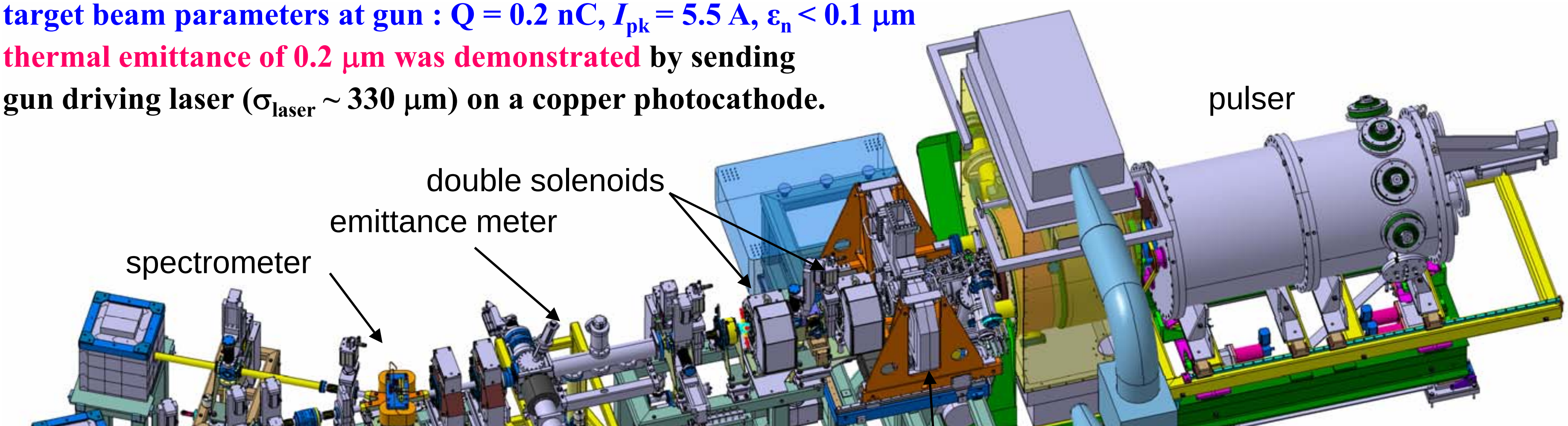
Low Emittance Gun (LEG) Test Facility - 500 keV Phase-I (2003 - 2008) and 4 MeV Phase-II (2008-2011)

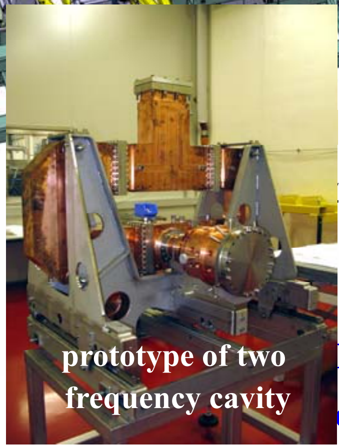
LEG = 1 MV pulser supplying max. gradient of 250 MV/m at 4 mm gap + Field Emitter Array (FEA) cathode

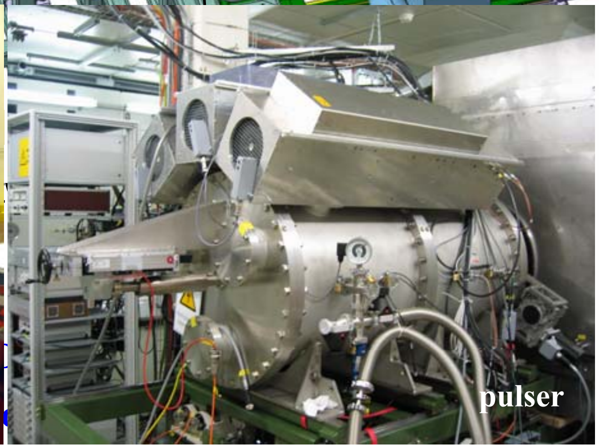
Beams are accelerated to 4 MeV and the longitudinal phase space is compensated by a two frequency RF cavity

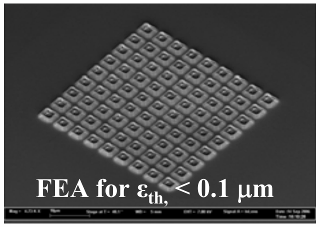
target beam parameters at gun : Q = 0.2 nC, I_{pk} = 5.5 A, ε_n < 0.1 μm

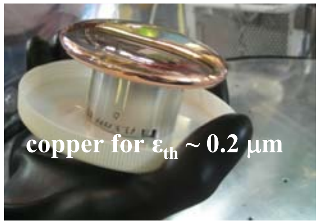
thermal emittance of 0.2 μm was demonstrated by sending gun driving laser (σ_{laser} ~ 330 μm) on a copper photocathode.




prototype of two frequency cavity


pulser


FEA for $\varepsilon_{th,}$ < 0.1 μm


copper for ε_{th} ~ 0.2 μm

Funded 250 MeV Injector Test Facility

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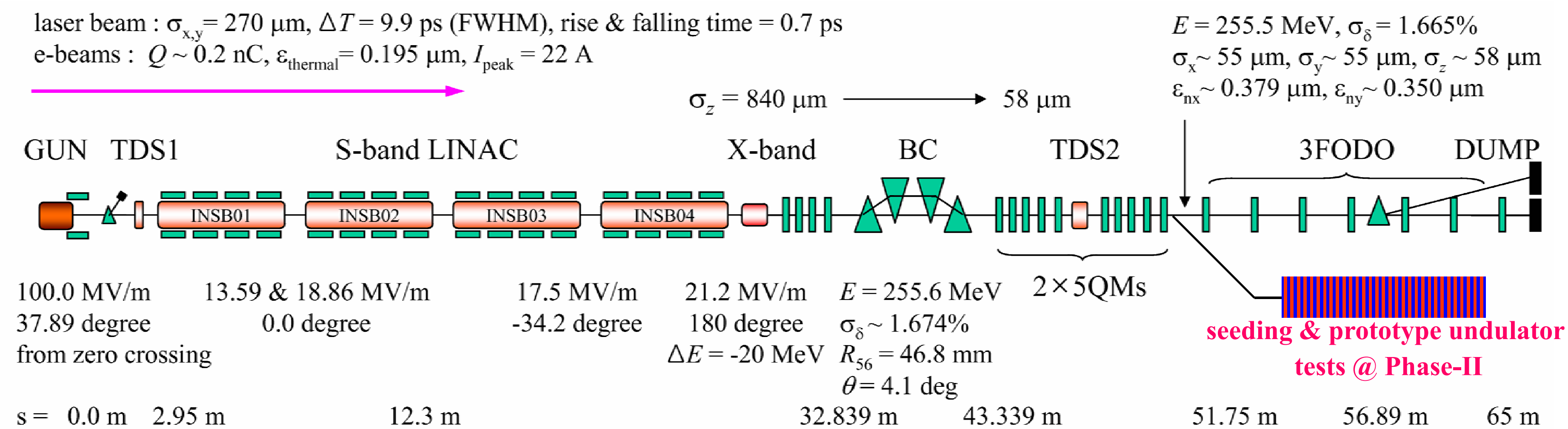
Layout of CTF3 RF Gun based 250 MeV Injector Test Facility (2008-2011)



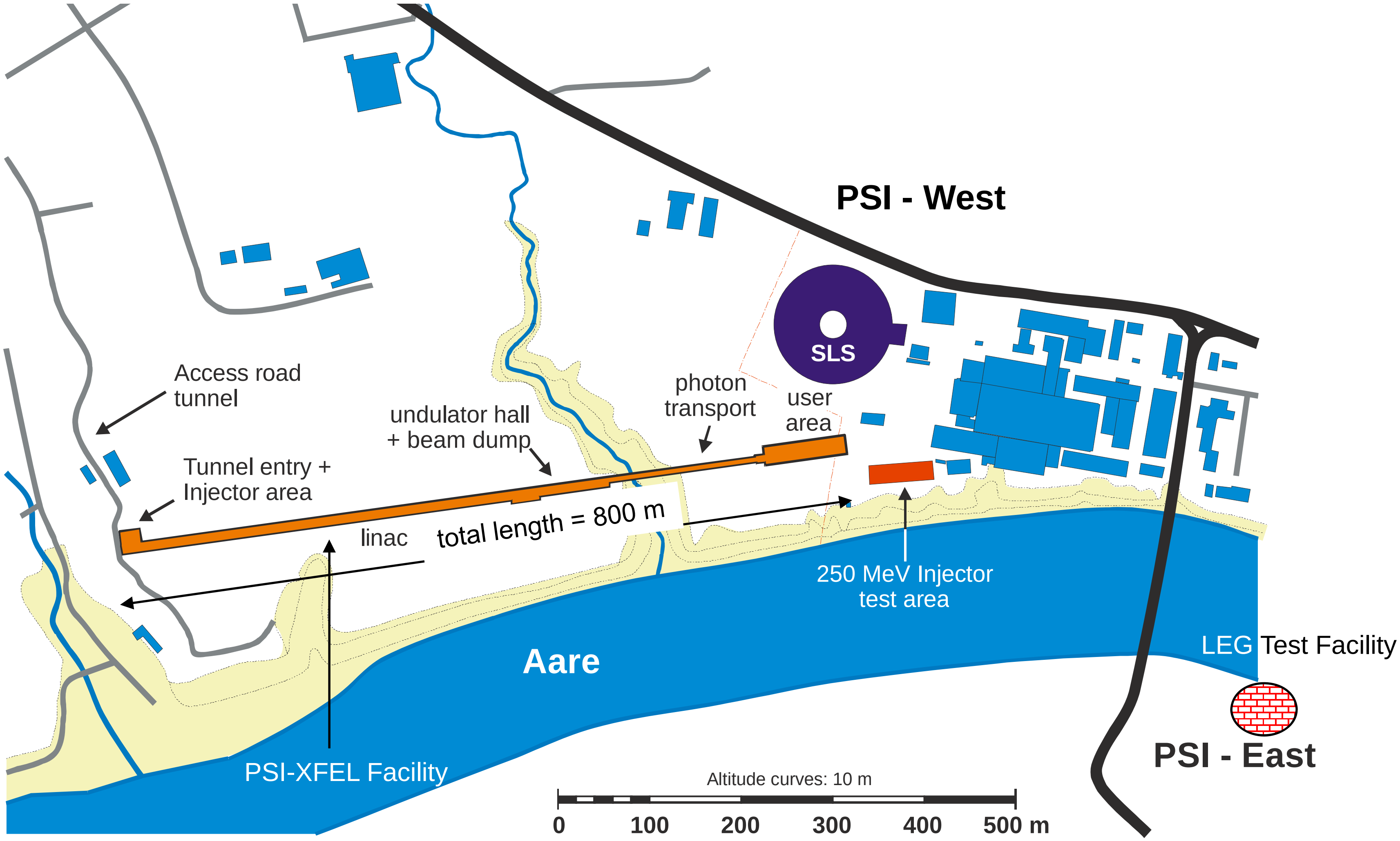
250 MeV Injector will be built to develop various advanced accelerator, undulator, and FEL technologies for the coming 6 GeV PSI-XFEL project:

- studying slice and projected emittance transportation along injector
- studying the invariant envelop matching and emittance damping in bootster linac
- studying bunch compression and Coherent Synchrotron Radiation (CSR) effects in a chicane
- developing slice beam parameter diagnostics technologies with LOLA cavities (TDS1 & TDS2) & 3 FODO cells
- developing ultra-stable RF low level system, timing system, and synchronization system
- developing beam based alignment technology and orbit and bunch length feedback system
- at the second phase, testing of prototype cryo in-vacuum undulator and HHG based external seeded FEL

At the beginning phase, a CTF3 RF gun based RF photoinjector will be tested. Then the pulser based advanced LEG will be tested in the 250 MeV injector.

Preparing 6 GeV PSI-XFEL Facility

2003-2011 : Pulser based Advanced Low Emittance Gun (LEG) Test Facility - Operating
2008-2011 : 250 MeV Injector Test Facility - Commissioning will be started at the end of 2009
2011-2016 : LEG + Short Linac + Cryo In-Vacuum Undulator based 6 GeV PSI-XFEL Facility



Layout & Parameters of PSI-XFEL Facility

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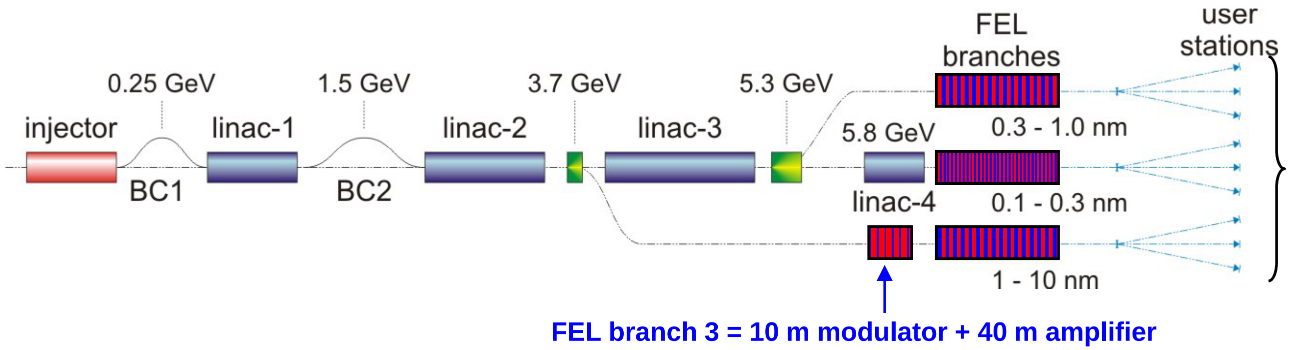
Ultra-low Emittance + Normal Conducting Short Linac + Cryo In-Vacuum Undulator



- photon pulse duration < 30 fs (rms)
- photons per pulse = 10^{11} - 10^{12}
- bandwidth of HGHG mode ~ 0.05% (FWHM)
- undulator for branch 1 = Cryo In-Vacuum
- undulator length < 60 m

LEG based Parameters for the SASE mode

FEL Branch 3 (1 - 10 nm) will be operated with the SASE mode as well as the HHG based Seeded HGHG mode

	branch 1	branch 2	branch 3	
Beam energy	3.3 – 5.8	3.3 – 5.3	3.7	GeV
Beam current	1.5	1.5	1.5	kA
Normalized slice emittance	0.2	0.2	0.2	μm
RMS slice energy spread	500	500	500	keV
Repetition rate	10 – 100	10 – 100	10 – 100	Hz
Undulator period	15	36	52	mm
Undulator aw	1.2	1-2.4	1-2.3	
Target wavelength range	0.1 – 0.3	0.3 – 1	1 – 10	nm
Photon energy range	12 – 4	4.4 – 0.39	1.2 – 0.13	keV
Peak Brilliance	10^{32} - 10^{33}	10^{32} - 10^{33}	10^{31} - 10^{32}	ph/s/mm²/mrad²/0.1% bw
Polarization	linear	linear/circular	linear/circular	-

Goal of the LEG Test Facility Phase-I

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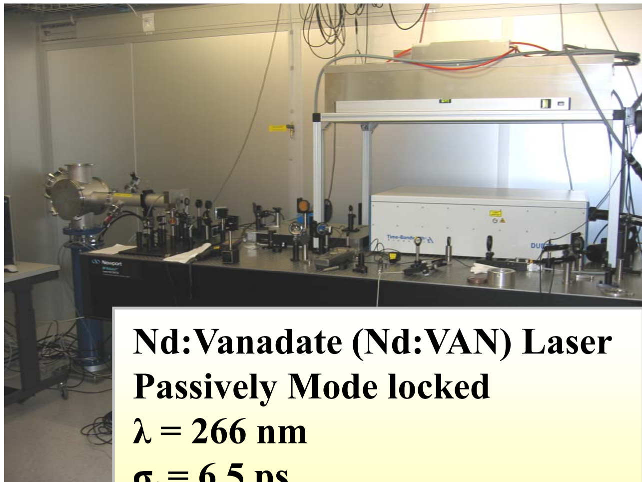
☐ Phase-I with Maximum 500 keV Beams (December 2007 - August 2008)

- Development of 500 kV Pulser Technology
- Demonstration of 125 MV/m Gradient at 4 mm gap or finding the maximum stable Gradient (up to now, max ~ 95 MV/m with SS, ~ 51 MV/m with Cu)
- Finding the Best Cathode Material Supplying Ultra-low Thermal Emittance, High QE, and High Gradient
- Getting Experiences on Laser Driven Photo-emission
- Measurement of Electron Beam Properties ($\varepsilon_{nx,ny}$, I_{peak}, Q) at 500 keV

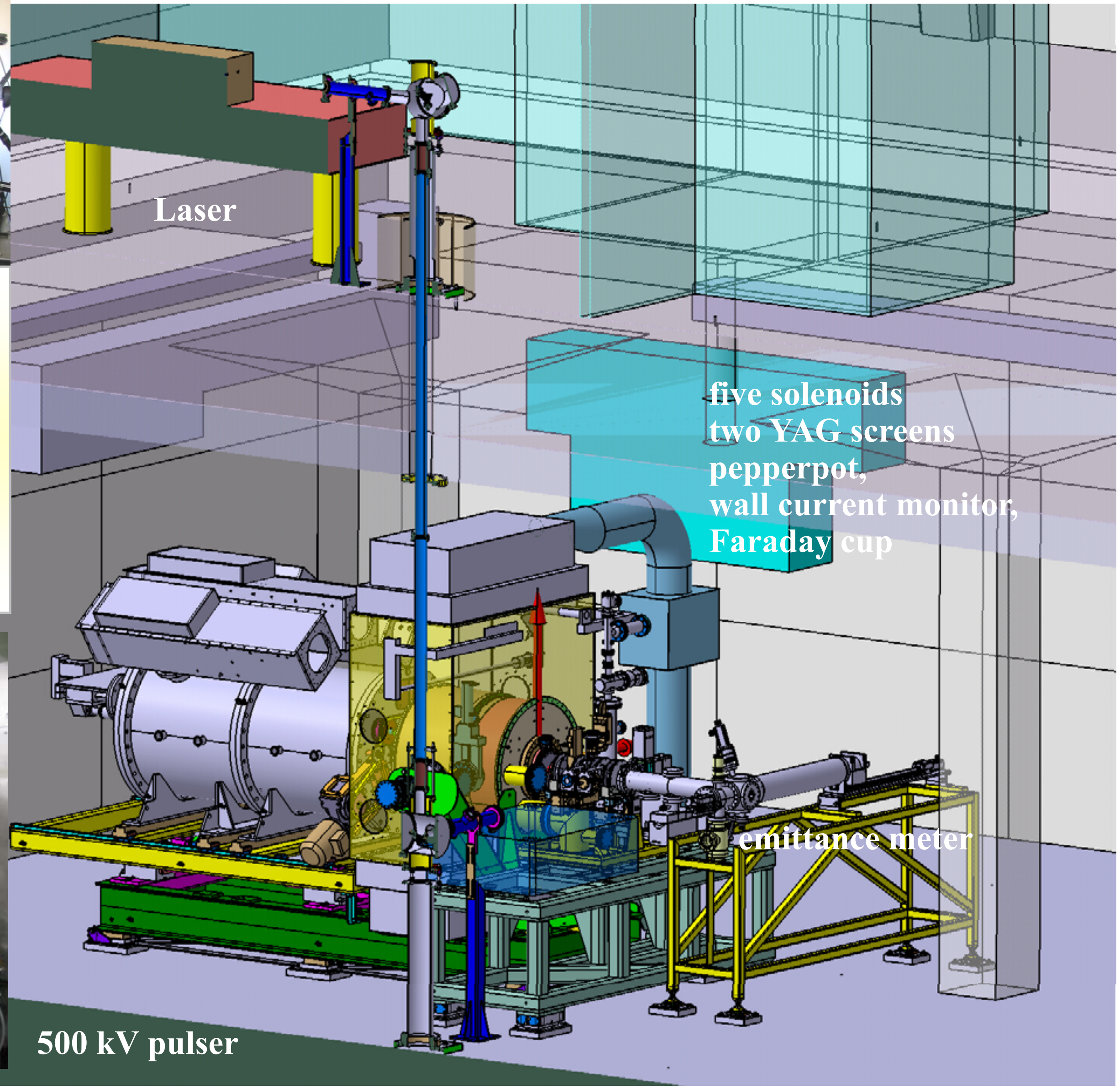
Target PSI-XFEL Injector Parameters : Q = 0.2 nC, I_{pk}= 5.5 A, ε_n< 0.1 μm

see our TUPPH001 poster

Layout of the LEG Test Facility Phase-I

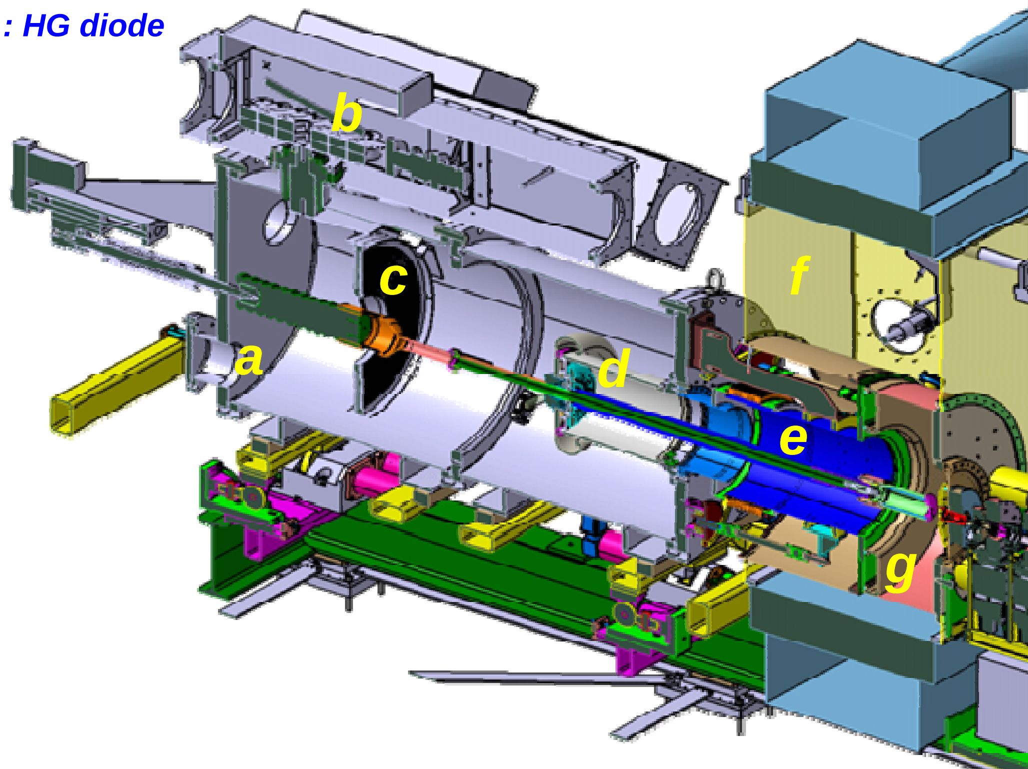


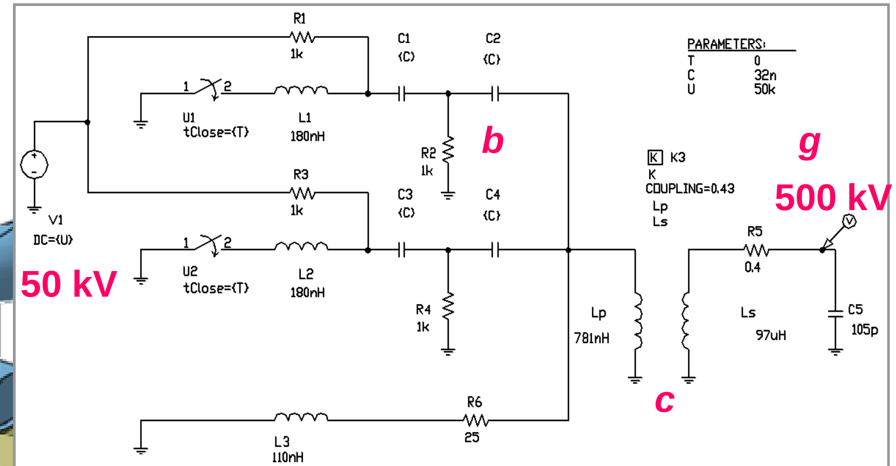
Nd:Vanadate (Nd:VAN) Laser
Passively Mode locked
$\lambda = 266$ nm
$\sigma_t = 6.5$ ps,
Gaussian profile
repetition rate = 10 Hz
energy at laser exit ~ 15 μJ
energy at cathode ~ 4 μJ



500 kV Pulser for the LEG Phase-I

a : SF_6 pressure vessel
b : Storage capacitors and primary switch
c : HV transformer
d : Ceramic feedthrough
e : Vacuum chamber
f : Clean cubicle
g : HG diode



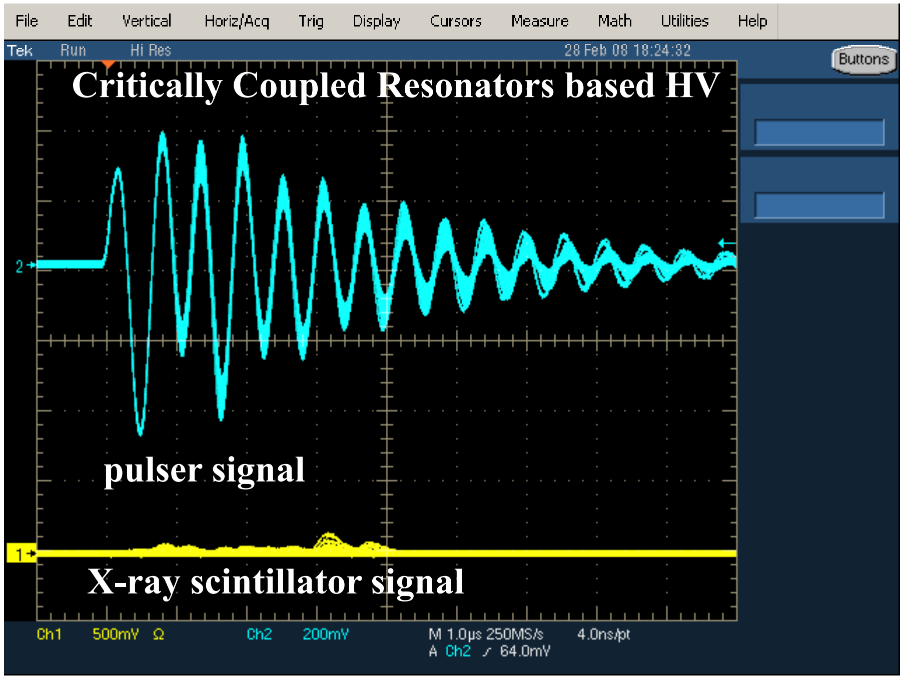


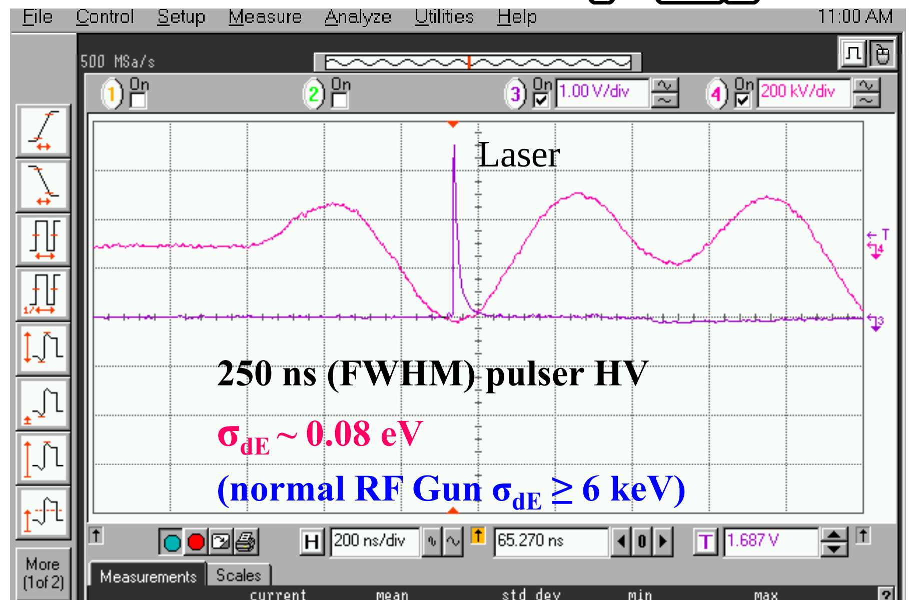
Critically Coupled Resonators based HV

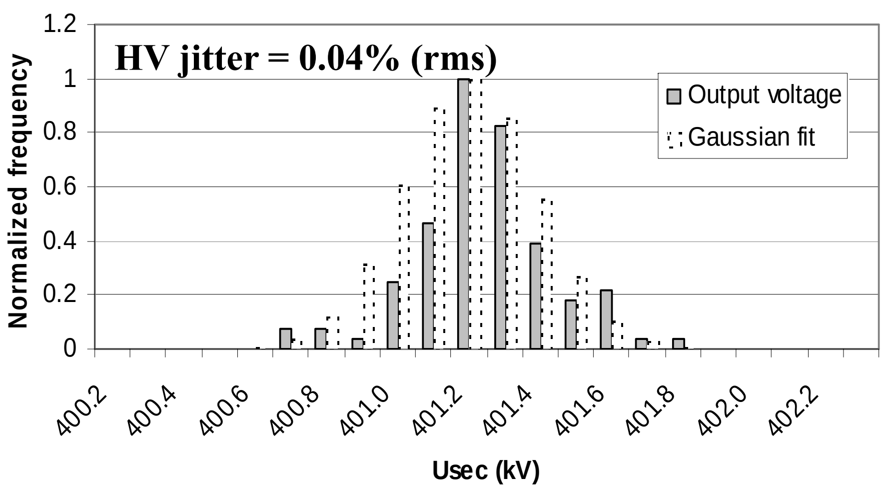
M. Paraliev *et al*, IEEE Pulsed

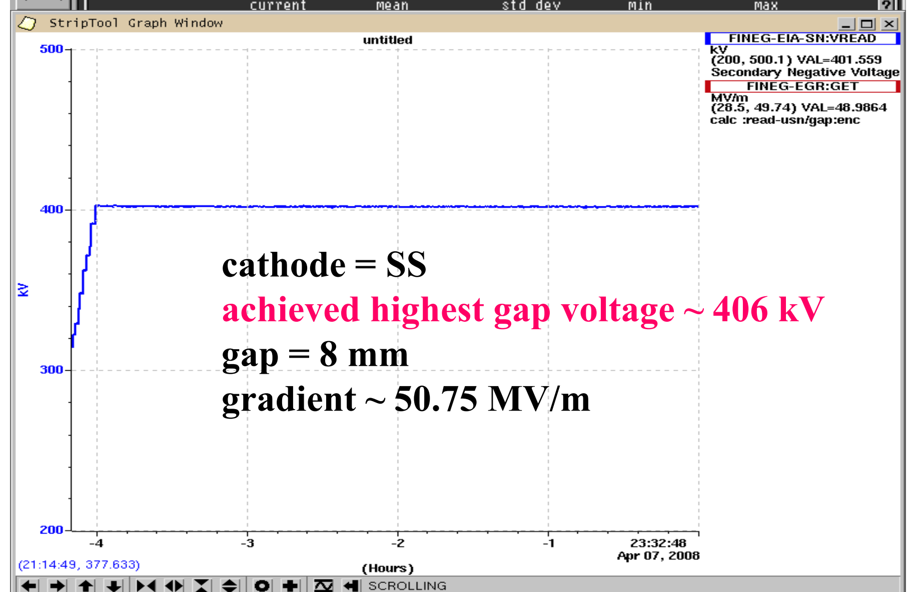
- **max pulser HV = 500 kV / 1 MV @ Phase-II**
- **variable gap = 0.0 mm ~ 30 mm**
- **nominal gap = 4 mm**
- **target gradient at Phase-I = 125 MV/m**
- **target gradient at Phase-II = 250 MV/m**
- **achieved max gradient ~ 140 MV/m without laser**
- **stably operational max gradient ~ 95 MV/m**
- **pulser max repetition = 50 Hz / 100 Hz @ Phase-II**
- **pulser length = 250 ns (FWHM)**
- **achieved pulser timing jitter = 90 fs (rms)**
- **E-spread along bunch (~ 40 ps) ΔE_{p2p} ~ 0.49 eV**
- **pulser HV jitter = 0.04% (rms) / 0.01% @ Phase-II**

500 kV Pulser for the LEG Phase-I

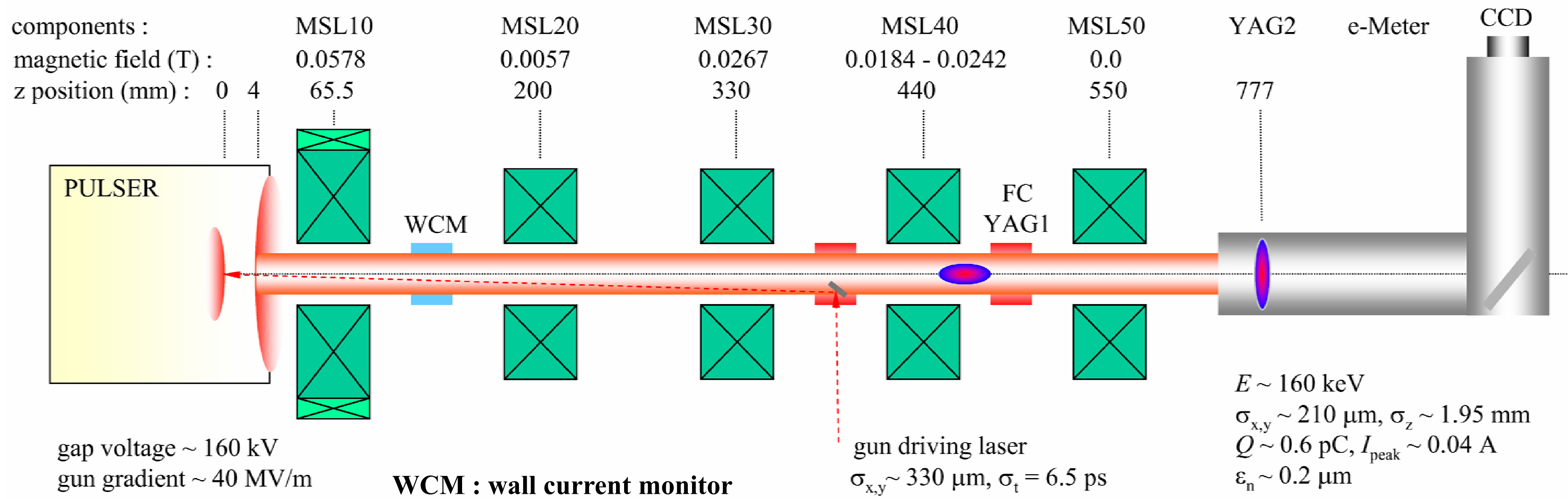








Beamline Layout of the LEG Phase-I

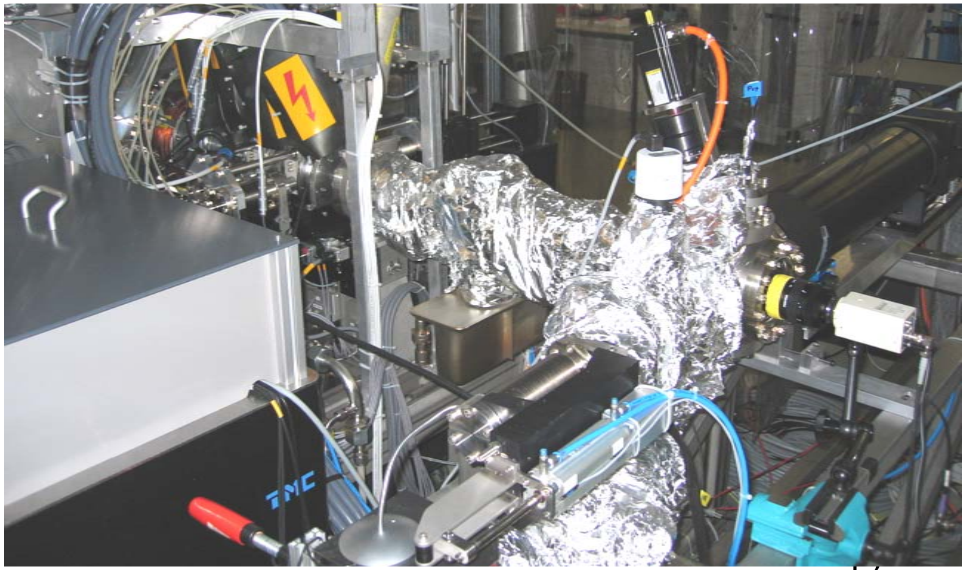


WCM : wall current monitor

FC : Faraday cup

diamond turned Cu cathode
average roughness: ~ 5 nm
diameter = 95 mm

hand polished
SS cathode (316L)
diameter = 45-55 mm



Ultra-High Resolution Faraday Cup

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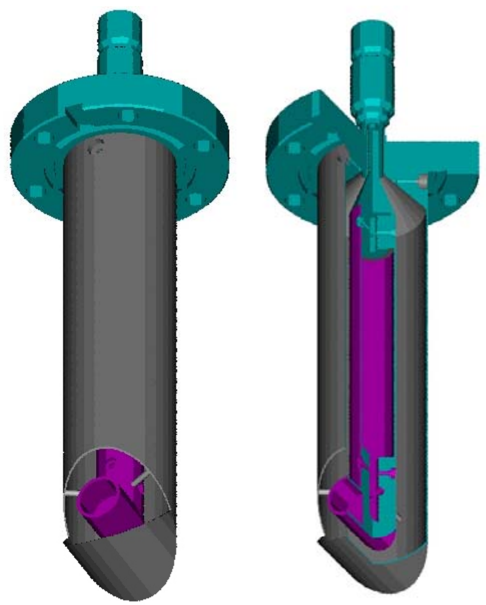
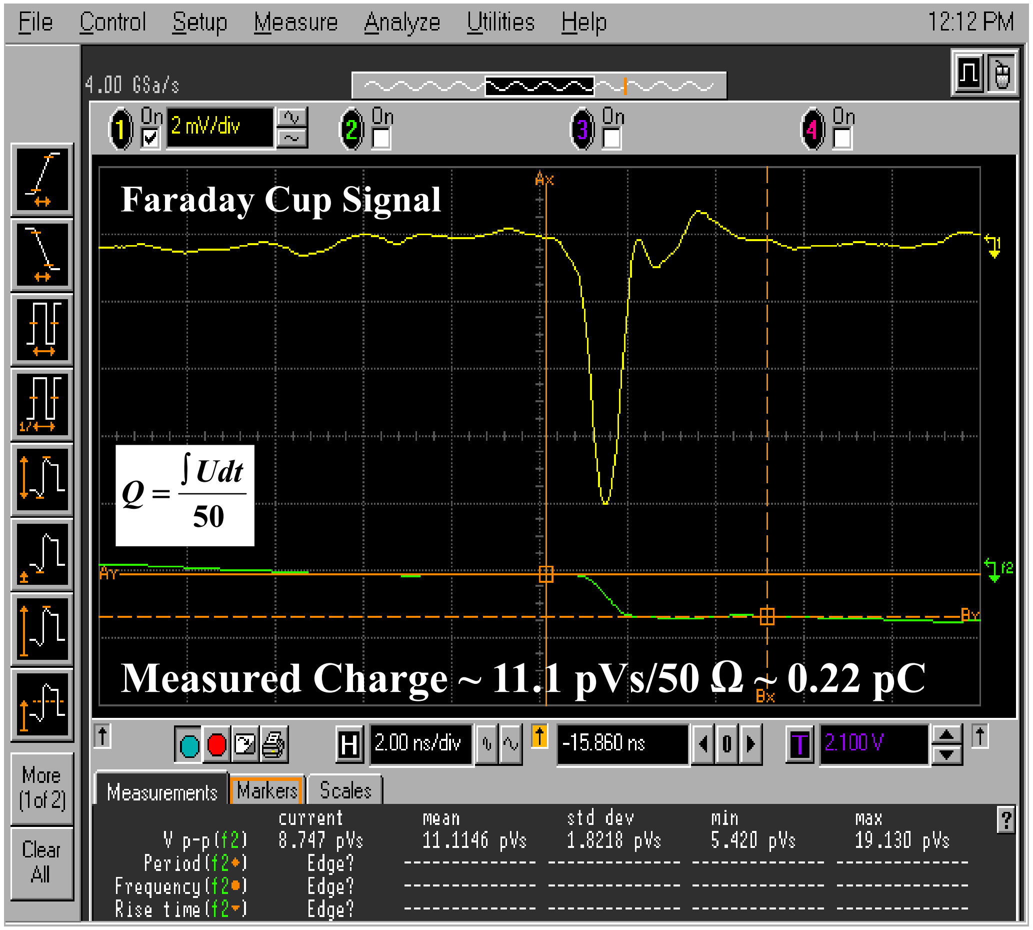
3D Image : Courtesy of V. Schlott





Coaxial Faraday Cup (CFC)

Originally developed for Swiss Light Source

Bandwidth up to 4 GHz

Impedance = 50 Ω

Measurable Bunch Charge ~ 0.2 pC

Ultra-High Resolution Imaging System

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Point Grey, Flea Miniature IEEE-1394 Camera

CCD Sensor : Sony ICX204AQ/AL 1/3", BW
Size : 30×31×29 mm
ADC : 12-bit
Resolution : 1024×768
Frame Rates : 1024×768 @ 30 FPS (Company Specification)
Pixel Size : 4.65 μm × 4.65 μm
Gain : -6.8 dB to 29.4 dB
Signal to Noise : higher than 59 dB
Shutter : 0.03 ms to 66.6 ms @ 15 FPS
Partial Image Modes : Pixel binning and Region Of Interest
Trigger Modes : 0, 1, 3

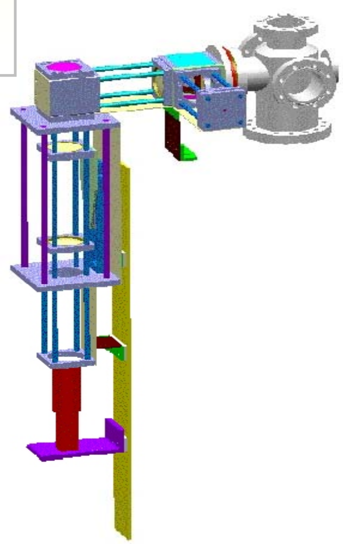
YAG1 Screen

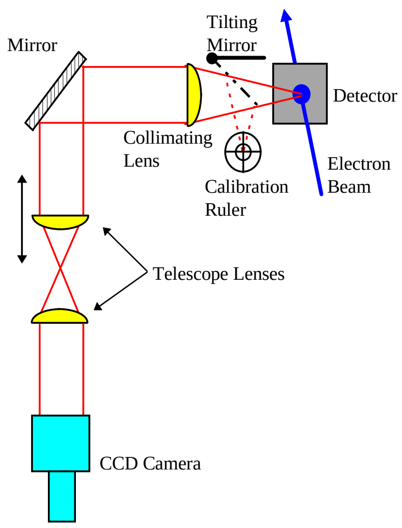
Al-coated YAG:Ce screen

Diameter = 16 mm, Optics Calibration = 23.8 μm/pixel

Point Spread Function of Optical System ~ 50 μm

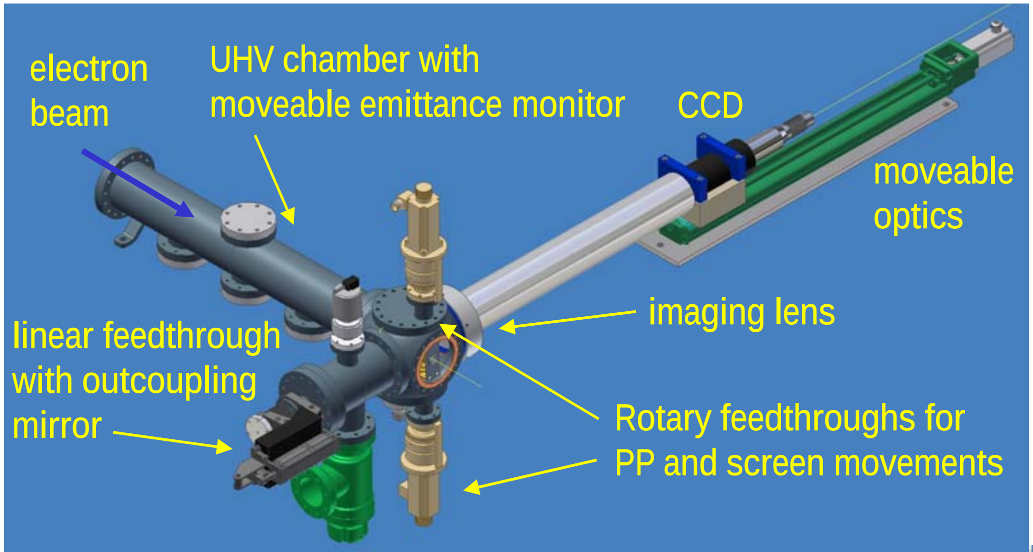
Resolution is not enough to measure sub-μm emittance !

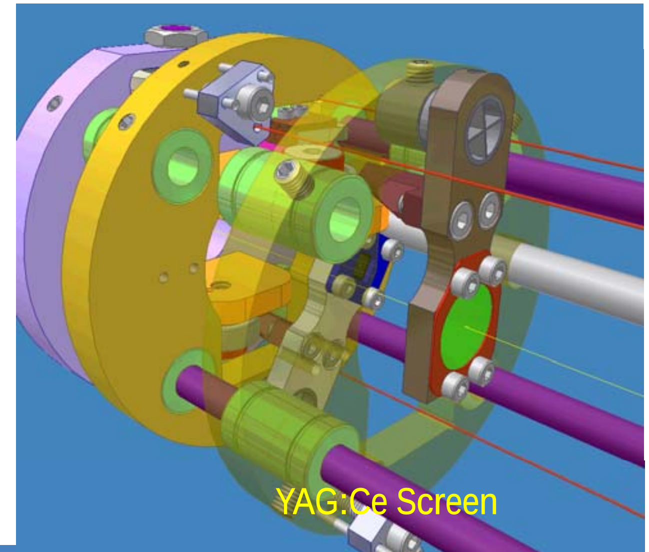


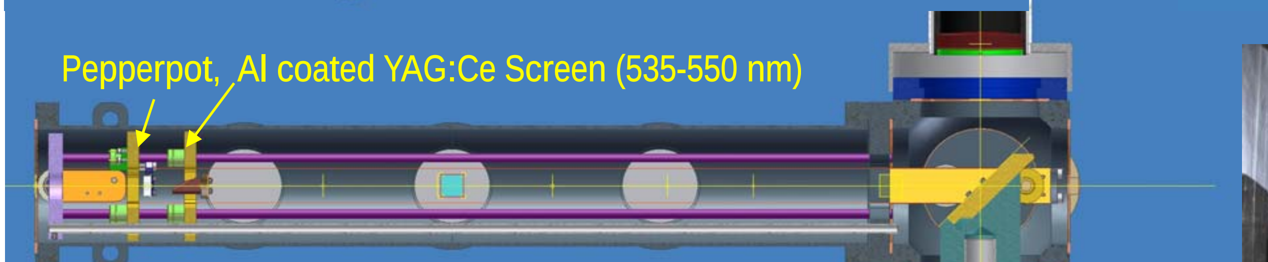


3D Image : Courtesy of V. Schlott

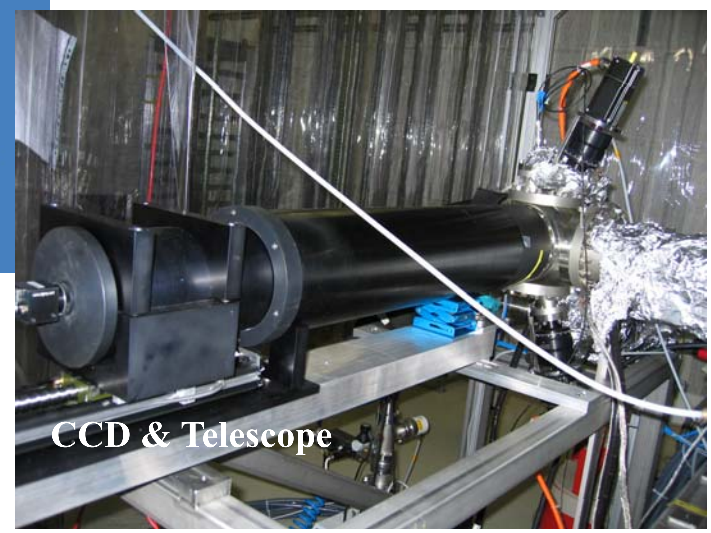
Ultra-High Resolution Imaging System







3D Image : Courtesy of V. Schlott



YAG2 Screen & Telescope

Thickness = 50 μm, Diameter = 5 mm

Optics Calibration = 4.367 μm/pixel

Point Spread Function of Optical System ~ 11. 8 μm

1:1 Image System with Telescope, Designed to measure sub-μm emittance.

Q.E. Measurements with a Copper Cathode

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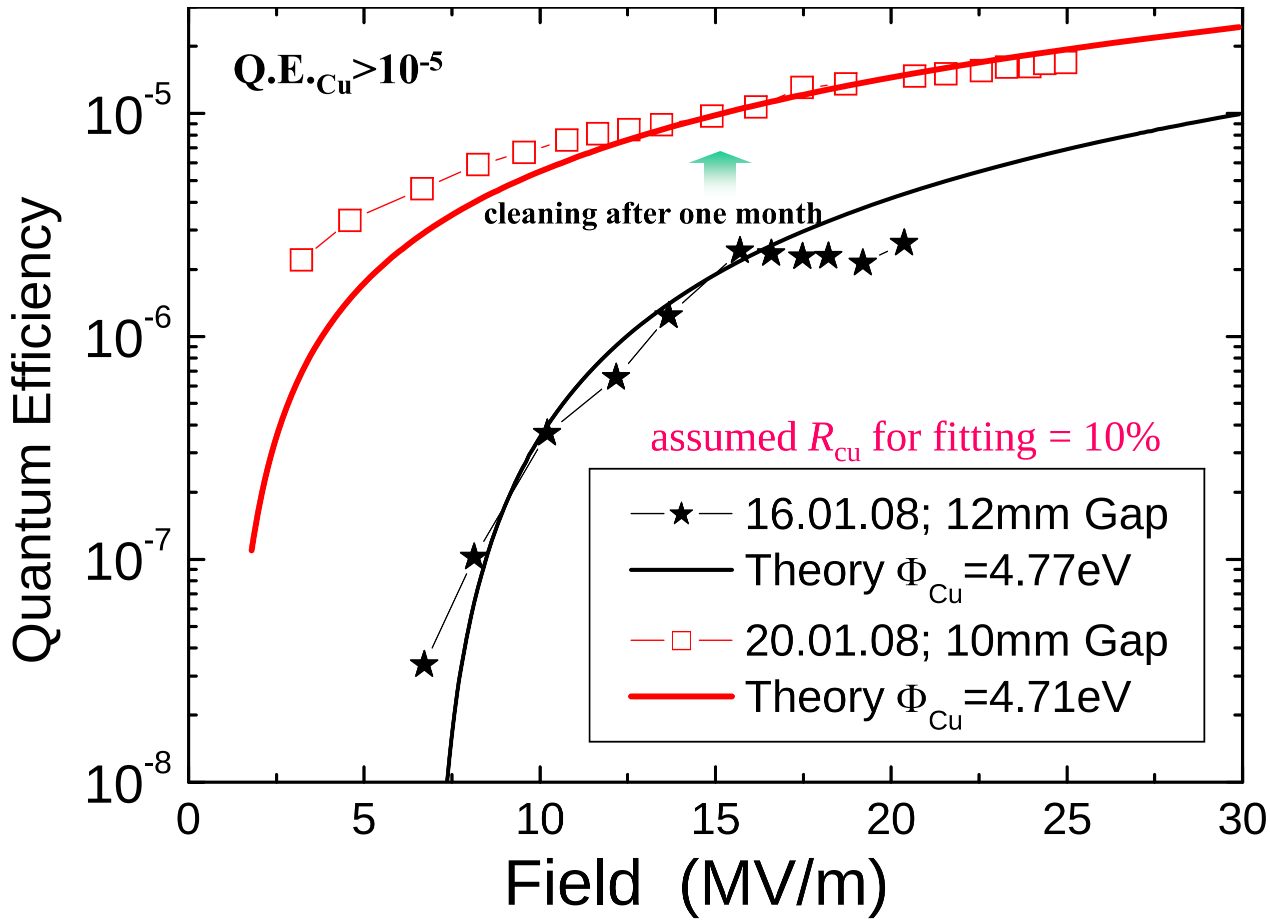
Fitted Plot : Courtesy of R. Ganter



Laser : 266 nm, 6 μJ, 10 Hz

Note that measured reflection R_{Cu}~ 25 % @ 266 nm

Max. Stable Gradient about 40 MV/m at 4 mm Gap

$$QE(\omega)=\frac{1-R(\omega)}{1+\frac{\lambda_{opt}}{2\lambda_{e-e}(E_m)}\frac{\hbar\omega\sqrt{\Phi_{eff}}}{E_m^{3/2}}\left(1+\sqrt{\frac{\Phi_{eff}}{\hbar\omega}}\right)}\frac{(E_F+\hbar\omega)}{2\hbar\omega}\times\left[1+\frac{E_F+\Phi_{eff}}{E_F+\hbar\omega}-2\sqrt{\frac{E_F+\Phi_{eff}}{E_F+\hbar\omega}}\right]$$

Schottky Effects & Three Steps Model
D.H. Dowell *et al*, PRSTAB 9, 063502 (2006)

Meaningful Thermal Emittance

- Note that thermal emittance is the most biggest contribution in slice emittance
- We can reduce slice emittance by reducing thermal emittance on the cathode !

$$\varepsilon_{nx,ny} = \sqrt{\varepsilon_{th}^2 + \varepsilon_{lsc}^2 + \varepsilon_{nsc}^2 + \varepsilon_{rf}^2 + \varepsilon_{optics}^2} \qquad \varepsilon_{slice} \geq \varepsilon_{th}$$

$$\varepsilon_{lsc} \propto \frac{Q}{(2\sigma_r + \sigma_z)E}$$

$$\varepsilon_{nsc} \propto \frac{FQ}{\sigma_r^2 \sigma_z}$$

$$\varepsilon_{rf} \propto f_{rf}^2 \sigma_r^2 \sigma_z^2 E$$

$$\varepsilon_{optics} \propto \frac{\sigma_\delta \sigma_r^2}{f_{sol}}$$

$$\varepsilon_{th} \approx \sigma_{x,y} \sqrt{\frac{h\nu - \phi_0 + \phi_{\text{schottky}}}{3m_e c^2}}, \quad \sigma_x = \sigma_y \quad \text{for a round beam}$$

$$\text{Here } \phi_{\text{schottky}} \sim 3.7947 \times 10^{-5} \sqrt{E(V/m)} \text{ eV}$$

D. H. Dowell *et al.*, PRST-AB 9, 063502 (2006)

K. L. Jensen *et al.*, Journal of Applied Physics 102, 074902 (2007)

C. Travier *et al.*, NIMA 340, 26 (1994)

- Expected Thermal Emittance from Q.E. Measurement

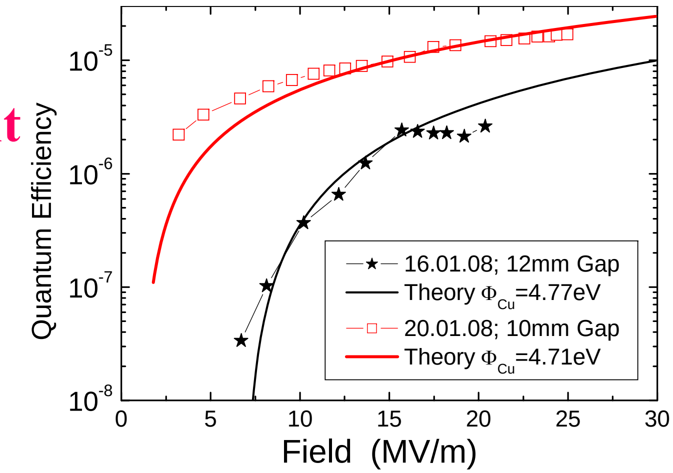
for a diamond turned copper, $\varphi_0 = 4.71$ eV

at 40 MV/m, $\varphi_{\text{schottky}} \sim 0.240$ eV, $h\nu = 4.66$ eV

expected $\varepsilon_{th,40} \sim 0.12$ µm for $\sigma_{x,y} \sim 330$ µm

at 100 MV/m, $\varphi_{\text{schottky}} \sim 0.380$ eV, $h\nu = 4.66$ eV

expected $\varepsilon_{th,100} \sim 0.15$ µm for $\sigma_{x,y} \sim 330$ µm



Recently Reported Thermal Emittance

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- SDL group (W. Graves *et al*., PAC2001)

  ε_{th} ~ 0.51 μm with a copper cathode and S-band RF gun, Q ~ 2 pC, σ_z ~ 1.0 ps, I_{peak} ~ 3 A

  σ_{laser} ~ 400 μm, $E_{cathode}$ ~ 95 MV/m

  RF effects, space charge effects, chromatic effects

- SLAC GTF Group (J. F. Schmerge *et al*., FEL2004)

  ε_{th} ~ 0.6 μm with a copper cathode and S-band RF gun, Q ~ 15 pC, σ_z~ 0.86 ps, I_{peak} ~ 7 A

  σ_{laser} ~ 500 μm, $E_{cathode}$ ~ 110 MV/m

  Mainly space charge effects and also RF effects, chromatic effects

- PITZ Group (S. Lederer *et al*., FEL2007)

  ε_{th} ~ 0.55 μm with Cs_2Te cathode and L-band RF gun, Q ~ 6 pC, σ_z~ 3 ps, I_{peak} ~ 0.8 A

  σ_{laser} ~ 350 μm, $E_{cathode}$ ~ 43.2 MV/m

  Mainly space charge effects chromatic effects and/or weak RF effects,

  limitation in slit method with a low Q

- **But many friends predicted a lower thermal emittance :**

  copper cathode, ε_{th} < 0.4 μm @ 100 MV, σ_{laser} ~ 500 μm

D. H. Dowell, High QE Workshop, 2006

To Measure Realistic Thermal Emittance

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- We did following things to measure more realistic thermal emittances:
  - ultra-low charge (0.2 pC ~ 0.6 pC) was used to avoid space charge effects
  - pulsed DC voltage (ΔE_{p2p} < 0.49 eV along bunch) and no RF electromagnetic fields
  - short laser pulse (6.5 ps rms) to reduce variation of sinusoidal pulser voltage
  - ultra-high resolution diagnostic systems (Faraday cup, imaging system)
  - subtraction of dark current induced background noise
  - solenoid scan instead of the slit or pepperpot method due to a low charge & image noise

$$\varepsilon_{nx,ny} = \sqrt{\varepsilon_{th}^2 + \cancel{\varepsilon_{lsc}^2} + \cancel{\varepsilon_{nsc}^2} + \cancel{\varepsilon_{rf}^2} + \cancel{\varepsilon_{optics}^2}}$$

Measured Thermal Emittance @ PSI LEG

ε_{th} ~ 0.2 μm with a copper cathode and pulsed DC gun, Q ~ 0.2-0.6 pC, σ_z ~ 6.5 ps

I_{peak} ~ 0.01- 0.03 A, σ_{laser} ~ 330 μm, $E_{cathode}$ ~ 40 MV/m

$$\phi_{0,\mathrm{measured}} = 4.34\ \mathrm{eV},\ \phi_{\mathrm{schottky}} = 0.24\ \mathrm{eV},\ h\nu = 4.66\ \mathrm{eV}$$

If our measured result is scaled to SDL case, predicted thermal emittance @ 95 MV/m :

ε_{th} ~ 0.27 μm with a copper cathode and pulsed DC gun, Q ~ 0.2-0.6 pC, σ_z ~ 6.5 ps

I_{peak} ~ 0.01- 0.03 A, σ_{laser} ~ 400 μm, $\phi_{\mathrm{schottky}} = 0.37\ \mathrm{eV},\ h\nu = 4.66\ \mathrm{eV}$

Comparison of Measured ε_{th}

	LEG	SDL	GTF	PITZ
cathode material	Cu	Cu	Cu	Cs_2Te
measurement method	solenoid	solenoid	quadrupole	slit
ratio of SC contribution to ε_n	1.0	3.3	22	15
ratio of RF contribution to ε_n	~ none	1.5	1.8	1.0
ratio of chromatic contribution	1.0	> 200	> 200	> 200
gradient on the cathode (MV/m)	40	95	110	43.2
laser spotsize (μm)	330	400	500	350
measured ε_{th} (μm)	~ 0.2	~ 0.51	~ 0.60	~ 0.55
LEG's ε_{th} is scaled to SDL*	~ 0.27	~ 0.51	×	×
LEG's ε_{th} is scaled to GTF*	~ 0.34	×	~ 0.60	×

* Here LEG's thermal emittance was scaled by considering other labs' laser spot and gradient.

$$\varepsilon_{lsc} \propto \frac{Q}{(2\sigma_r + \sigma_z)E}$$

$$\varepsilon_{nsc} \propto \frac{FQ}{\sigma_r^2 \sigma_z}$$

$$\varepsilon_{rf} \propto f_{rf}^2 \sigma_r^2 \sigma_z^2 E$$

$$\varepsilon_{optics} \propto \frac{\sigma_\delta \sigma_r^2}{f_{sol}}$$

$\sigma_{dE,\ LEG}$ ~ 0.08 eV

$\sigma_{dE,RF\ GUN} \geq 6$ keV

- It seems that we can not ignore space charge, RF fields, chromatic effects, and image noise in slit or pepperpot method in other labs' measurements.
- At 40 MV/m, our measured ε_{th} of ~ 0.2 μm is much closer to its expected thermal emittance of 0.12 μm, which is obtained from Q.E. measurements.

Solenoid Scan to Measure Thermal Emittance

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PSI

Since there was a limitation with pepperpot to get a good image on YAG2 screen for 0.6 pC, we used the solenoid scan to measure thermal emittance.

$$l_{eff} << f_{sol} = \frac{1}{k l_{eff}}, \quad k = \left(\frac{B_{\max}}{2p/e}\right)^2$$

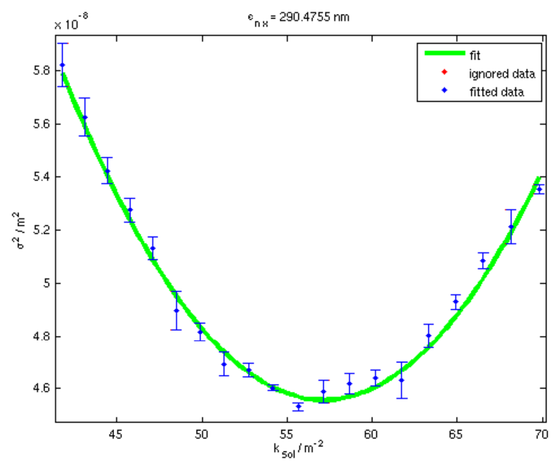
$$\sigma^2 = k^2 \overbrace{(L^2 l_{eff}^2 \varepsilon\beta_s)}^{c_2} + k \overbrace{(2L^2 l_{eff}\varepsilon\alpha_s - 2L l_{eff}\varepsilon\beta_s)}^{c_1} + \overbrace{(\varepsilon\beta_s - 2L\varepsilon\alpha_s + L^2\varepsilon\gamma_s)}^{c_0}$$

$$\varepsilon_n = \gamma\beta\varepsilon = \gamma\beta \frac{\sqrt{c_0 c_2 - c_1^2/4}}{L^2 l_{eff}}$$

$$\beta_s = \frac{1}{\varepsilon}\frac{c_2}{L^2 l_{eff}}$$

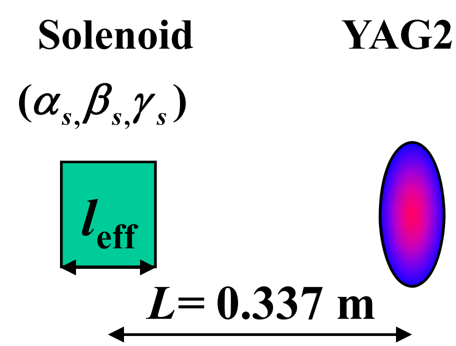
$$\alpha_s = \frac{1}{\varepsilon}\left(\frac{c_1}{2L^2 l_{eff}} + \frac{c_2}{L^3 l_{eff}^2}\right)$$

$$\gamma_s = \frac{1}{\varepsilon}\left(\frac{c_0}{L^2} + \frac{c_1}{2L^3 l_{eff}} + \frac{c_2}{L^4 l_{eff}^2}\right)$$



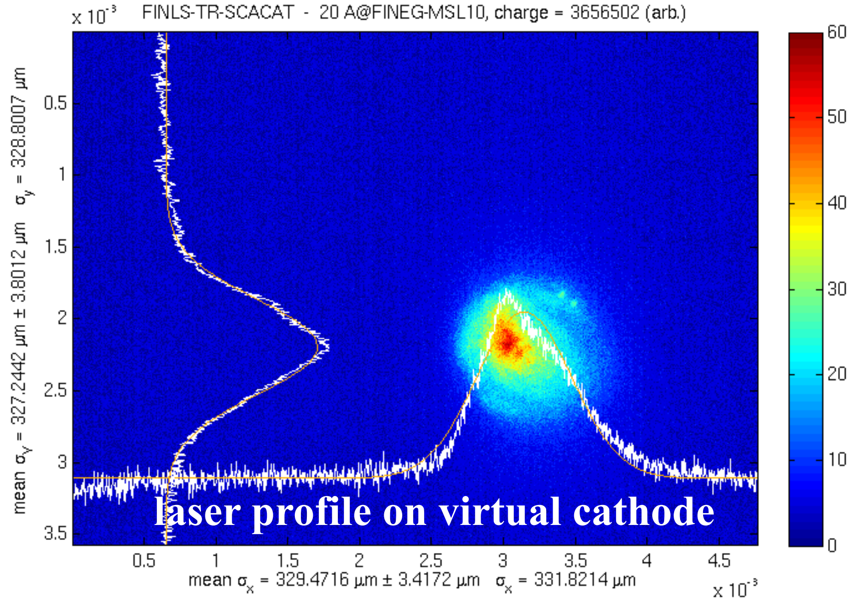
Same Principles used for QM Scan

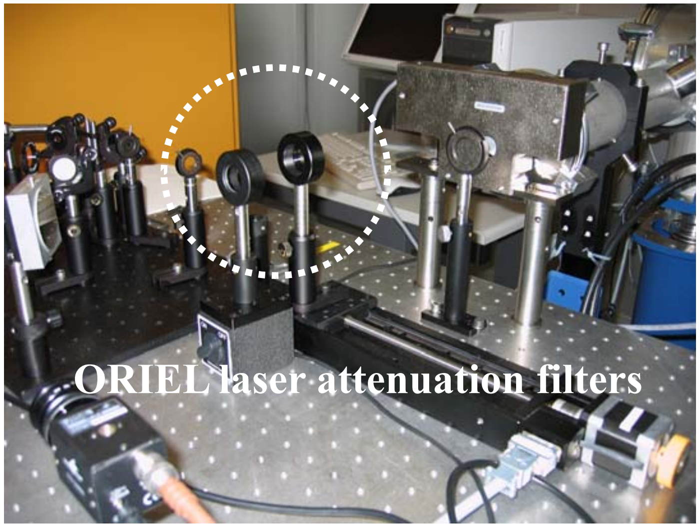
After optimizing first three solenoids (MSL10, MSL20, MSL30) to get a smallest round beam on YAG2 screen, we performed the solenoid scanning with the 4th solenoid MSL40.
Here, l_{eff} ~ 39.8 mm



Thermal Emittance with a Cu Cathode

Date = February 27th, 2008
gap size = 4 mm, gap voltage = 160 kV
gradient = 40 MV/m, cathode = Copper (OFHC)
MSL10C = 0 A
MSL10 = 20.0 A
MSL20 = 4.99 A
MSL30 = 25 A
MSL40 = 16 ~ 21 A with a scanning step of 0.25 A.
MSL50 = 0 A
H steerer = 0.17 A, V steerer = 0.10 A
Used screen = YAG2
Background Images = 50 images one time taken
ROI region = 750×750 from 1024×768
Number of image = 10 frames
Fitting method = Gaussian fit from 100% projection
YAG2 position = 60.0 mm (777 mm from cathode)
Telescope position = 10.5 mm from origin.
Q ~ 0.66 pC (= 33 pVs from Faraday cup)
laser length = 6.5 ps
laser rms size = 336 μm from the profile monitor
laser rms size = 329 μm from the virtual cathode
laser energy at laser room = 1.4 μJ with 10% attenuator
laser energy at bunker = (not detectable exactly)





MSL40 Solenoid Scan with a Cu Cathode

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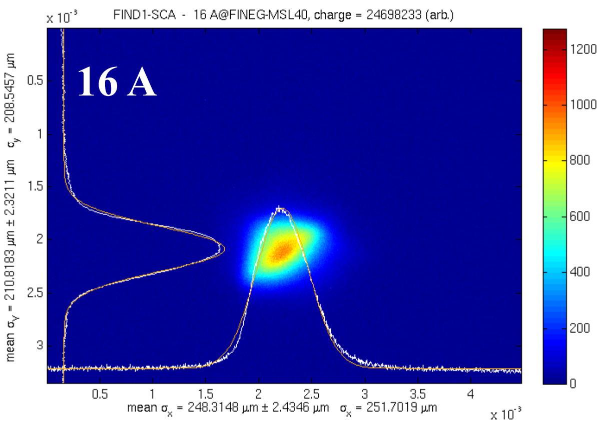
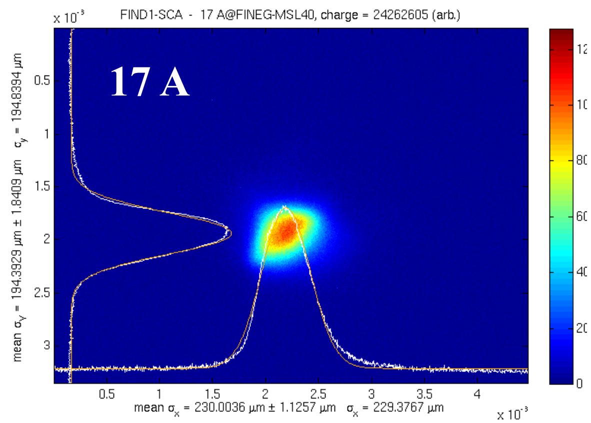
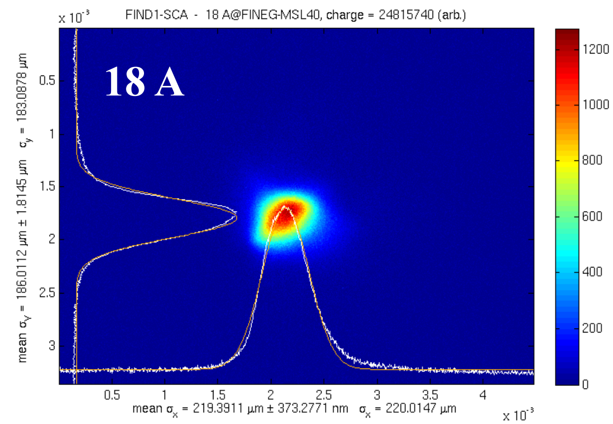
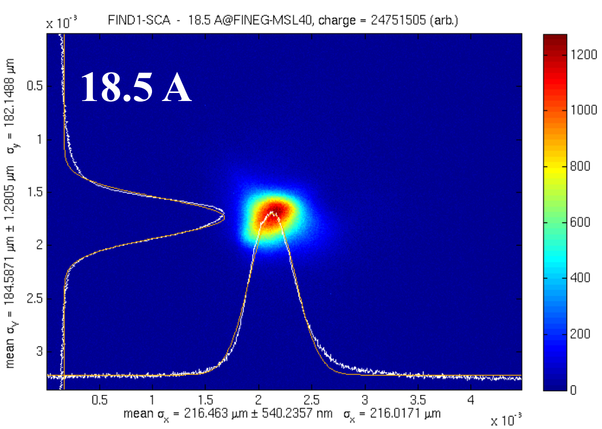
BG Image = 50 frame-averaged before start scanning due to ignorable dark current

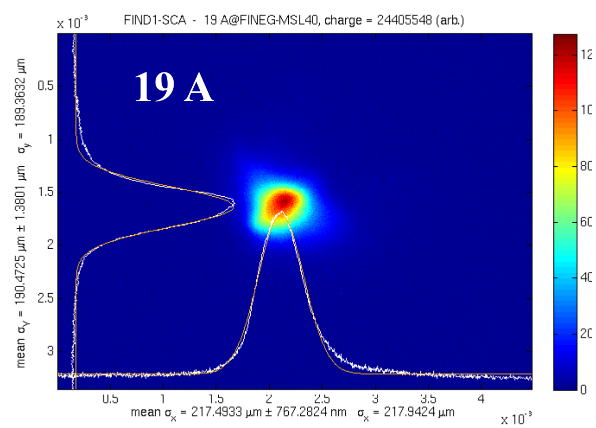


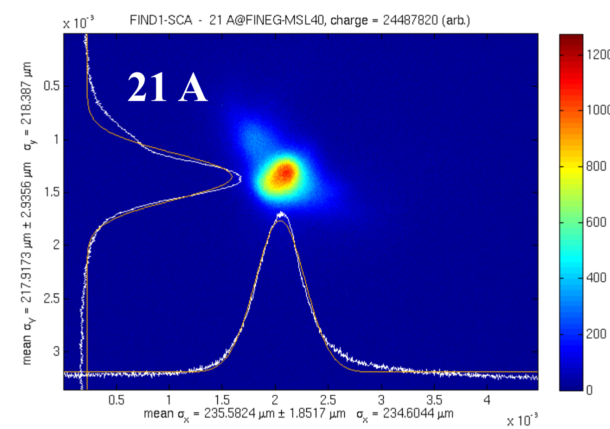




small vertical dispersion



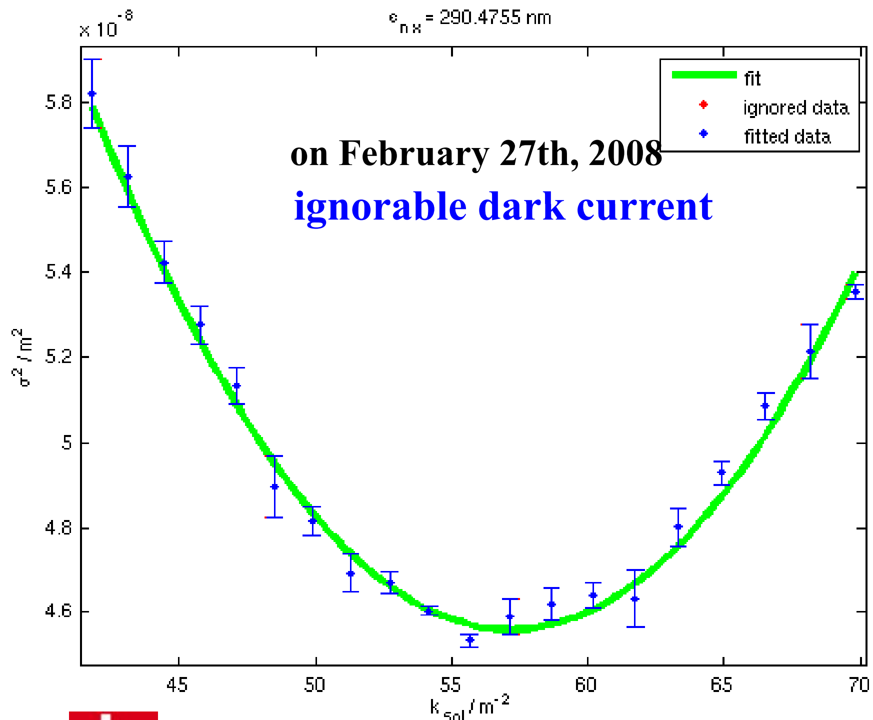


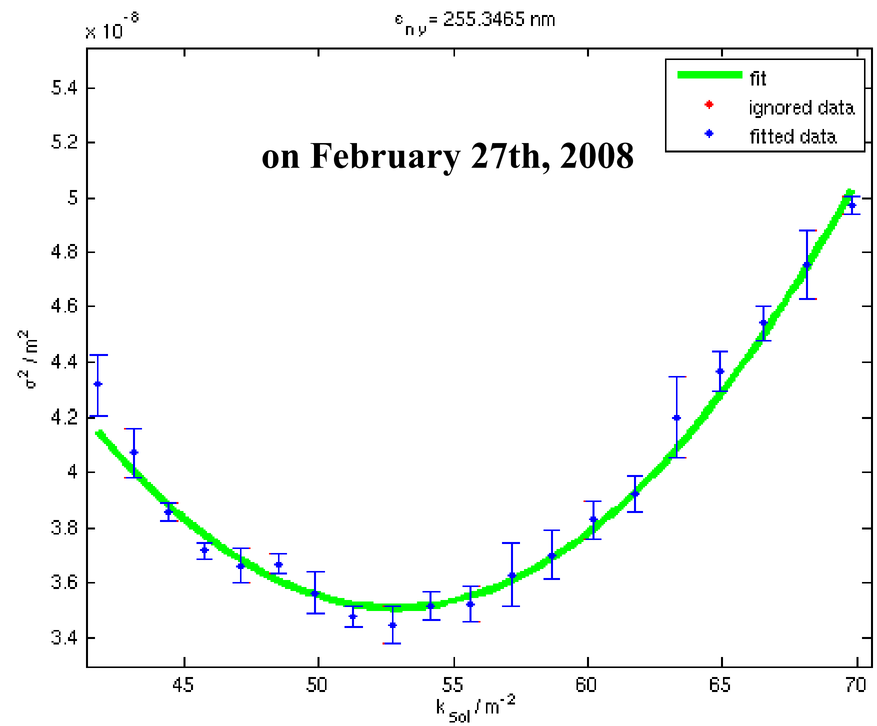


Excellent Thermal Emittance ~ 0.2 μm range

Measured emittance with a copper cathode on February 27th. 2008
normalized horizontal emittance ~ 0.29 ± 0.014 μm
normalized vertical emittance ~ 0.26 ± 0.013 μm

When we scanned MSL40 several times with the same (or similar) machine conditions, measured emittances were reproduced three times on February 27th, one time on February 28th, and one time on March 4th.
Their range was about 0.18 ± 0.011 μm ~ 0.29 ± 0.014 μm.





Excellent Thermal Emittance ~ 0.2 μm range

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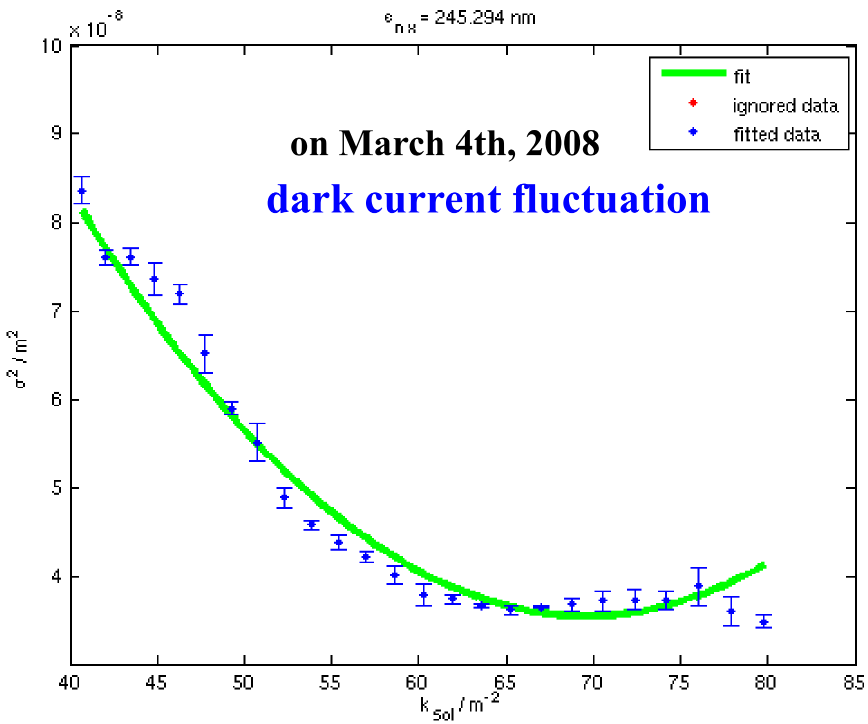

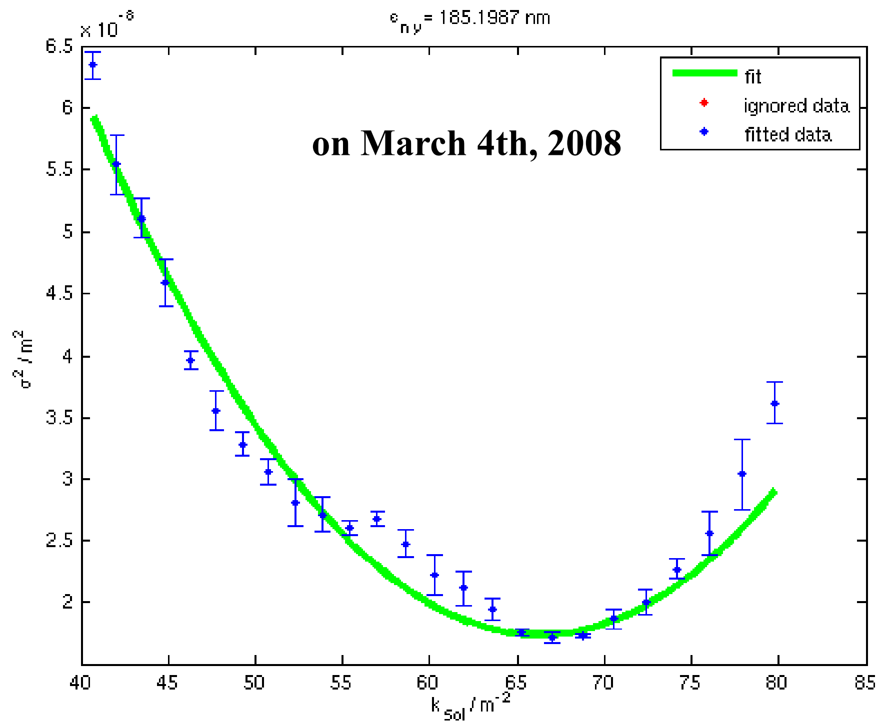

Difficulty - Background Dark Current

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Dark current was observed on screen from February 28th

Animation : Courtesy of T. Schietinger

Animation on dark current on February 29th.

Copper cathode

YAG1 images

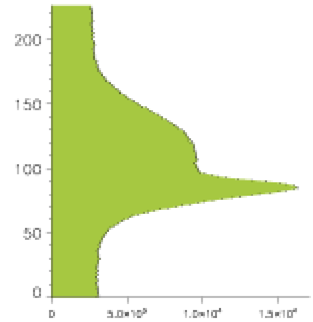
HV = 141 kV

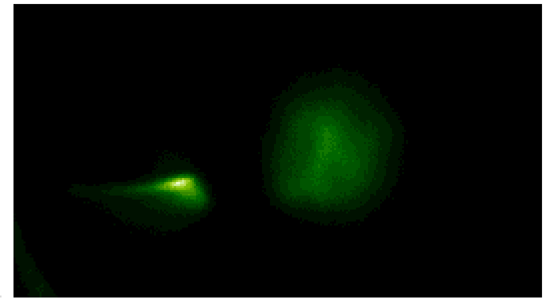
gap = 4 mm

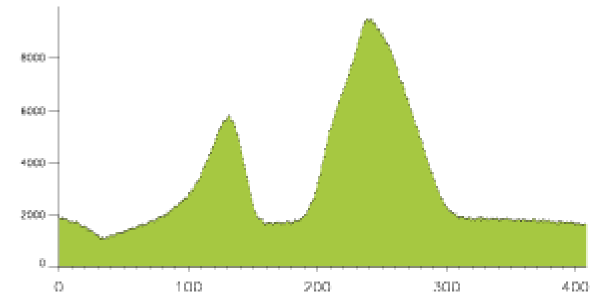
MSL10C = 0 A to 12 A with a step of 1 A

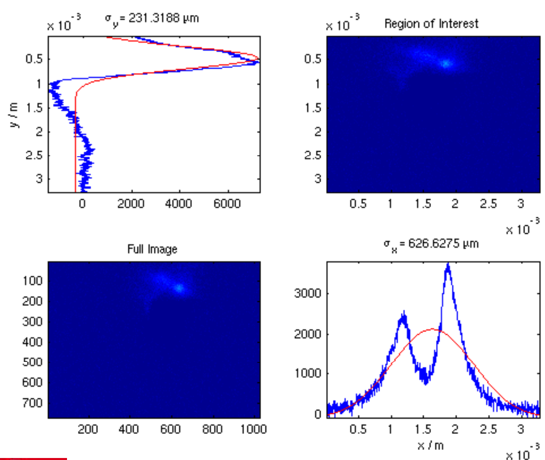
MSL10 = 22 A

MSL20 = 21 A

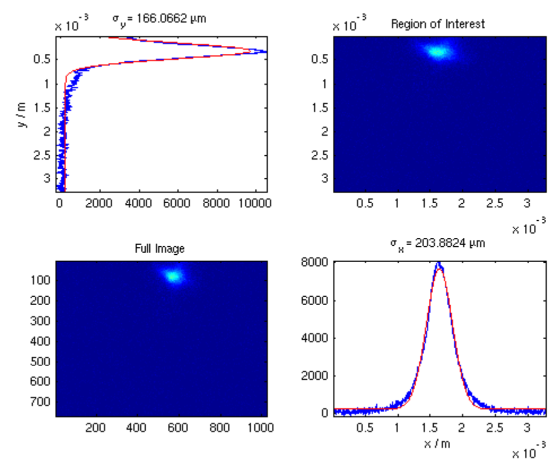






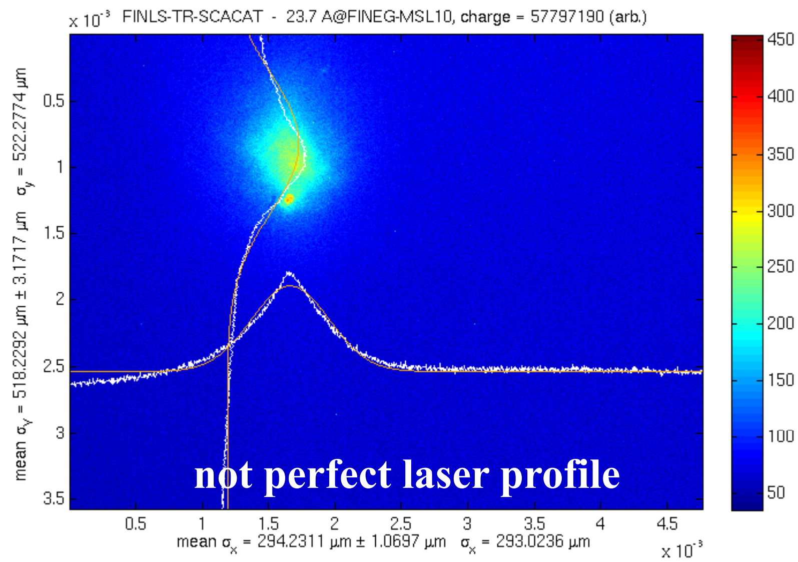


dark current
BG subtraction
at each scan step



Thermal Emittance with a SS cathode

Date = April 7th, 2008
gap size = 8 mm, gap voltage = 401.2 kV
gradient = 50.15 MV/m, cathode = Hand polished SS (316L)
MSL10C = 0 A
MSL10 = 23.7 A
MSL20 = 23.0 A
MSL30 = 25.0 A
MSL40 = 8 ~ 30 A with a scanning step of 0.5 A.
MSL50 = 0 A
H steerer = 0.18 A, V steerer = 0.43 A
Used screen = YAG2
Background Images = taken at each scan step
ROI region = 750×750 from 1024×768
Number of image = 10 frames
Fitting method = Gaussian fit from 100% projection
YAG2 position = 60.0 mm (777 mm from cathode)
Telescope position = 10.6 mm from origin.
Q ~ 0.7 pC (= 35 pVs from Faraday cup)
laser length = 6.5 ps
laser rms size ~ 300 μm but asymmetric (profile monitor)
laser attenuation = 10% & 25% attenuators



diameter ~ 55 mm

Photo : Courtesy of F. Le. Pimpec

MSL40 Solenoid Scan with a SS cathode

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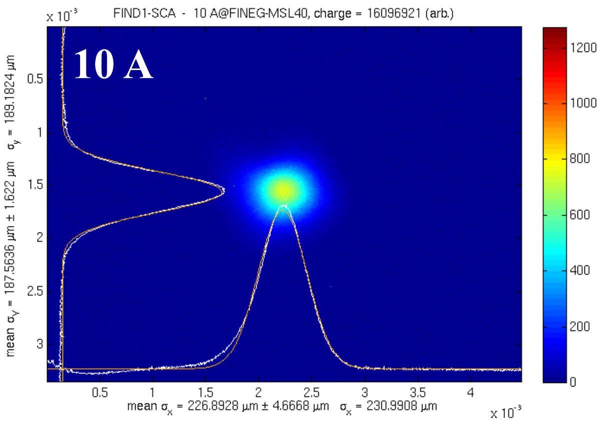
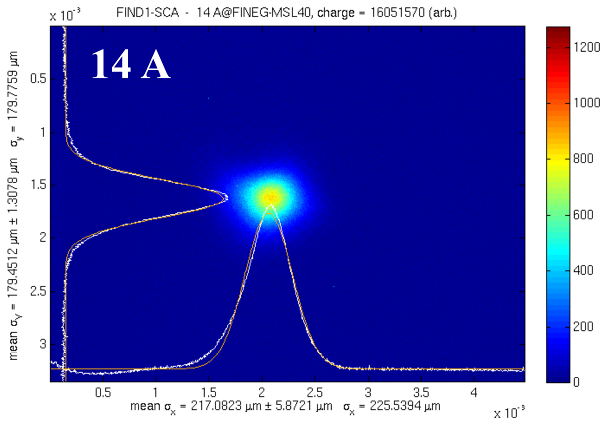
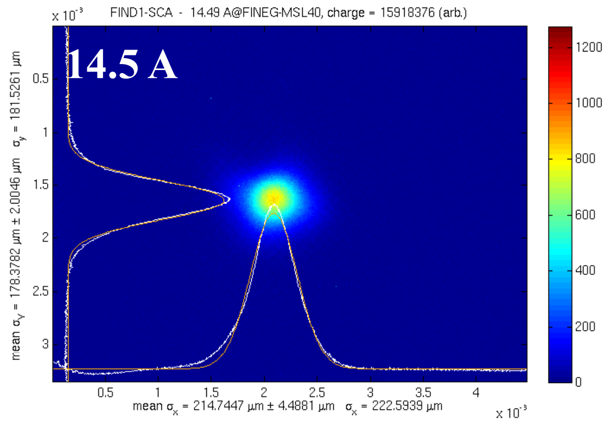
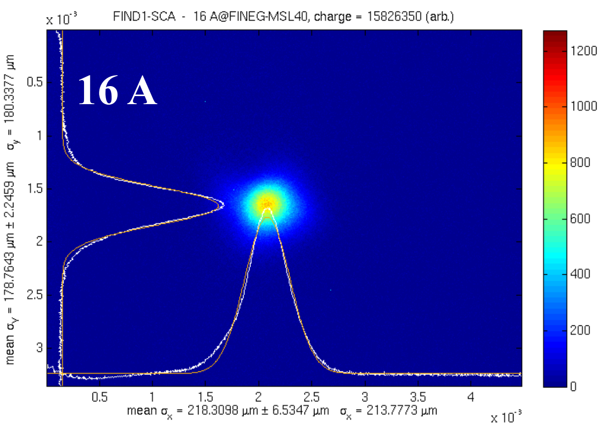
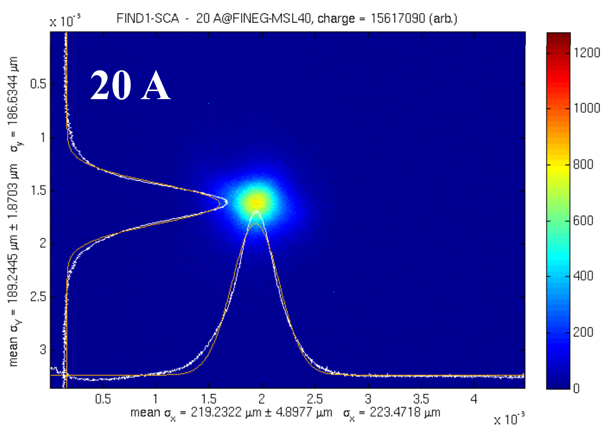
BG Images = 50 frame-averaged before each scan step even weak dark current

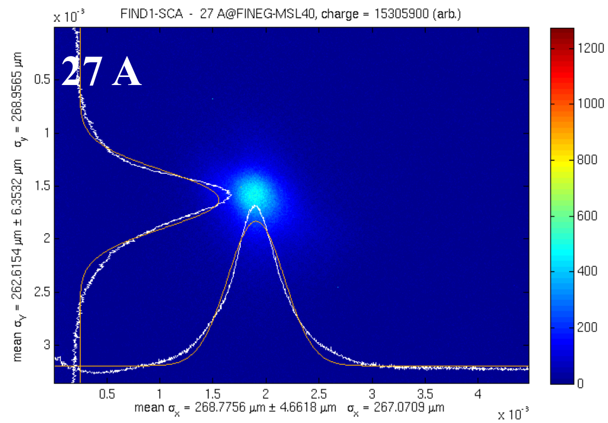












April 7th, 2008

Thermal Emittance with a SS cathode

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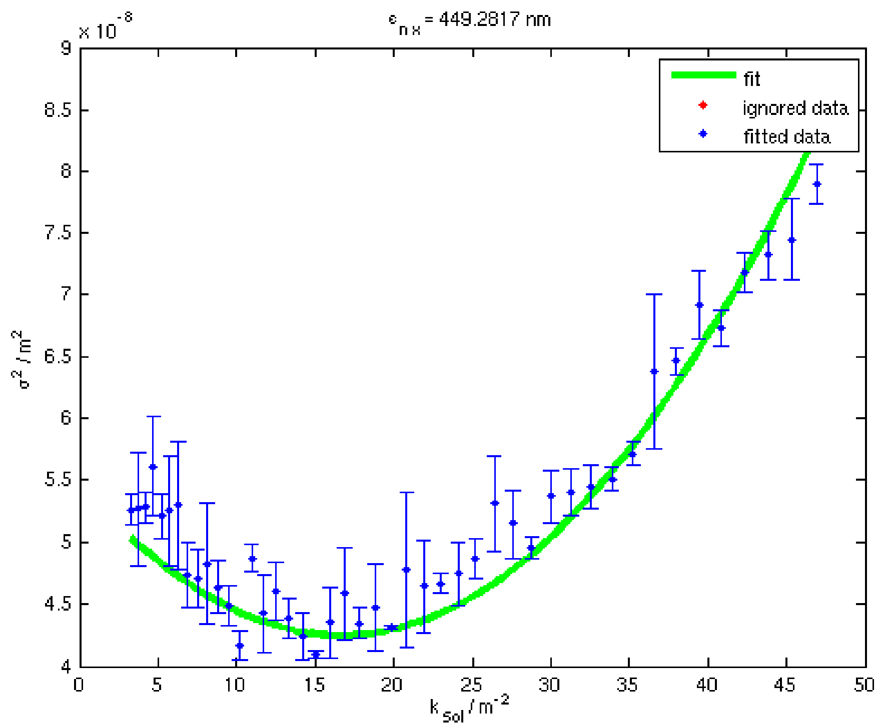
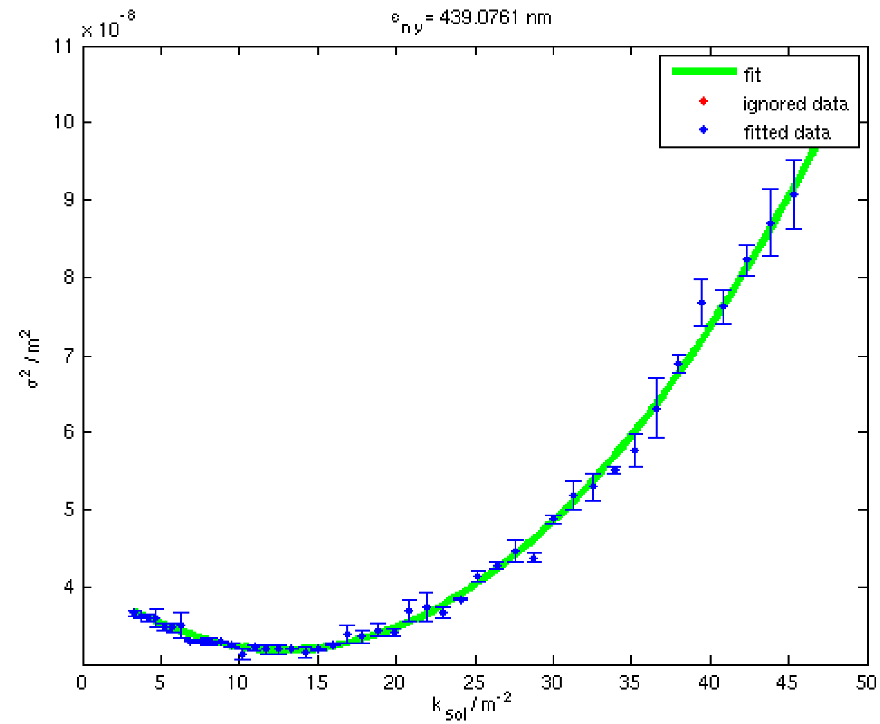
Measured emittance on April 7th, 2008

normalized horizontal emittance ~ 0.45 ± 0.036 μm

normalized vertical emittance ~ 0.44 ± 0.022 μm





April 7th, 2008

Summary

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Now PSI colleagues are extremely busy to upgrade the 4 MeV LEG test facility and to construct the 250 MeV injector. We have to demonstrate performance of our LEG and 250 MeV injector by October 10, 2010.

To study possibility of a small slice emittance of about 0.2 μm range for the PSI-XFEL project, we built a 500 kV pulser based Low Emittance Gun (LEG) test facility in 2007.

Our 500 kV pulser can supply an excellent energy spread along whole bunch (σ_{dE} ~ 0.08 eV at 500 keV), which certainly reduces contribution of the chromatic effects and nonlinear electromagnetic RF field effects to the emittance.

By the help of excellent diagnostic systems (Faraday cup and imaging), we can measure beam parameters with an ultra-low charge of 0.2 pC.

The ultra-low single bunch charge certainly reduces contribution of space charge forces in the thermal emittance measurements.

Up to now, our best measured thermal emittance is about 0.2 μm with a Cu cathode and about 0.45 μm with a SS cathode.

Summary & Acknowledgements

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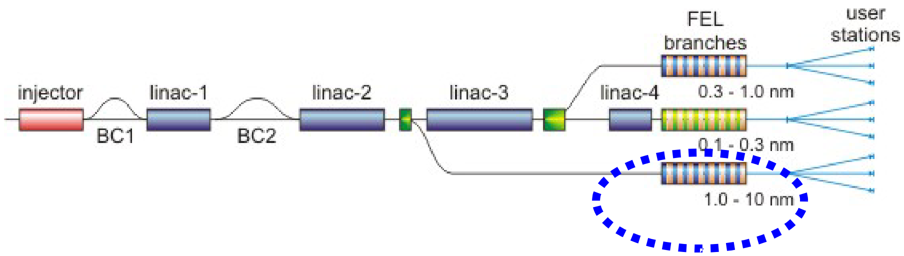
We tried to measure a low thermal emittance with a copper cathode by using 500 kV pulser, and ultra-low single bunch charge with the solenoid scanning. It seems that our measured thermal emittance is much closer to theoretically expected value of 0.12 μm, which comes from our Q.E. measurements.

It seems that it is not easy to measure a low thermal emittance with the slit method and conventional RF guns due to RF effects, space charge effects, chromatic effects, and noise issue in the slit method.

We have lots of further optimization margin (count coil, beam based alignment, optimization of laser spotsize, optimization of wavelength of laser beam, and so on), and the expected thermal emittance is about 0.1 μm range from Q.E. measurements. Therefore we expect that we can measure a smaller realistic thermal emittance in the future.

All commissioning crew sincerely thank to all PSI colleagues who have been working for the LEG Test Facility ! Additionally to about 50 experts who have been working for the 4 MeV Phase-II upgrade.

HHG Seeded HGHG @ FEL Branch 3



FEL3 branch (1 ~ 10 nm)
Externally HHG seeded HGHG operation

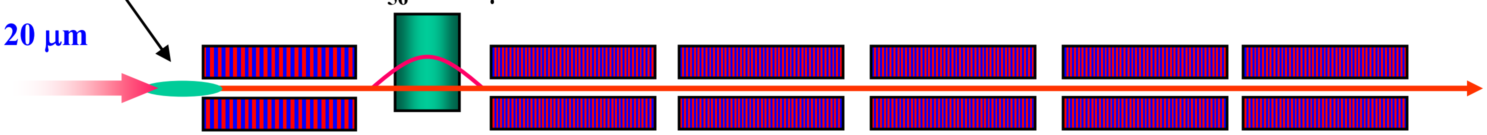
ELECTRON Beams

E = 3658 MeV, σ_δ = 0.098%
σ_x = 32 µm, σ_y = 19 µm, σ_z = 14.2 µm (47 fs)
ε_{nx} ~ 0.397 µm, ε_{ny} ~ 0.347 µm
I_{peak} < 1.6 kA
$\varepsilon_{n,slice}$ < 0.33 µm
$\sigma_{dE,slice}$ < 29.8 keV for |dz| ≤ 20 µm

HHG based seeding FEL
dispersion section
R_{56} ~ 7.4 µm

FEL Photon

HGHG Harmonics = 3rd / 5th
λ_{FEL} = 2 nm / 1.2 nm
E_{FEL} = 280 µJ / 40 µJ
$\sigma_{z,FEL}$ ~ 1.98 µm (7 fs) / 1.67 µm (6 fs)



SEEDING SOURCE

E_{seed} = 5.63 nJ
$P_{pulse,seed}$ ~ 1 MW
$P_{CW,,aussian,seed}$ ~ 300 kW
$\sigma_{z,seed}$ ~ 2.03 µm (7 fs)
λ_{seed} = 6 nm

λ = 6 nm

modulator
in-vacuum undulator

λ_u = 52 mm, gap g = 8 mm
B_r ~ 1.12 T for $Nd_2Fe_{14}B$
B_0 ~ 1.43$B_r$exp(-πg/λ_u) ~ 0.9878 T
K_{max} = 4.797
$\langle\beta\rangle_{x,y}$ = 10 m
L = 9.0 m
λ_x = 6 nm (external-seeded FEL)

see our MOPPH062 poster

λ/3 = 2 nm / λ/5 = 1.2 nm

radiator
in-vacuum undulator

λ_u = 34 mm, gap g ~ 5 mm / 8.7 mm
B_r ~ 1.12 T for $Nd_2Fe_{14}B$
B_0 ~ 1.43$B_r$exp(-πg/λ_u) ~ 1.0090 T / 0.7208 T
K_{max} = 3.204 / 2.289
$\langle\beta\rangle_{x,y}$ = 10 m
L = 4.5 × 5 = 22.5 m
λ_x = 2.0 nm / 1.2 nm (external-seeded FEL)
λ_3 = 0.67 nm / 0.4 nm (3rd Nonlinear Harmonics)
λ_5 = 0.4 nm / 0.24 nm (5th Nonlinear Harmonics)