RF GUN, LASER & ELECTRON BEAM COMMISSIONING

The 23rd KEKB Accelerator Review Committee

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Accelerator Laboratory Division V, Injector G

SuperKEKB REQUIREMENTS

	Electron HER 7 GeV	Positron LER 4 GeV
Normalized Emittance	**40 / 20 [µm]**	**100 / 15 [µm]**
Energy Spread	**0.07%**	**0.16%**
Bunch Charge at Injection Point	**4.0 nC**	**4.0 nC**

Stable electron beam with high charge and low emittance is required for SuperKEKB

SuperKEKB Project ×40

SuperKEKB RF Gun

Requirements
- 4 nC electron charge generation
- 10 μm emittance preservation
- Long term operation

Operating at 4 nC
- Less space charge effect
  - Longer pulse: 20-30 ps
- Necessary strong focusing field
  - Preserves the emittance
- Stable long time operation
  - Lower electric field: < 100 MV/m

Side coupler or Disk and washer is preferred

S-band RF Gun System for SuperKEKB

RF gun cavity: strong focusing electric field

- Disk and washer (DAW): tested in 3-2
- Quasi travelling wave side coupler (QTWSC): A1 primary RF gun
- Cut disk structure (CDS): A1 secondary RF gun

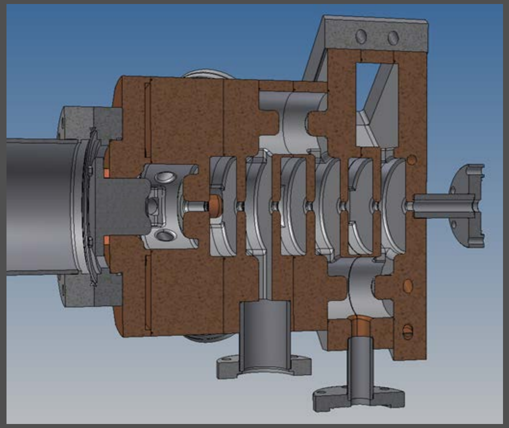
Photocathode: long life time

- Medium QE with long life time: 10^{-4}~10^{-3} @266nm > 1 year
- Metal composite: Ir_5Ce

Laser: simple, stable with temporal and spatial manipulation

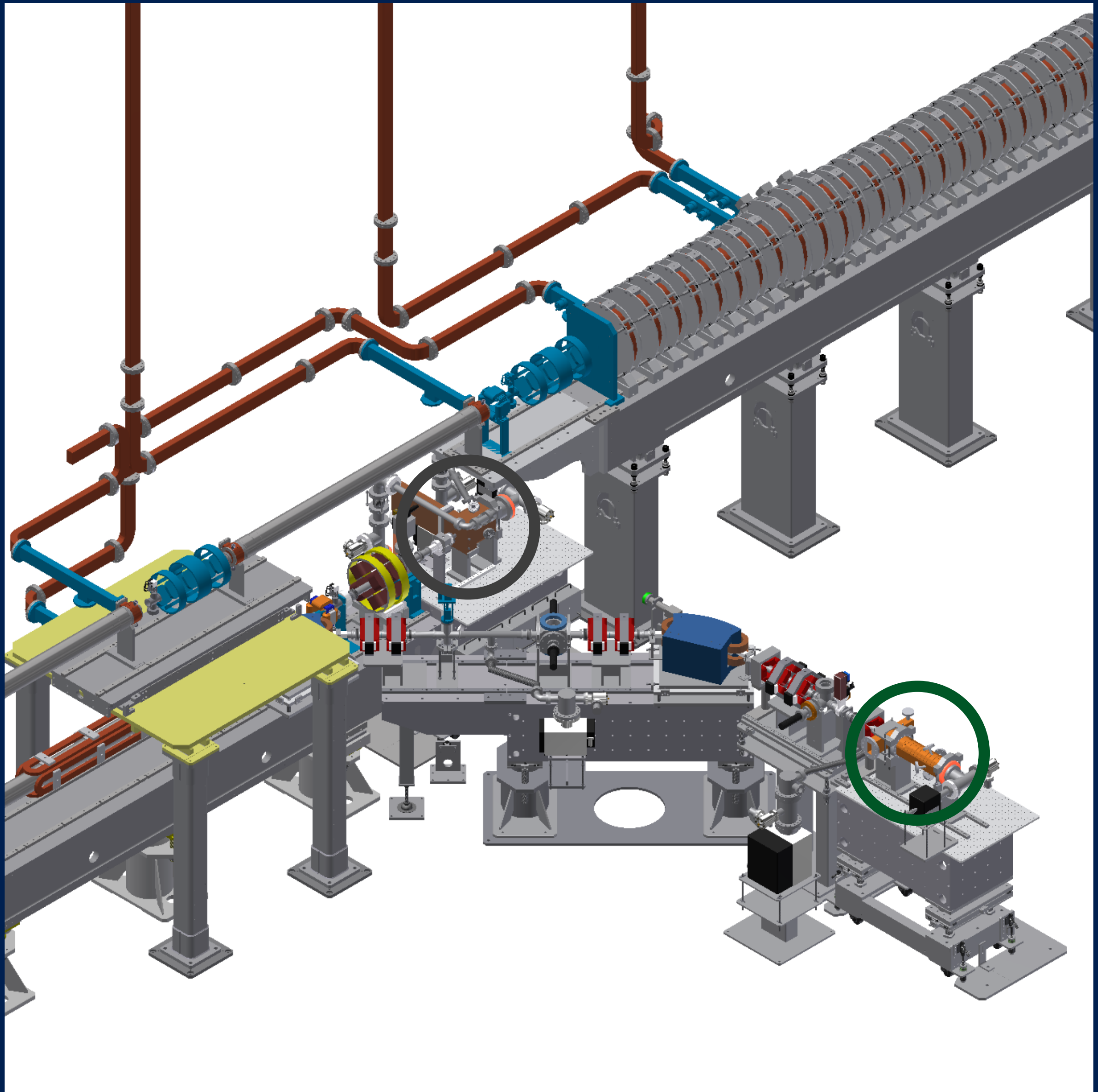
- Laser active material pumped by laser diode
  - Yb doped fiber & Neodymium (Nd) doped laser crystal: A1 ground laser hut
  - Yb doped fiber & Ytterbium (Yb) doped laser crystal: A1 underground laser hut
- Temporal and spatial reshaping for minimum energy spread and emittance

Injector Section for SuperKEKB



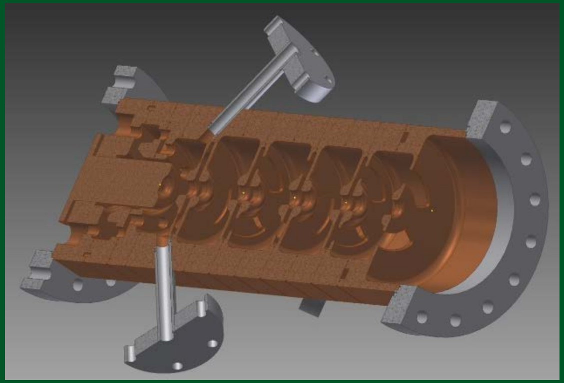
Primary RF gun

- QTWSC cavity
- Adopted in this stage
- <u>1st milestone: full regular operation for the injection of HER (R4.3)</u>



Thermionic gun

- In the 2nd layer
- Used for positron target, PF and PF-AR



Secondary RF gun

- CDS cavity
- Never used in this stage

Photocathode in Primary RF Gun

	Off line	Online	Improvement
Ir_7Ce_2	1.0 x 10^{-4}	1.5 x 10^{-5}	In 2020, online QE will be improved 10 times higher
FY2018 Ir_7Ce_2 + Heating	-	1.5 x 10^{-5}	
FY2019 Ir_2Ce + Heating	5.0 x 10^{-4}	1.5 x 10^{-4}	
FY2020 Ir_2Ce + Heating + Better Vacuum	5.0 x 10^{-5}	2.0 x 10^{-4}	

Current Nd/Yb Hybrid Laser System (R4.1)

Fiber Oscillators (114 MHz)
- Menlo Orange 1 (1064 nm by SPM)
- Menlo Orange 2 (1064 nm)
- Home made ANDi type 1064 nm
- → MEMS Switch 3 In 1 Out
- 4 months 0 fault operation!

Fiber Amplifiers
- Yb Single mode Fiber Amplifier 1
- → Semiconductor optics Amplifier (SOA) 114 MHz → 10 MHz
- → Yb Single mode Fiber Amplifier 2
- → Yb Single mode Fiber Amplifier 3

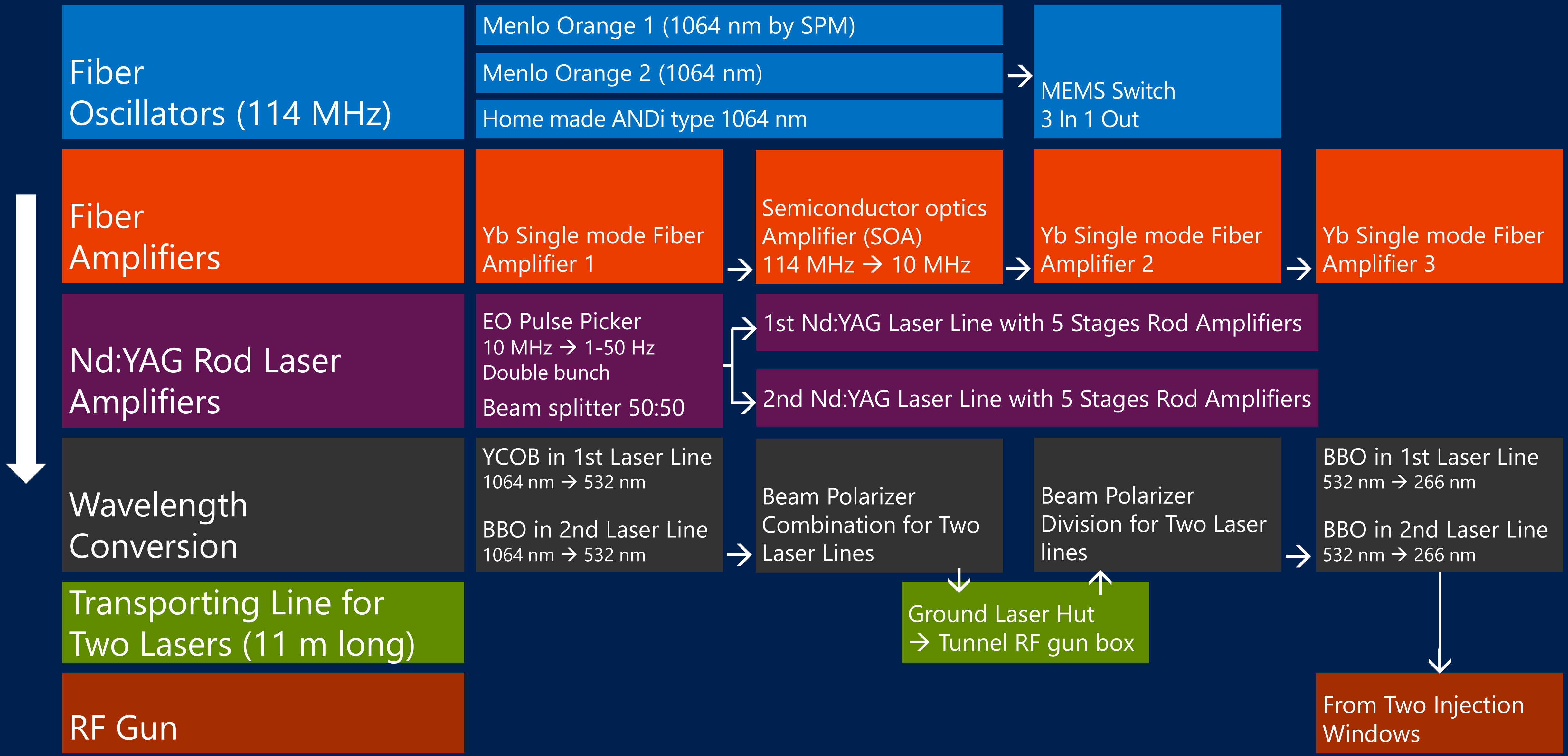
Nd:YAG Rod Laser Amplifiers
- EO Pulse Picker 10 MHz → 1-50 Hz Double bunch
- Beam splitter 50:50
- → 1st Nd:YAG Laser Line with 5 Stages Rod Amplifiers
- → 2nd Nd:YAG Laser Line with 5 Stages Rod Amplifiers
- 4 months 0 fault operation!

Wavelength Conversion
- YCOB in 1st Laser Line 1064 nm → 532 nm
- BBO in 2nd Laser Line 1064 nm → 532 nm
- → Beam Polarizer Combination for Two Laser Lines
- Beam Polarizer Division for Two Laser lines
- → BBO in 1st Laser Line 532 nm → 266 nm
- BBO in 2nd Laser Line 532 nm → 266 nm

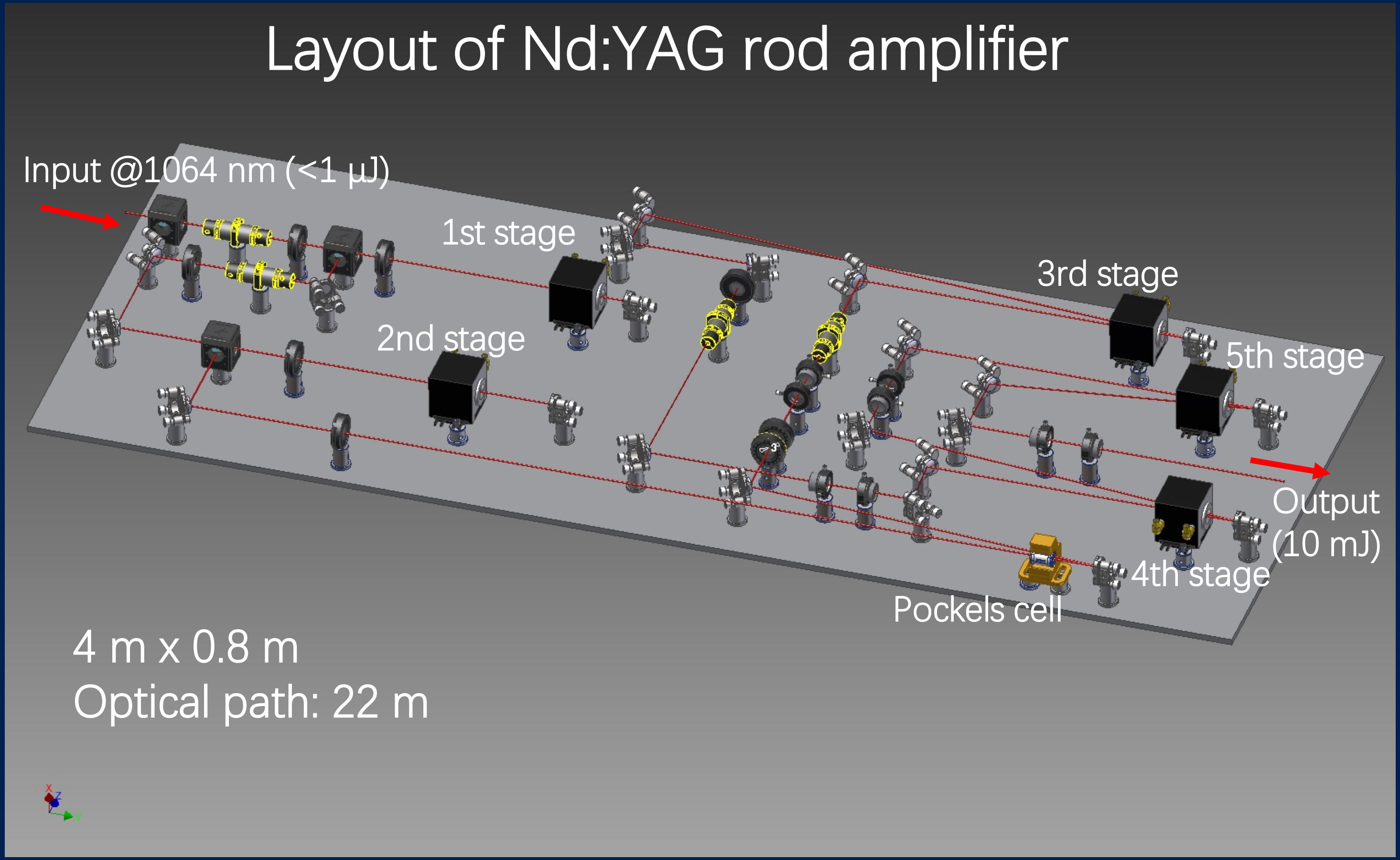
Transporting Line for Two Lasers (11 m long)
- Ground Laser Hut → Tunnel RF gun box

RF Gun
- From Two Injection Windows

Current Nd/Yb Hybrid Laser System (R4.1)

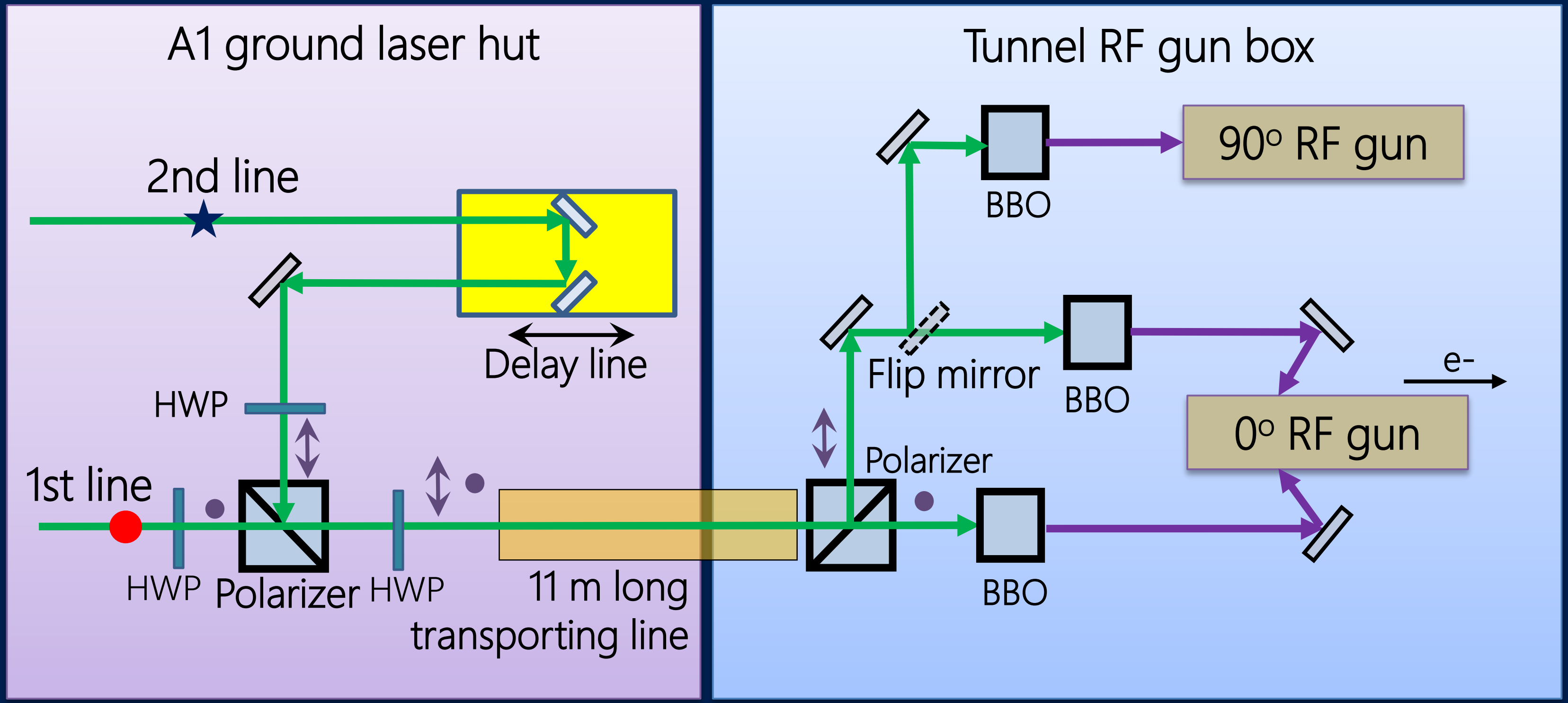


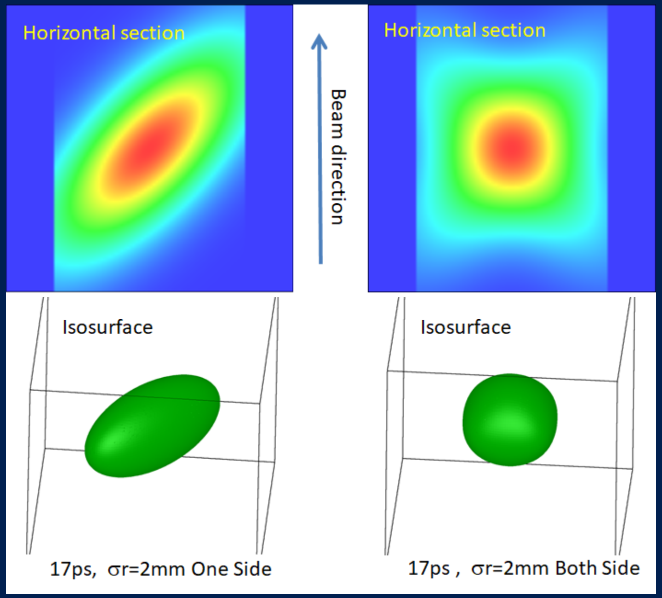
Stable & Efficient Nd:YAG Amplifier (R4.2)



- High amplification efficiency with sample configuration
- Lower pump currents by use of high dopant Nd:YAG crystals (2018 summer)
- Trouble shooting in short time for stable and smooth commissioning
- No problem occurred during stage (more than 4 months)

Two Lasers Injection Mode (R4.1)



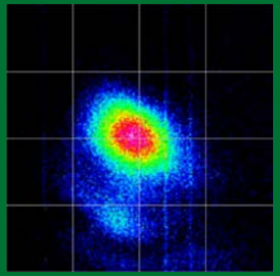


Irradiated by two lasers

• Laser with vertical polarization, ↕ laser with horizontal polarization, HWP: half wave plate

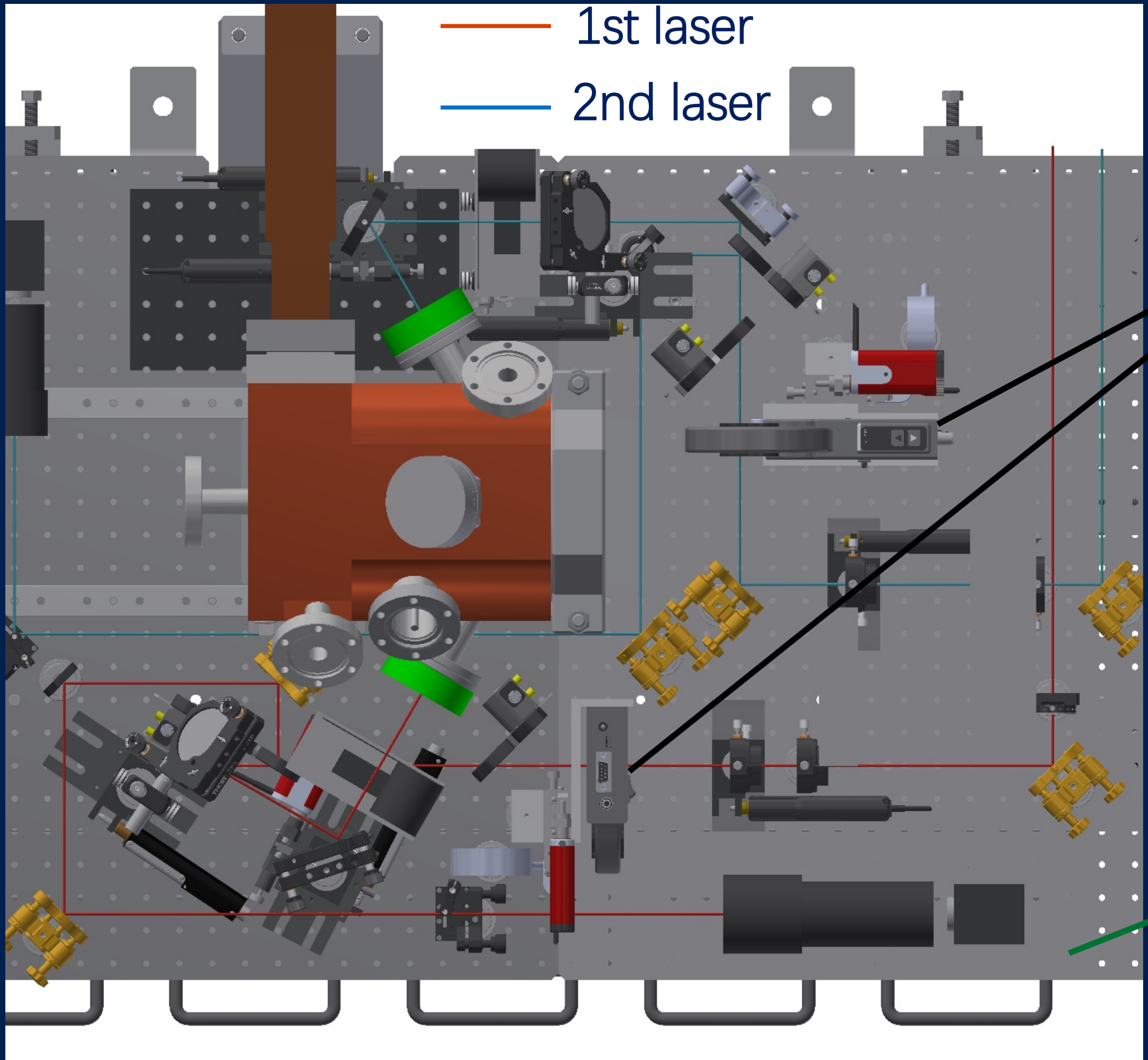
- Possible to generate high e⁻ charge
- Better emittance
- Backup for the smooth commissioning

Controllable and Monitorable Laser (R4.2)

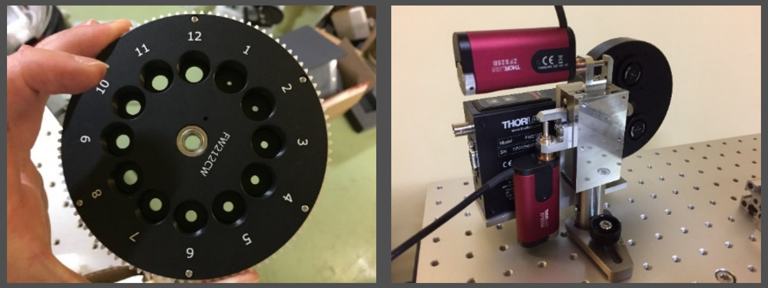


UV laser beam profile

- CCD setup at the virtual cathode position
- Net energy meter
- Remote control actuators for fine adjustment (20 pieces)

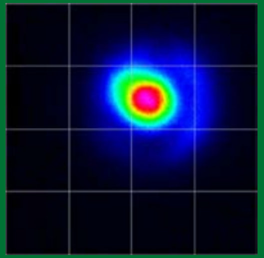


Optics layout in RF gun box



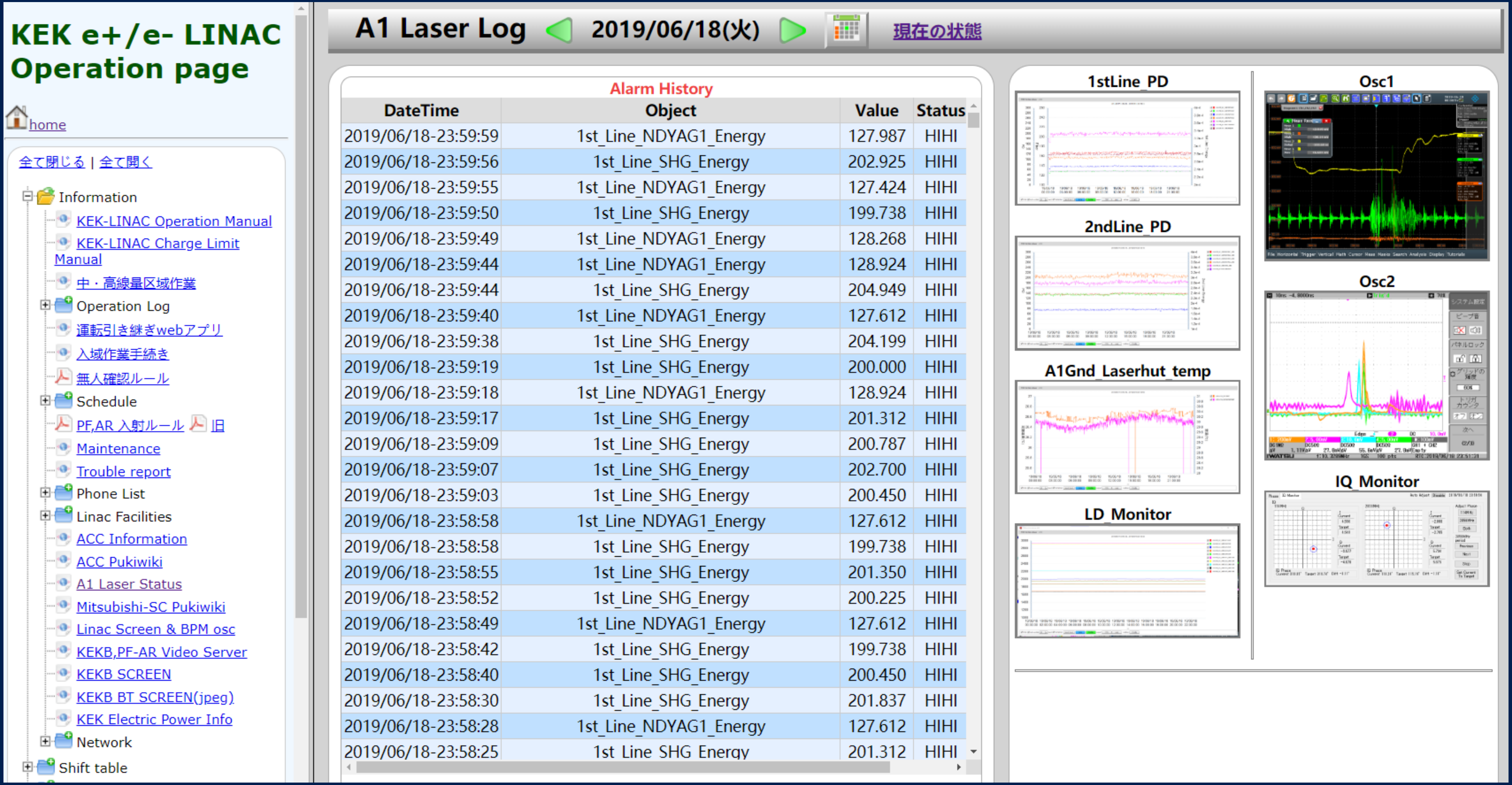
UV laser aperture

- Temporary setup for laser beam shaping
- Remote control



UV laser beam profile

Laser Status Monitoring System



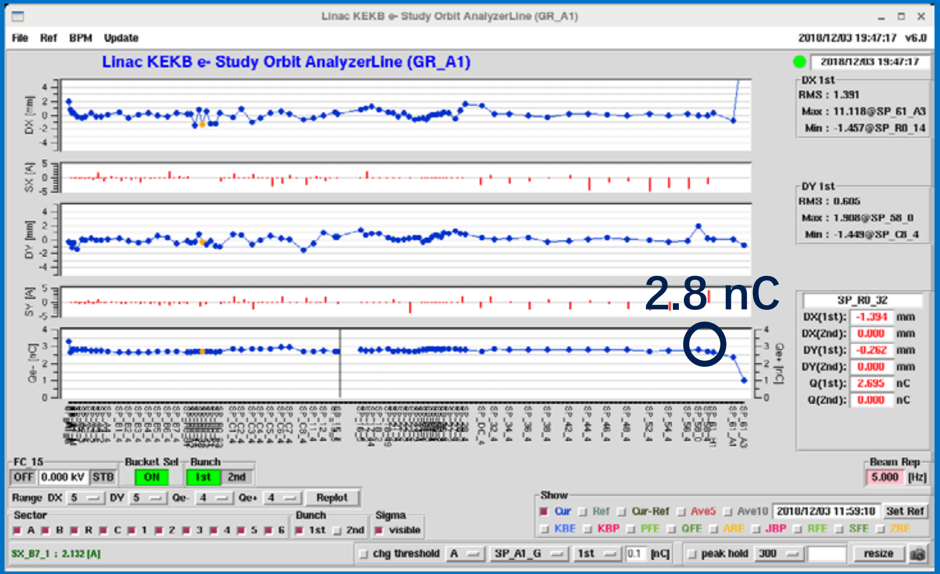
Alarm History

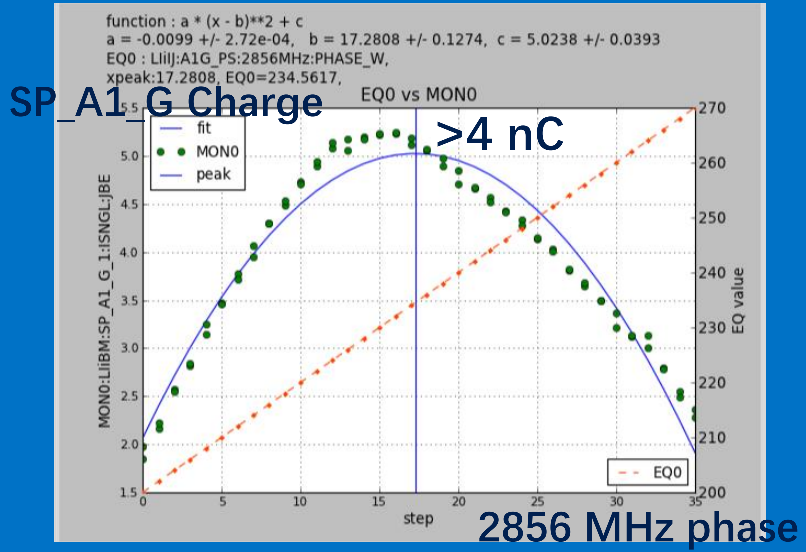
DateTime	Object	Value	Status
2019/06/18-23:59:59	1st_Line_NDYAG1_Energy	127.987	HIHI
2019/06/18-23:59:56	1st_Line_SHG_Energy	202.925	HIHI
2019/06/18-23:59:55	1st_Line_NDYAG1_Energy	127.424	HIHI
2019/06/18-23:59:50	1st_Line_SHG_Energy	199.738	HIHI
2019/06/18-23:59:49	1st_Line_NDYAG1_Energy	128.268	HIHI
2019/06/18-23:59:44	1st_Line_NDYAG1_Energy	128.924	HIHI
2019/06/18-23:59:44	1st_Line_SHG_Energy	204.949	HIHI
2019/06/18-23:59:40	1st_Line_NDYAG1_Energy	127.612	HIHI
2019/06/18-23:59:38	1st_Line_SHG_Energy	204.199	HIHI
2019/06/18-23:59:19	1st_Line_SHG_Energy	200.000	HIHI
2019/06/18-23:59:18	1st_Line_NDYAG1_Energy	128.924	HIHI
2019/06/18-23:59:17	1st_Line_SHG_Energy	201.312	HIHI
2019/06/18-23:59:09	1st_Line_SHG_Energy	200.787	HIHI
2019/06/18-23:59:07	1st_Line_SHG_Energy	202.700	HIHI
2019/06/18-23:59:03	1st_Line_SHG_Energy	200.450	HIHI
2019/06/18-23:58:58	1st_Line_NDYAG1_Energy	127.612	HIHI
2019/06/18-23:58:58	1st_Line_SHG_Energy	199.738	HIHI
2019/06/18-23:58:55	1st_Line_SHG_Energy	201.350	HIHI
2019/06/18-23:58:52	1st_Line_SHG_Energy	200.225	HIHI
2019/06/18-23:58:49	1st_Line_NDYAG1_Energy	127.612	HIHI
2019/06/18-23:58:42	1st_Line_SHG_Energy	199.738	HIHI
2019/06/18-23:58:40	1st_Line_SHG_Energy	200.450	HIHI
2019/06/18-23:58:30	1st_Line_SHG_Energy	201.837	HIHI
2019/06/18-23:58:28	1st_Line_NDYAG1_Energy	127.612	HIHI
2019/06/18-23:58:25	1st_Line_SHG_Energy	201.312	HIHI

http://www-linac.kek.jp/ope/opelog2/opelog.html

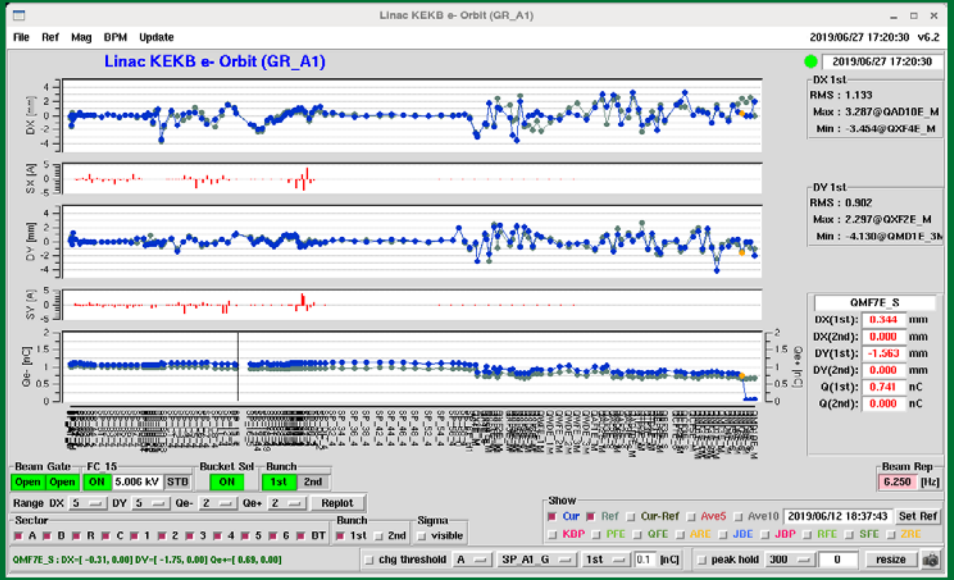
Electron Beam Commissioning (R4.2 & R4.4)

High Charge Test under Full Laser Energy





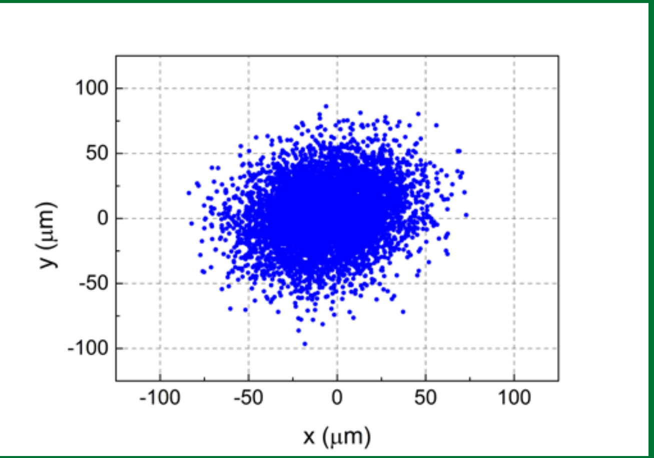
For Commi-ssioning



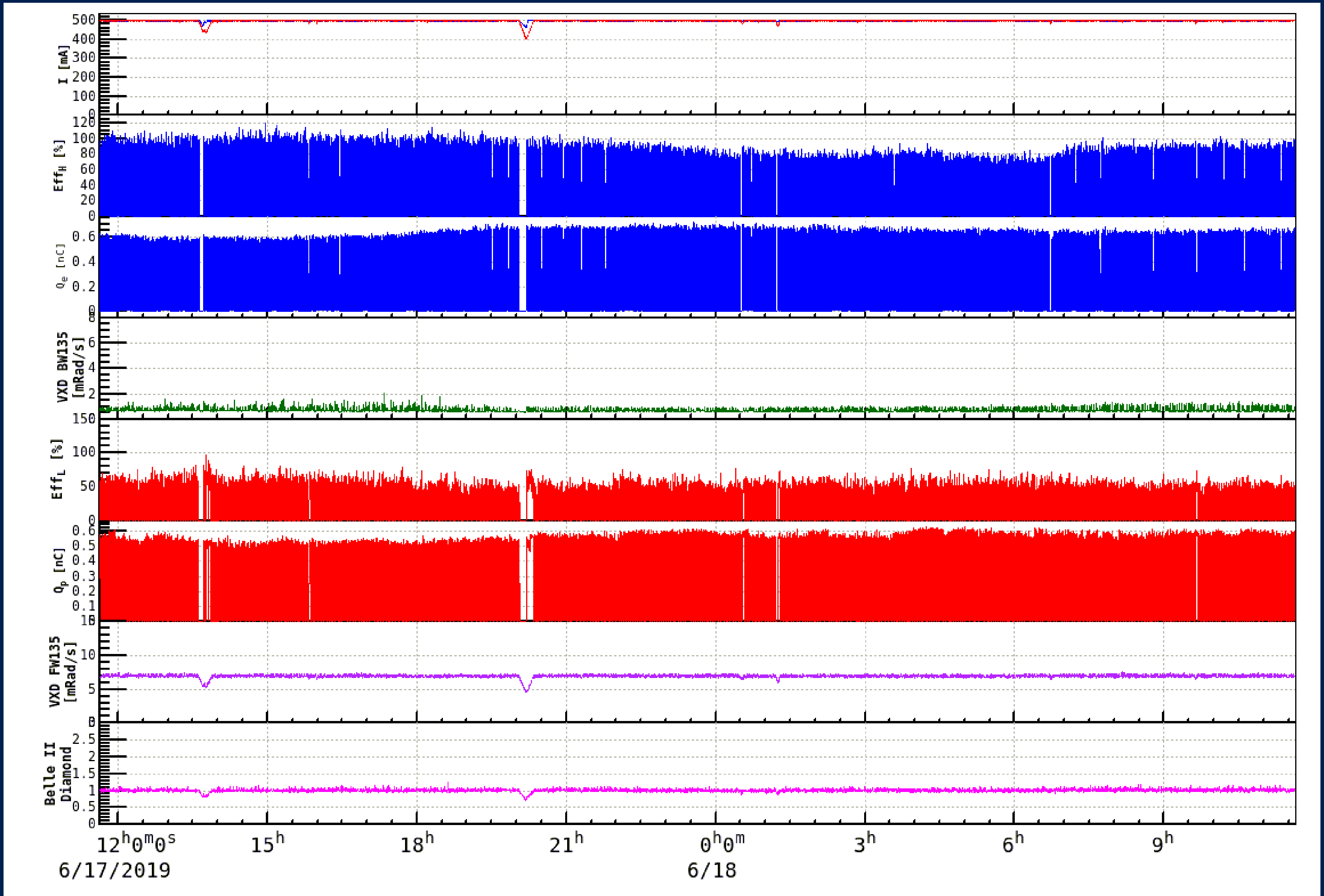
B-sector Wire Scanner
2019.06.27
1.2 nC @ SP_A1_G

4-wire ABCD:
$\gamma\varepsilon_x$=12.655 µm,
$\gamma\varepsilon_y$=11.225 µm

Laser pointing stability at the virtual cathode position



Stable & Continuous Operation in the Commissioning



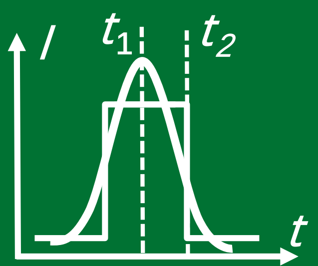
- More than 4 months stable and continuous regular injection (R4.3)
- Comparable low injection background
- Availability rate is 98.8% (MTBF: 394.1 h, MTTR: 4.6 h) (R4.3)
- Different correspondence for different study by altering e$^-$ charge only a few seconds (R4.2)

Updates (R4.1 & R4.2)

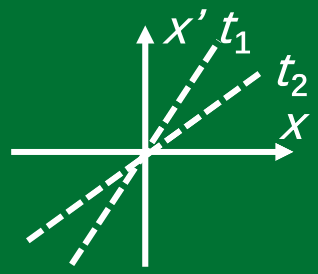
- Install new Menlo fiber oscillator (1030 & 1064 nm) (2019 summer)
- Photocathode development for higher QE (2019 summer)
  - $Ir_7Ce_2 \rightarrow Ir_2Ce$
- Rebuild transporting line by use of relay imaging system (2019 summer)
- Improve temperature stability in the laser hut (2019 summer)
- Realize real time UV laser beam profile monitor (2019 summer)
  - Available during continuous injection
- New RF gun for better vacuum level and higher RF power (from 2020)

Laser for Middle & Later Stages of Phase III

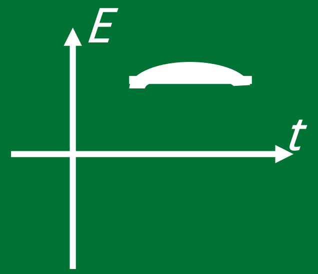
Laser temporal reshaping for low emittance, low energy spread, and injection noise suppression



Laser temporal distribution

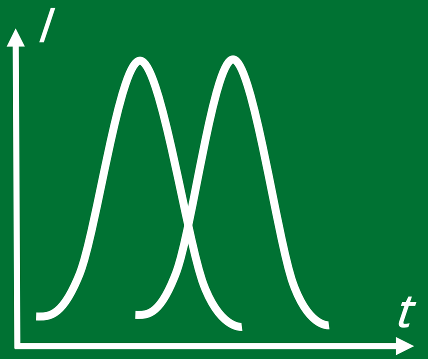


Phase space

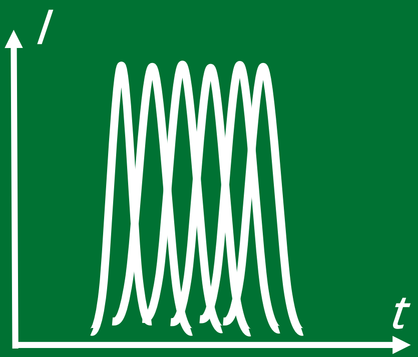


Energy spread

- Coherent pulse stacking technology by use of the birefringent effect of crystal
- Demonstrated in Nd laser system (Supported by Dr. Honda in 2018, R4.2)
- Due to the narrower spectrum width of the current Nd laser system (wider temporal width), the real rectangular shape is impossible (Fourier transform limit)



Nd laser system: 17 ps



Yb laser system: 2.5 ps

- Yb laser system is the best and only candidate for low energy spread and low emittance electron beam generation in Phase III

	2019 Q1	2019 Q2	2019 Q3	2019 Q4	2020 Q1	2020 Q2	2020 Q3	2020 Q4	2021 Q1	2021 Q2	2021 Q3	2021 Q4
Nd Laser System	Primary laser for RF gun and HER injection								Backup laser system for SuperKEKB			
Yb Laser System	Laser & monitoring system preparation with stacking						e⁻ beam test		For RF gun and HER injection			

Summery

- Continuous and stable full RF gun operation in this stage
- Simple and precise laser and electron beam adjustment thanks to the available monitors and remote control components
- Increase the stability of laser and electron beam
- Will focus on improving the quality of electron beam by the Yb laser system

THANKS

Backup

Recommendations of the 22nd Review

Recommendations:

R4.1: Prepare a maintenance plan for the RF gun and associated hardware to improve the long term reliability.

R4.2: Develop a detailed plan to make the existing gun and laser meet the beam parameters needed for SuperKEKB Phase-III commissioning, with only modest upgrades since the e-source is very important for commissioning plan. Consult nearby local laser experts as needed.

R4.3: Run the RF gun with full beam parameters for several weeks continuously to make sure no hidden problems arise.

R4.4: Continue to work on temporal pulse shaping to allow higher bunch charges and smaller energy spreads.

R4.5: Work on any new gun or laser ideas and R&D paths with a lower priority.

Plan

- 2019 summer: Improve stability of laser system and performance of photocathode
- 2020 summer (2019 winter): Improve the quality of electron beam
  - Laser pulse temporal reshape: rectangular pulse shape
  - Laser pulse spatial reshape: flat-top beam pattern

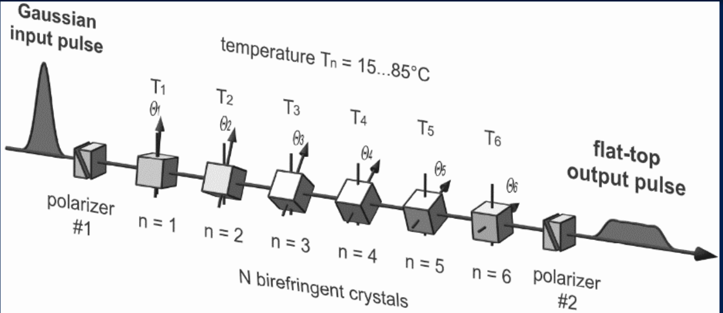
Updates in 2019 Summer

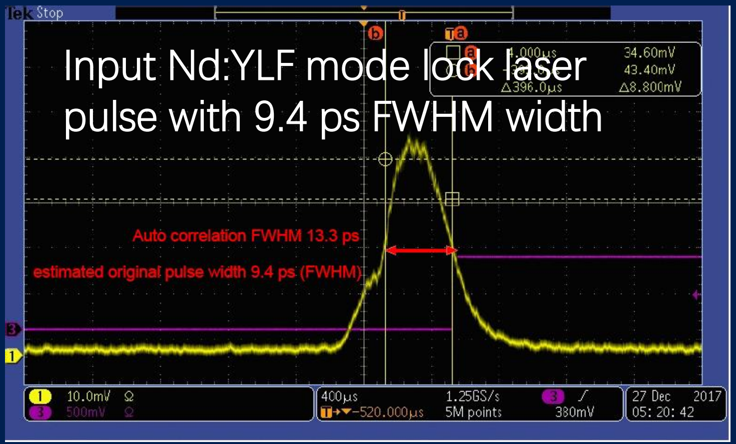
- Install new Menlo fiber oscillator
- Rebuild transporting line by use of relay imaging system
- Improve temperature stability in the laser hut
  - Water cooling for optics table
  - Exchange powerful air-conditioner
  - Add insulation layer for the west wall of laser hut
- Realize real time UV laser beam profile monitor
  - Available during continuous injection

Updates in 2020

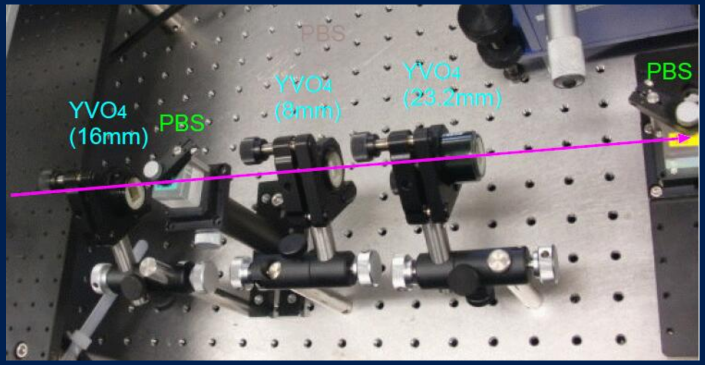
- Temporal reshape: Pulse stacking for low energy spread

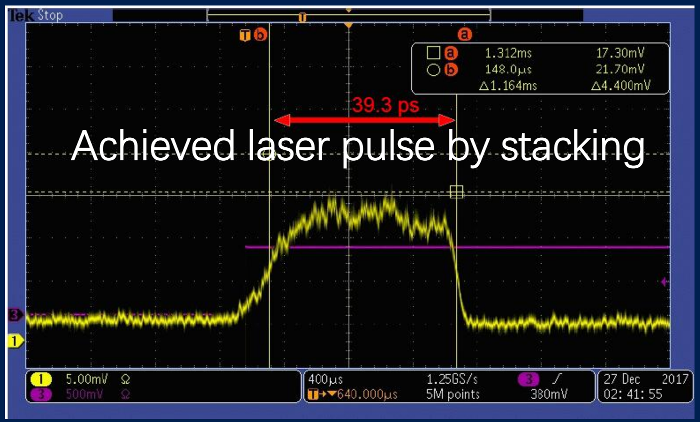
Input laser pulse with temporal Gaussian shape (FWHM~10 ps) → Pulse stacking setup made by a crystal array (birefringent effect of crystal) → Output laser pulse with temporal rectangular shape (FWHM~40 ps)





Two stages stacking system made by YVO_4 crystals

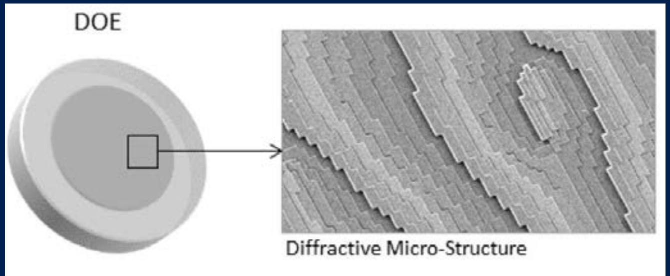




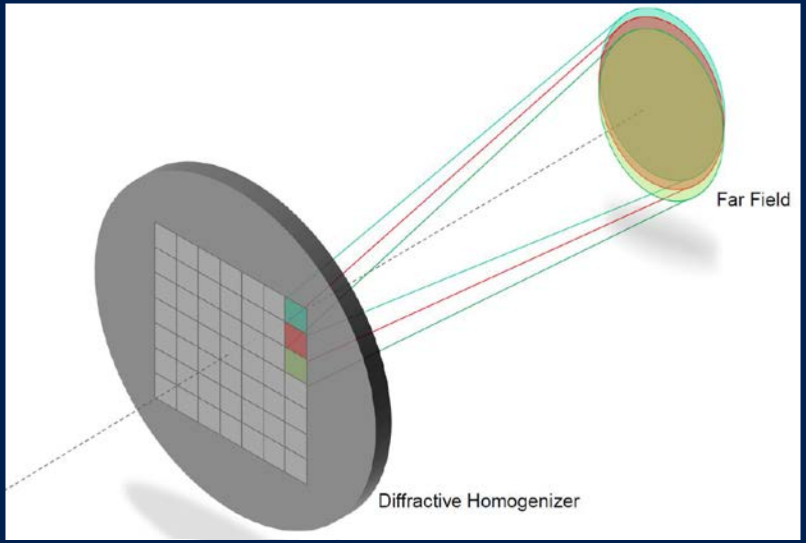
* Supported by Dr. Yosuke Honda

Updates in 2020

- Spatial reshape: Diffractive optics element (DOE) for low energy spread and emittance

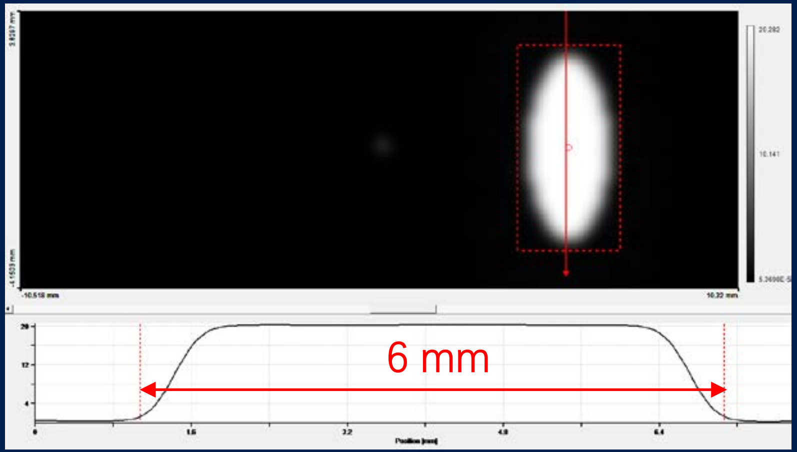


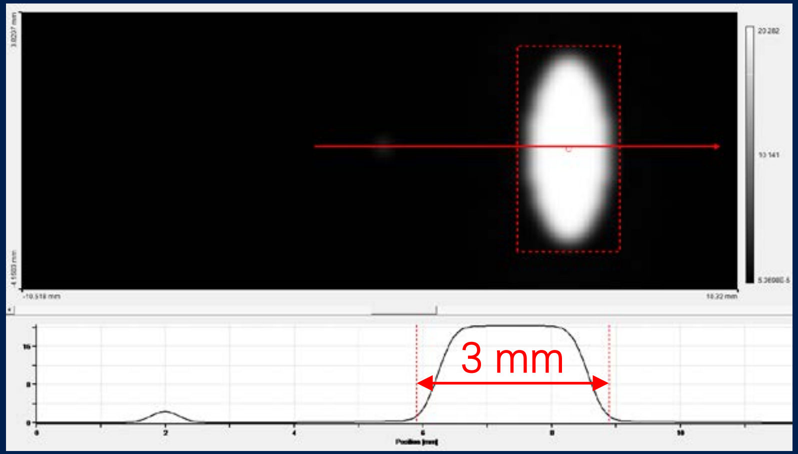
DOE with micro configuration as homogenizer



The homogenization is obtain with the sum of the N*N sub-elements contributions

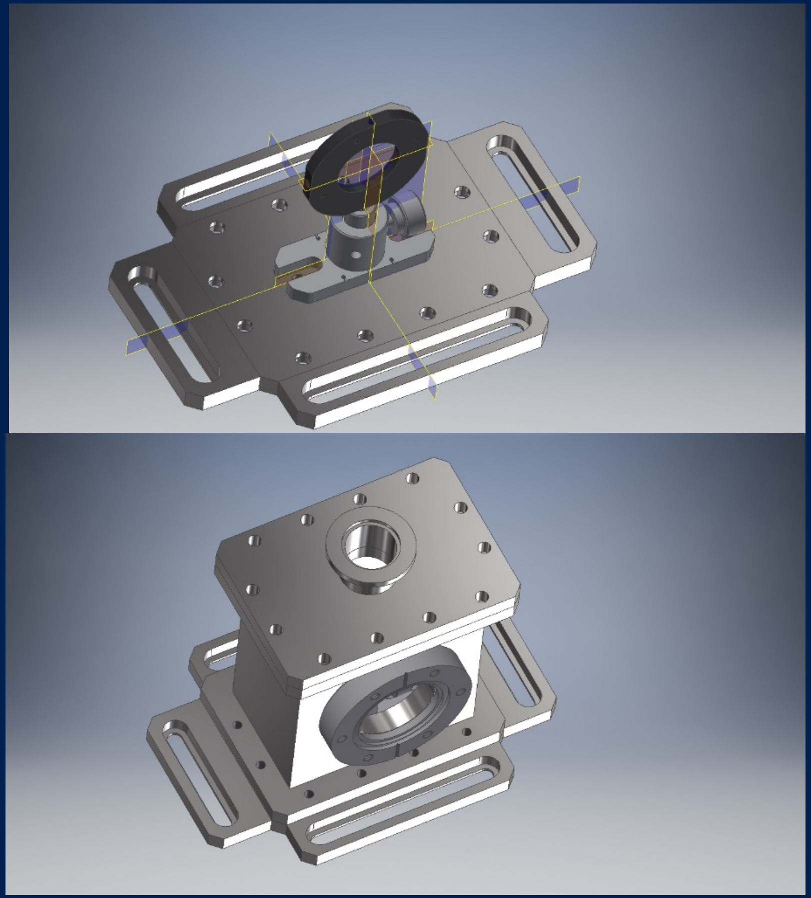
Simulation results: elliptical beam pattern

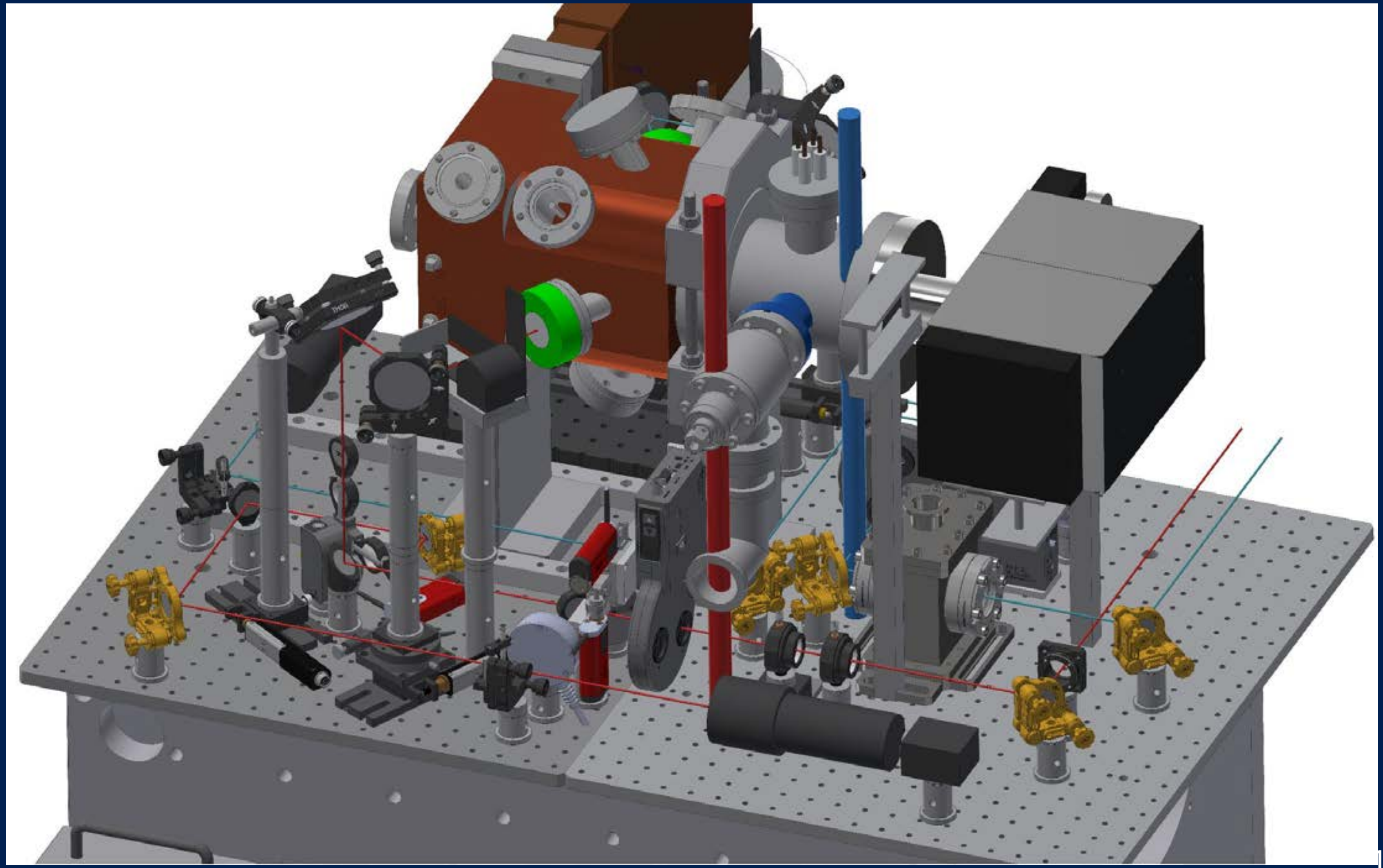




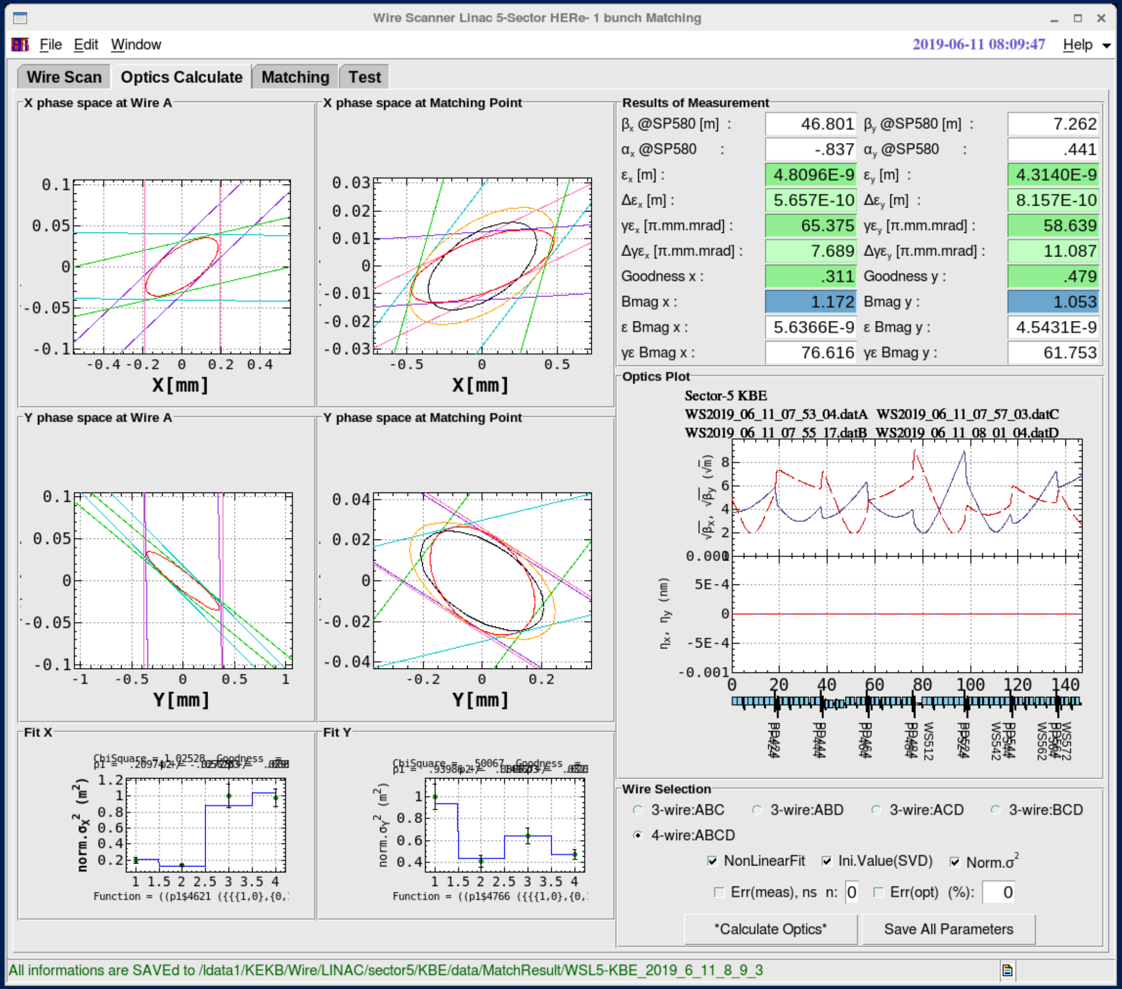
Updates in 2020

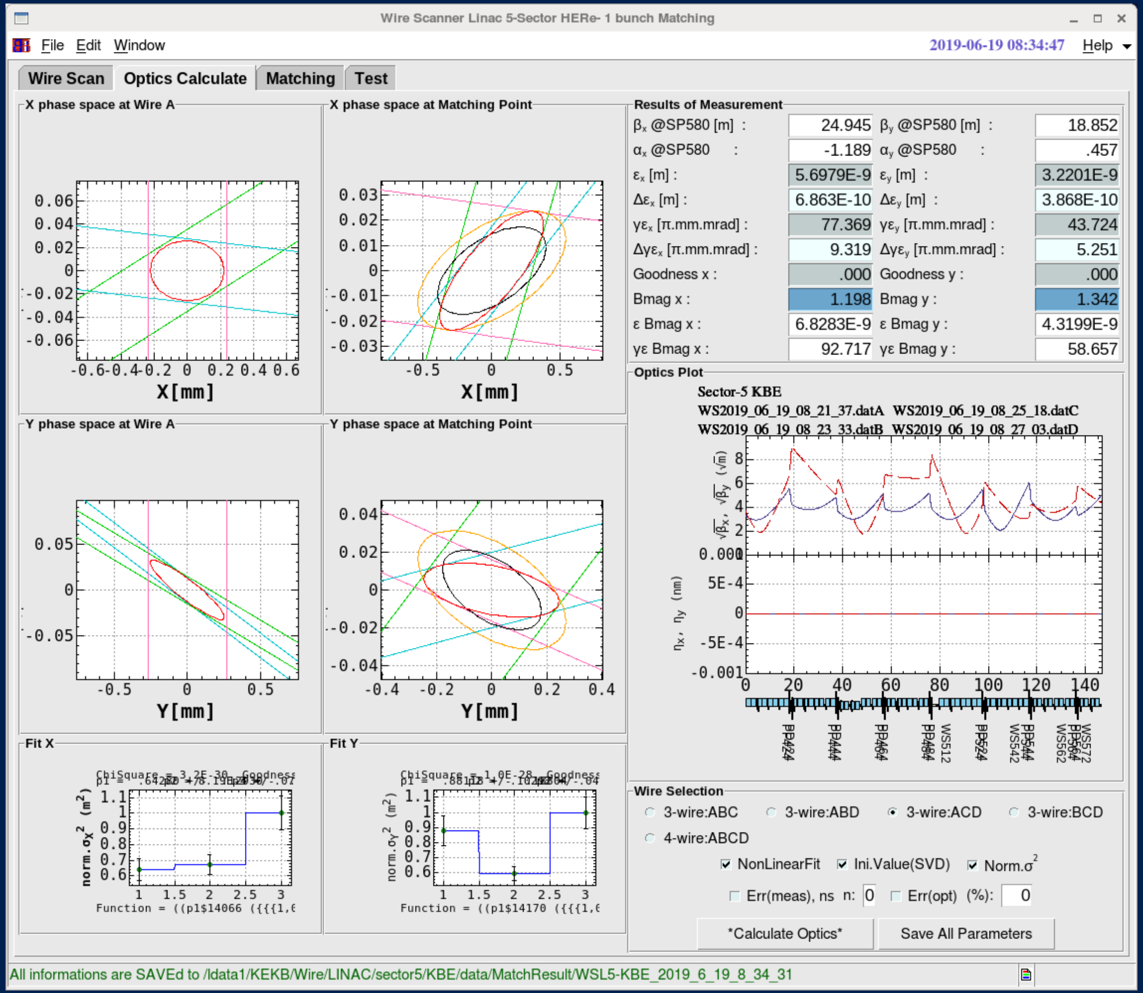
- Transverse reshape (spatial domain): Diffractive optics element (DOE)
  - Two pieces of DOE are purchased (delivery date is September)
  - One will be used for testing in 2020



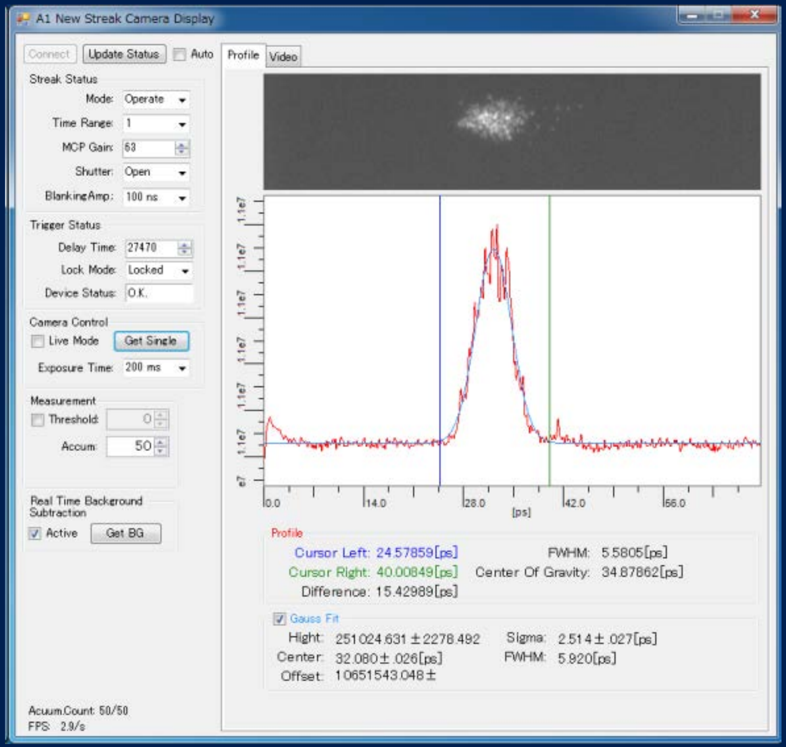


Wire Scanner Result @ 5 Sector

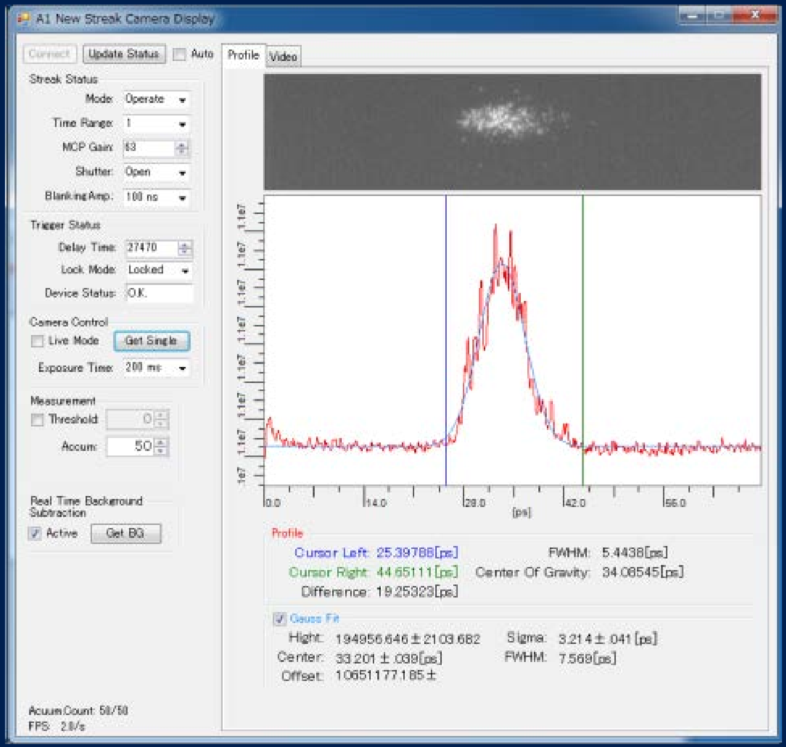




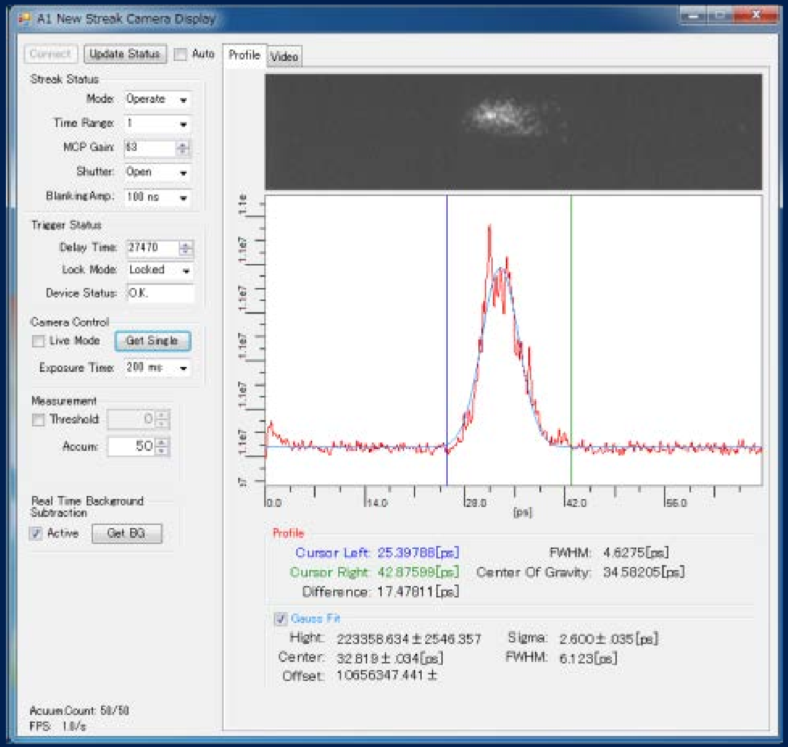
Streak Camera Test Data by 2 Lasers



2 lasers mode



1st laser



2nd laser

Statistics

SKEKB 運転中の期間

	レーザー運転時間			故障																				MTBF (h)	MTTR (h)	稼働率 (%)
				発振器		Fiber		1st Line		2nd Line		1st/2nd 共通部		制御関連		Trig 信号関連		RF 信号関連		設備		合計				
	運転期間 (h)	停止時間 (h)	運転時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	総故障回数	総故障時間 (h)			
3/11 09:00 ～ 3/18 09:00	168	0	168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	168.0	0.0	100.0
3/18 ～ 3/25	168	0	168	1	1.2	0	0	0	0	0	0	0	0	2	3.63	0	0	0	0	0	0	3	4.83	56.0	1.6	97.2
3/25 ～ 4/1	168	1.17	166.83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	166.8	0.0	100.0
4/1 09:00 ～ 4/4 16:00	79	0	79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79.0	0.0	100.0
4/17 14:00 ～ 4/22 09:00	115	0	115	0	0	0	0	1	22	0	0	0	0	0	0	0	0	0	0	0	0	1	22	115.0	22.0	83.9
4/22 09:00 ～ 5/6 09:00	336	3.23	332.77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	332.8	0.0	100.0
5/6 ～ 5/13	168	0	168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	168.0	0.0	100.0
5/13 ～ 5/20	168	4.1	163.9	1	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.4	163.9	0.4	99.8
5/20 ～ 5/27	168	1.15	166.85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	166.9	0.0	100.0
5/27 ～ 6/3	168	1.5	166.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	166.5	0.0	100.0
6/3 ～ 6/10	168	0	168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	168.0	0.0	100.0
6/10 ～ 6/17	168	2.08	165.92	1	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0.5	165.9	0.5	99.7
6/17 ～ 6/24	168	0	168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	168.0	0.0	100.0
6/24 ～ 7/1	168	0	168	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	168.0	0.0	100.0
合計	2378	13.23	2364.77	3	2.1	0	0	1	22	0	0	0	0	2	3.63	0	0	0	0	0	0	6	27.73	394.1	4.6	98.8

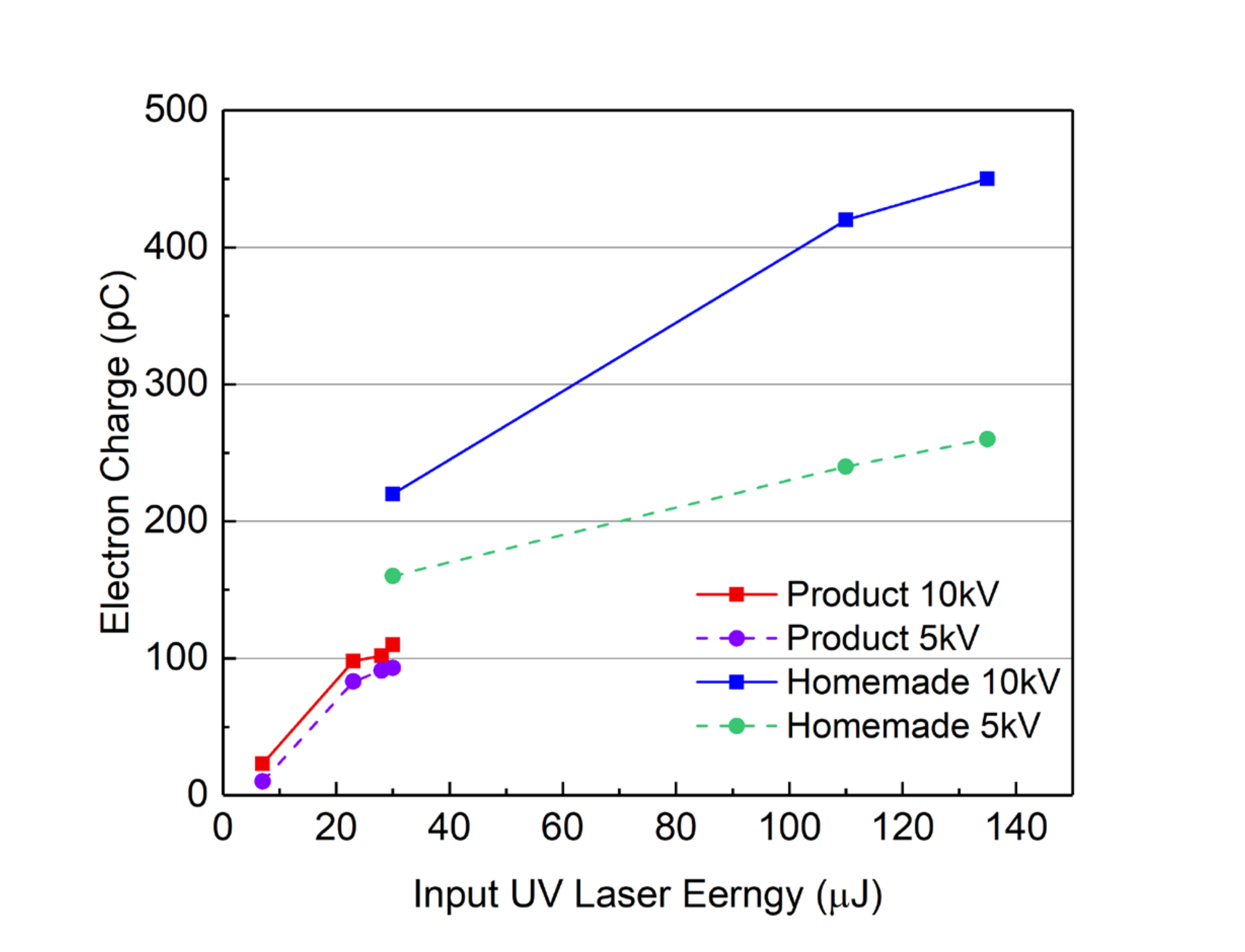
Linac 運転全期間

	レーザー運転時間			故障																				MTBF (h)	MTTR (h)	稼働率 (%)
				発振器		Fiber		1st Line		2nd Line		1st/2nd 共通部		制御関連		Trig 信号関連		RF 信号関連		設備		合計				
	運転期間 (h)	停止時間 (h)	運転時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	回数	故障時間 (h)	総故障回数	総故障時間 (h)			
2/4 09:00 ～ 7/1 09:00	3218	37.91	3180.09	5	2.27	0	0	4	229.72	5	47.45	0	0	2	3.63	0	0	1	1.57	3	8.55	20	293.19	159.0	14.7	91.6

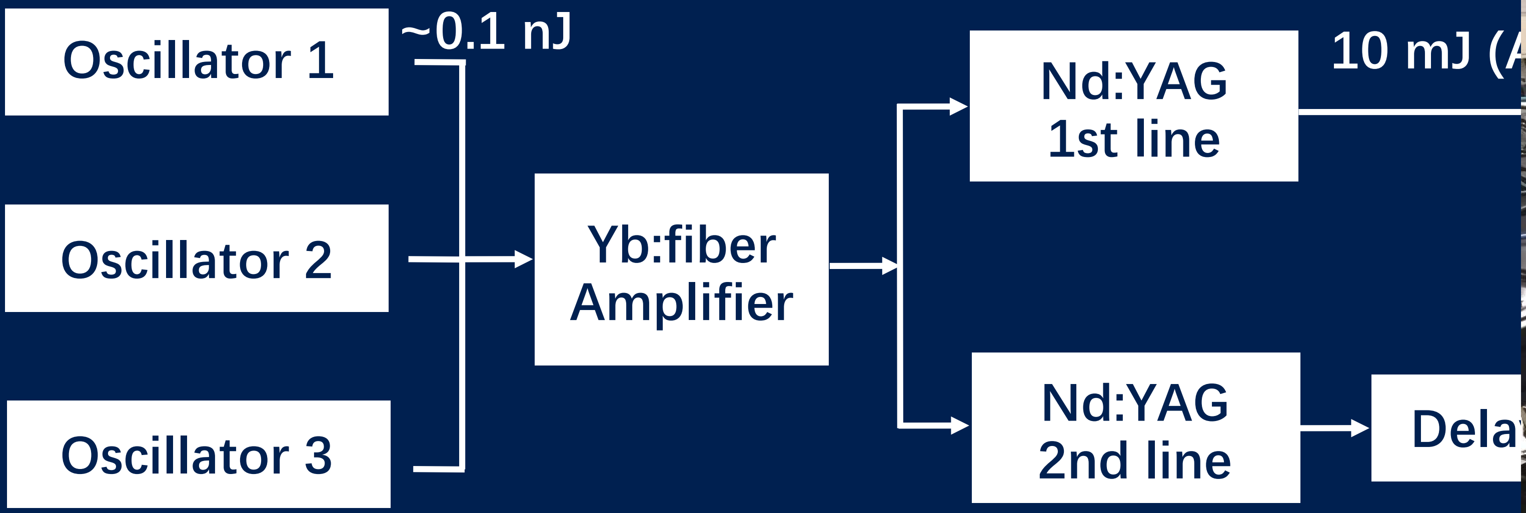
発振器		1st Line		2nd Line		制御関連		RF 信号関連		設備	
########	同期外れ	########	EO軌道変動	########	EO軌道変動によるNDYAG1減少	########	制御用IOC停止	########	10MHz 変1	########	ハット内温度上昇
########	同期外れ	########	NDYAG3 出	########	EO軌道変動によるNDYAG1減少	########	制御用IOC停止			########	ハット内温度上昇
########	114MHz IQ 位相ずれ	2019/3/4	NDYAG3故	########	EO軌道変動による復旧調整					2019/3/3	ハット内温度上昇
########	同期外れ	########	NDYAG3故	2019/3/9	NDYAG1出力変動						
########	地震による114MHz IQ ずれ			2019/3/9	NDYAG1故障						

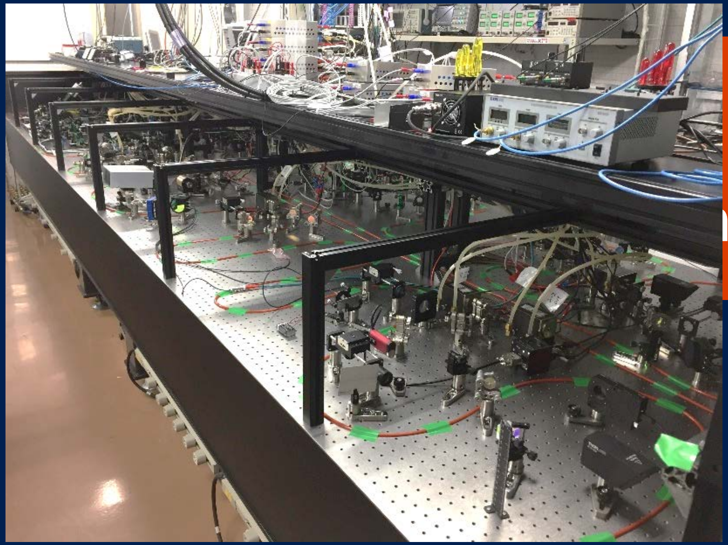
MTBF (Mean Time Between Failure、平均故障間隔) MTTR (Mean Time To Repair、平均修理時間)
稼働率 = MTBF ÷ (MTBF+MTTR)

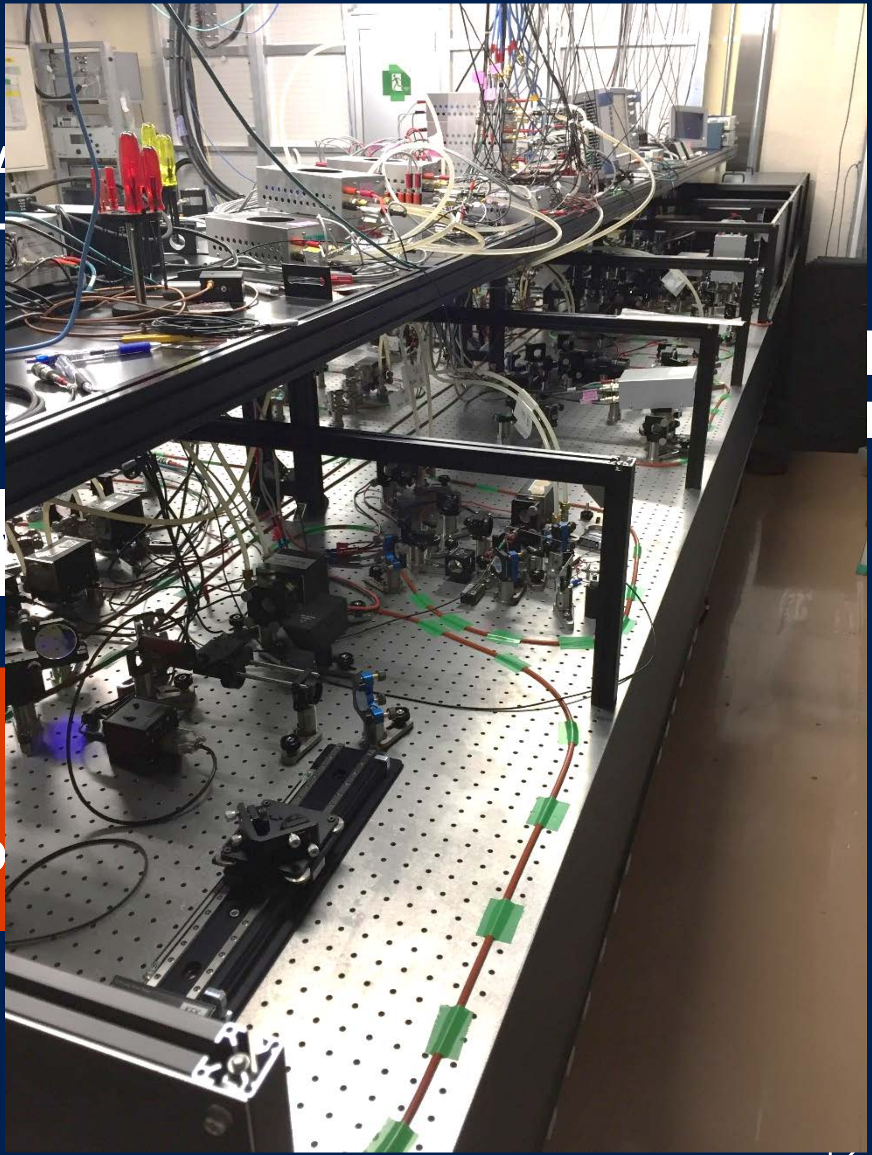
Ir_2Ce: Simple Test Result



Yb:fiber/Nd:YAG laser in Phase II





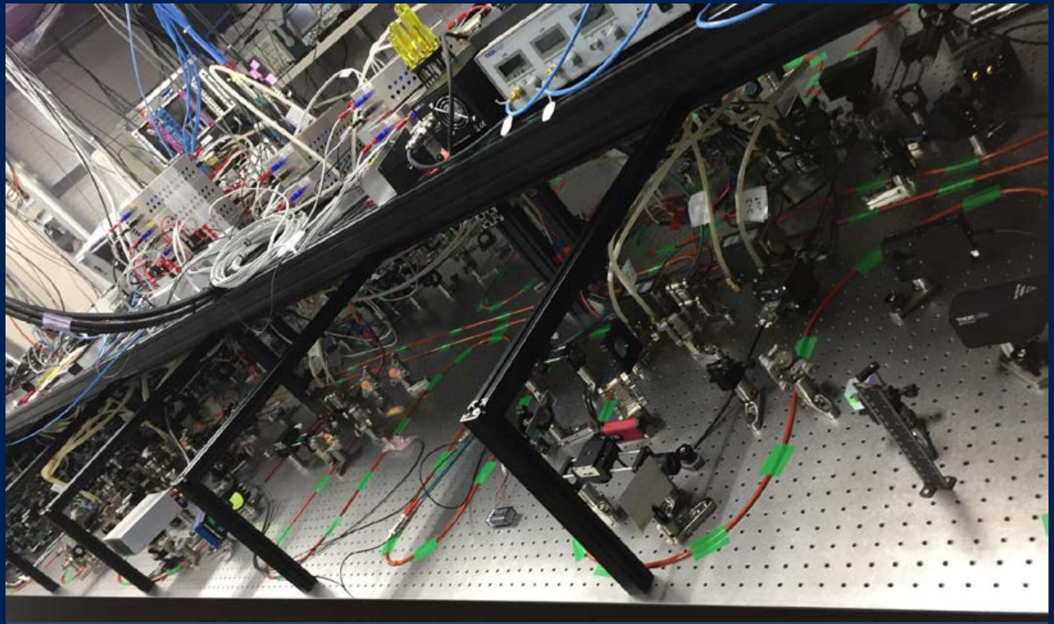


n

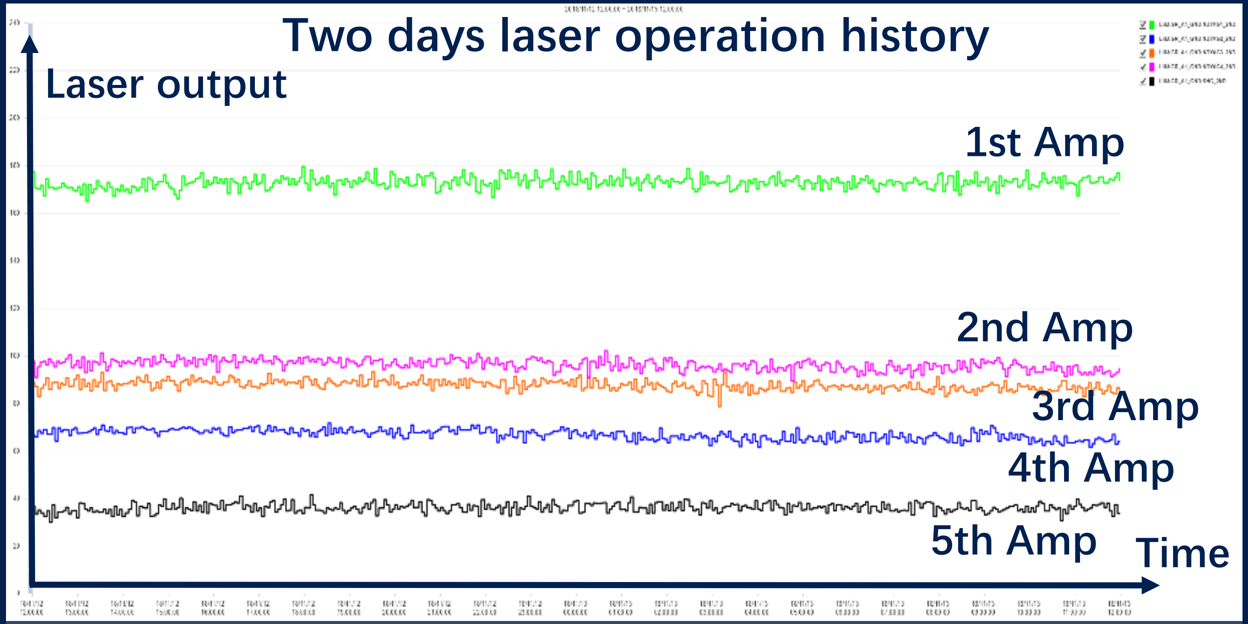
e o

Improvement of e⁻ Stability in Phase III

Stable e⁻ → Improved the laser stability by water cooling for optics table



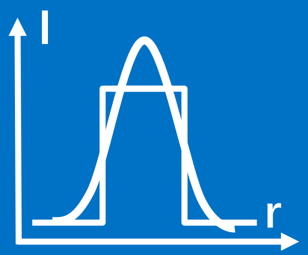
- Temperature stability for laser environment
- Flexible silicon tube for cooling



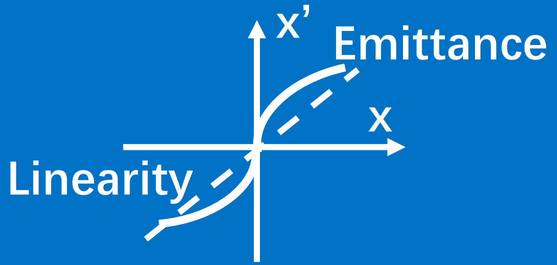
- Better stability for long time laser operation (fluctuation<5%)
- Less adjustment for continuous e⁻ generation

For High Quality e⁻

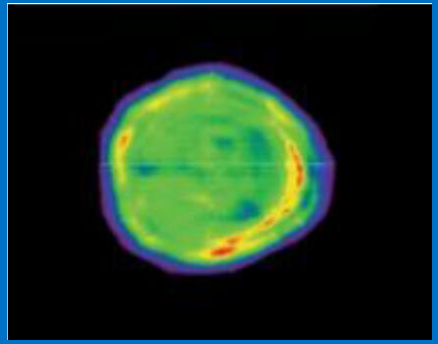
Laser Spatial Reshaping

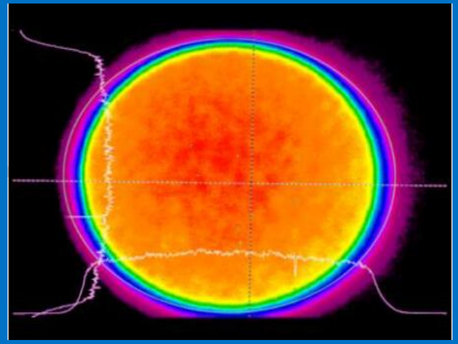


Laser spatial distribution



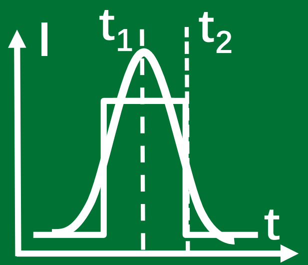
Phase space



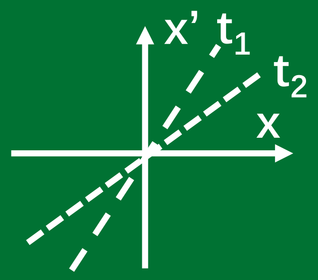


- Laser beam shaper for flat-top
- For Nd and Yb laser
- Under purchasing

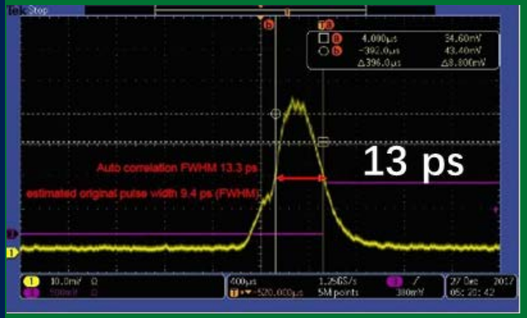
Laser Temporal Reshaping

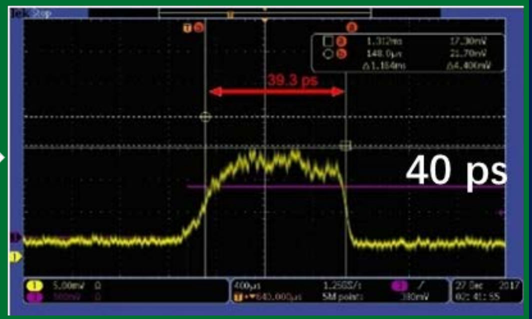


Laser spatial distribution



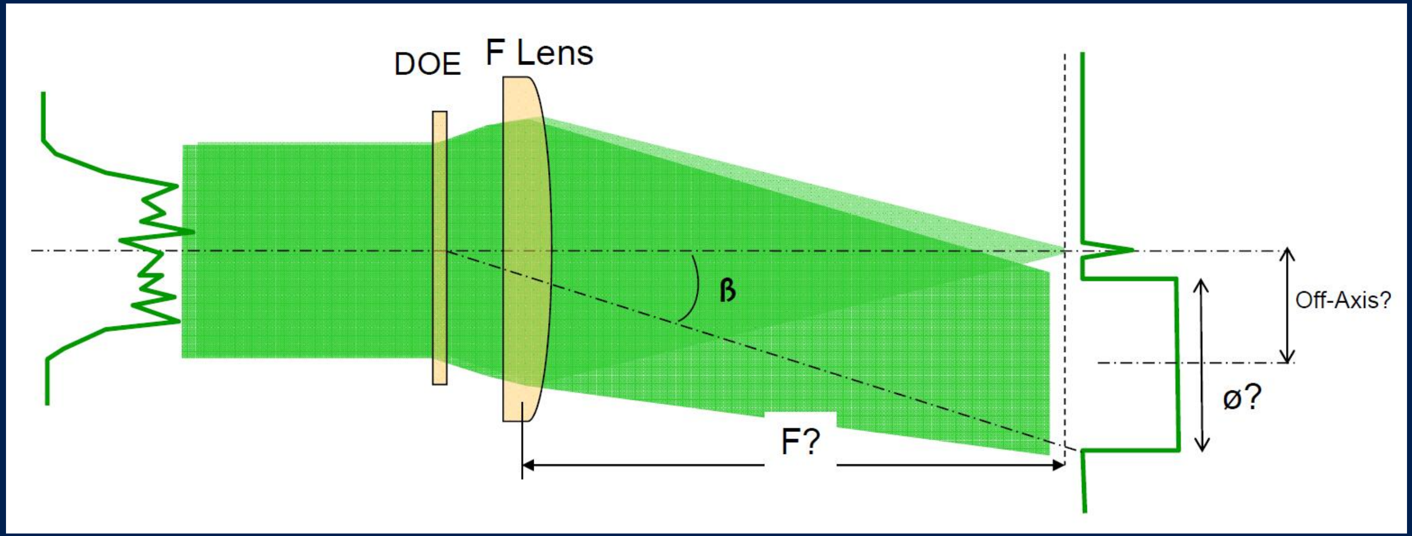
Phase space

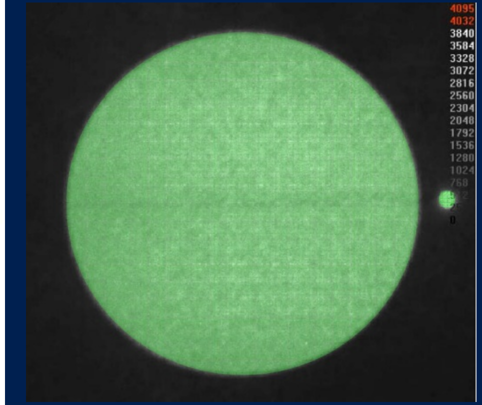




- Pulse stacking by birefringent crystals
- Demonstrated in Nd laser
- Will be used in Yb:YAG laser for real flat

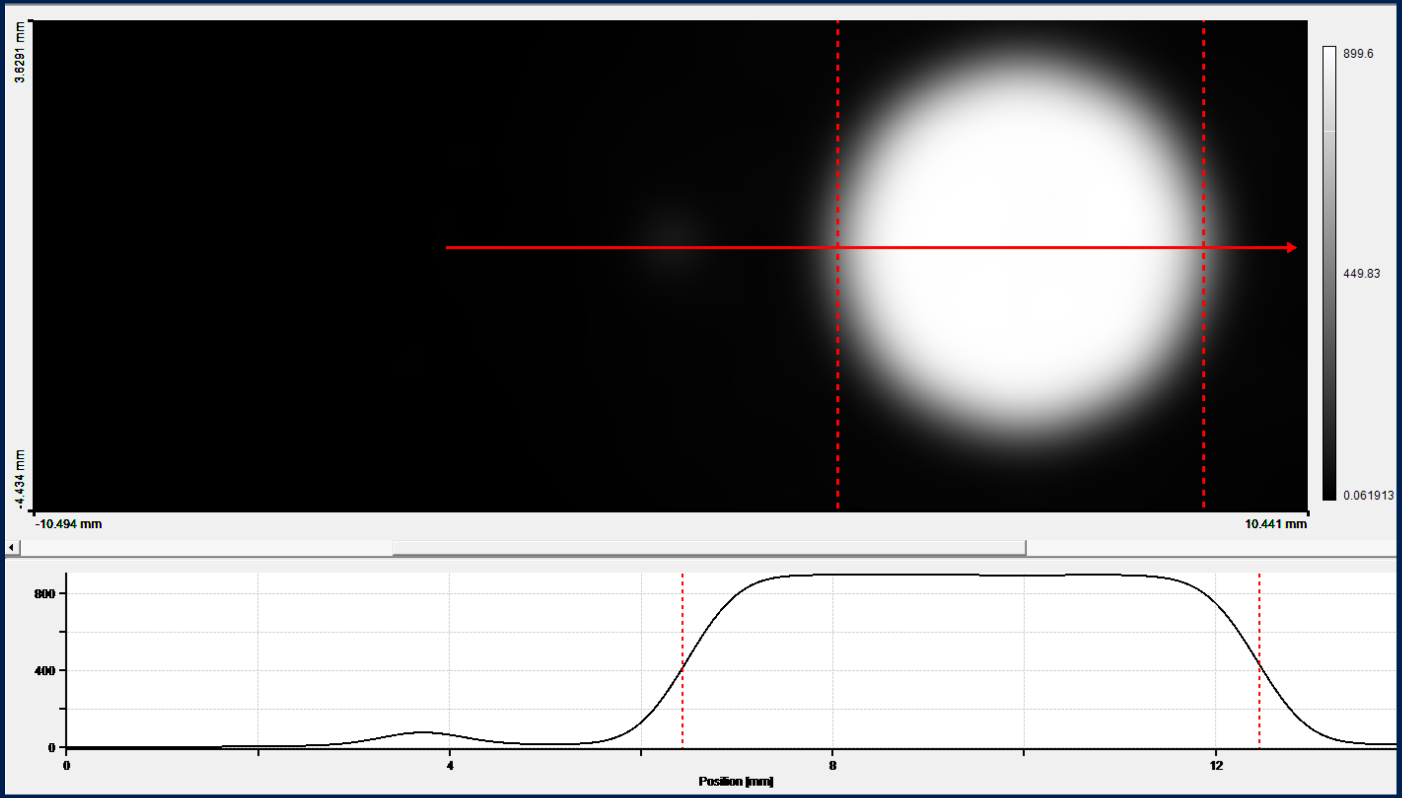
Beam homogenizer



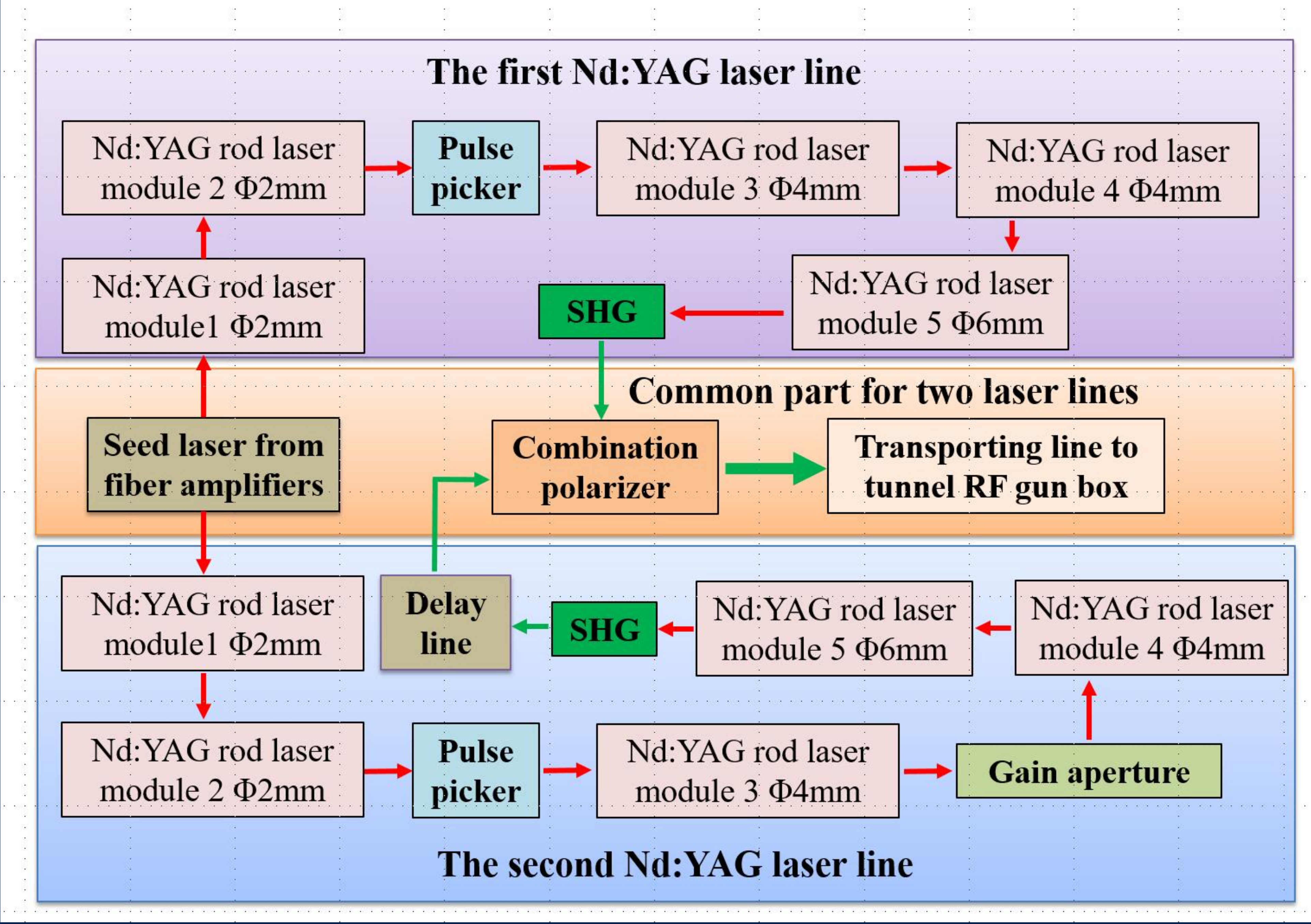


- F: 1 m (Focal length of F lens)
- Φ: 6 mm (on target surface)
- Off-axis: 6 mm (distance between optical axis and center of target spot)
- $\beta \approx 1^{o}$

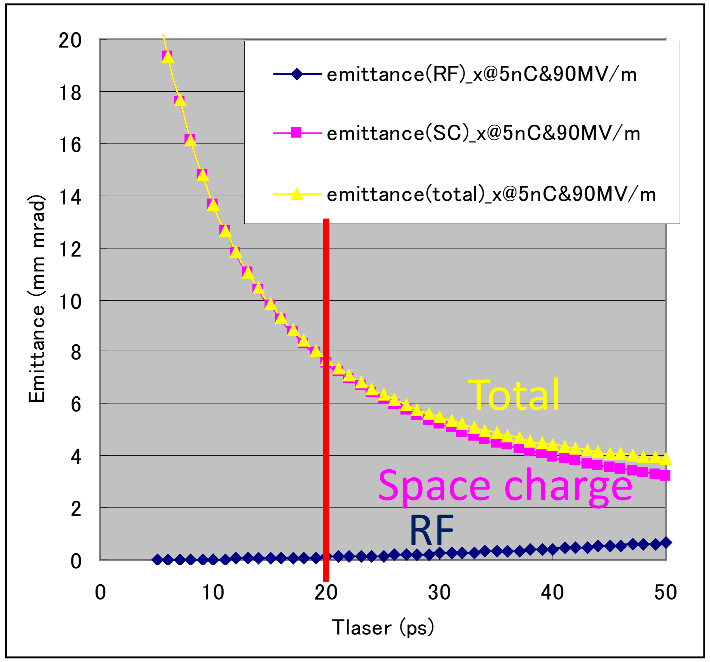
Beam homogenizer



- Simulation result
- peak to valley modulations on the top hat: ±10%~15%
- Transmitting rate> 80%


The first Nd:YAG laser line
Nd:YAG rod laser module 2 Φ2mm
Pulse picker
Nd:YAG rod laser module 3 Φ4mm
Nd:YAG rod laser module 4 Φ4mm
Nd:YAG rod laser module1 Φ2mm
SHG
Nd:YAG rod laser module 5 Φ6mm
Common part for two laser lines
Seed laser from fiber amplifiers
Combination polarizer
Transporting line to tunnel RF gun box
Nd:YAG rod laser module1 Φ2mm
Delay line
SHG
Nd:YAG rod laser module 5 Φ6mm
Nd:YAG rod laser module 4 Φ4mm
Nd:YAG rod laser module 2 Φ2mm
Pulse picker
Nd:YAG rod laser module 3 Φ4mm
Gain aperture
The second Nd:YAG laser line

RF-Gun for 5 nC

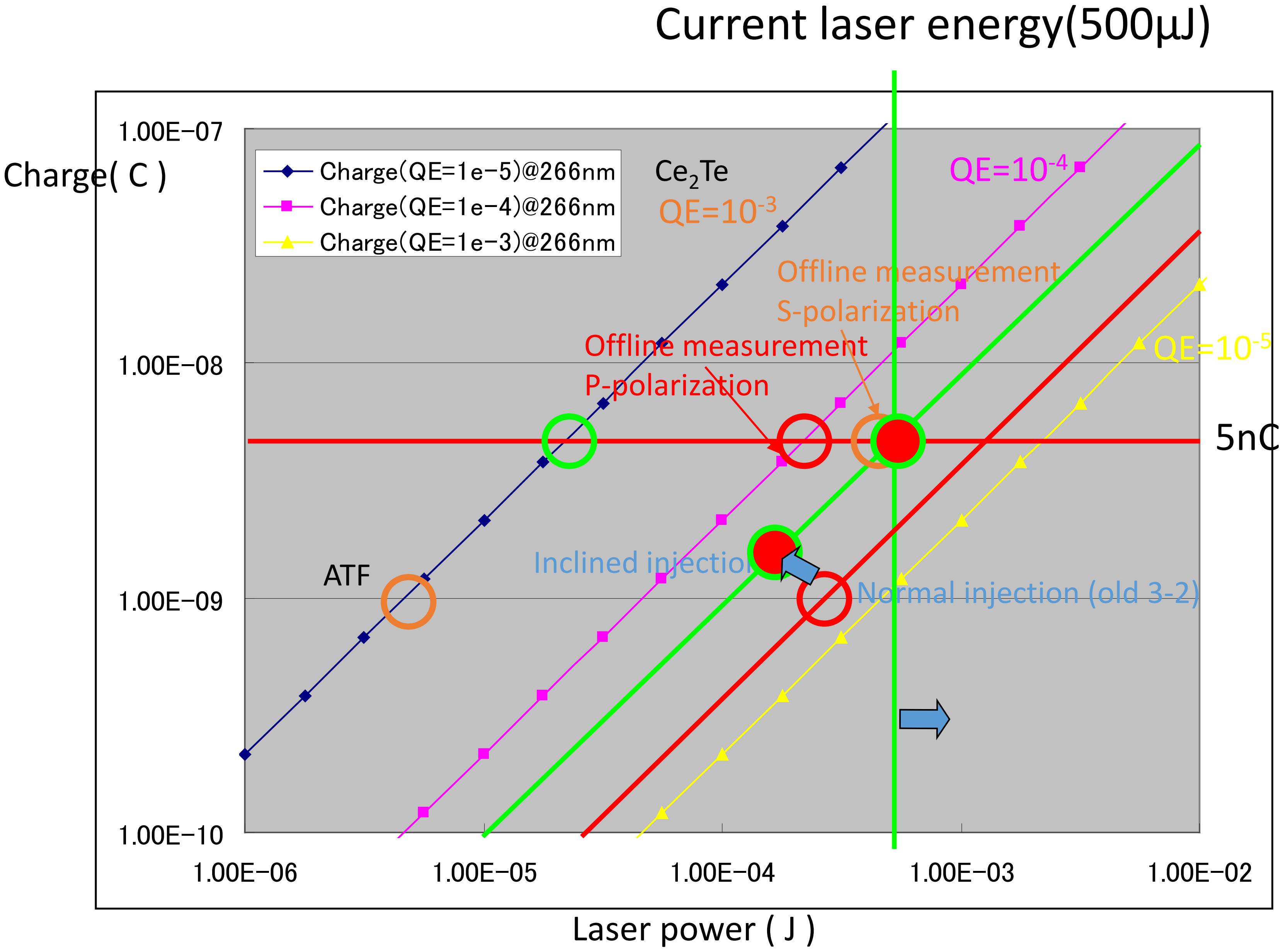


- Space charge is dominant.
  - Longer pulse length : 20 - 30 ps
- Stable operation is required.
  - Lower electric field : < 100MV/m
- Focusing field must be required.
  - Solenoid focus causes the emittance growth.
  - **Electric field focus preserve the emittance.**

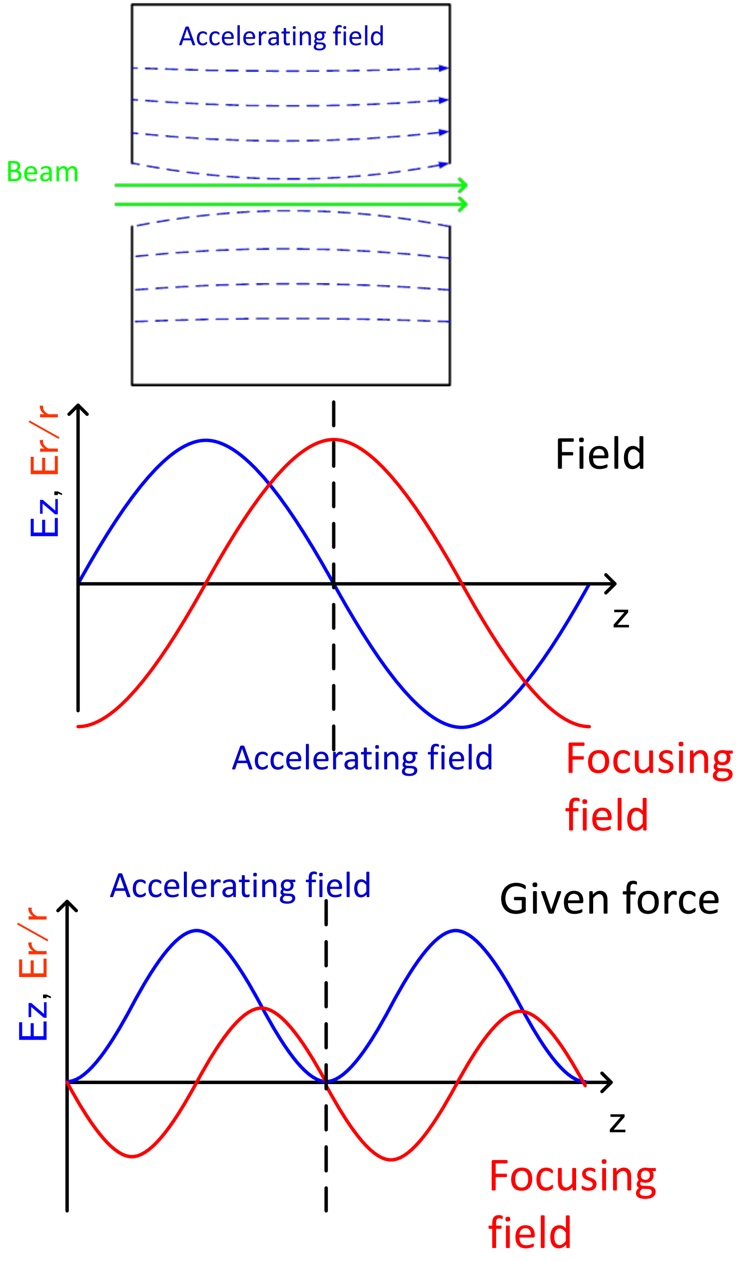
~~Epaxial coupled cavity~~ : BNL

Annular coupled cavity : Disk and washer / Side couple

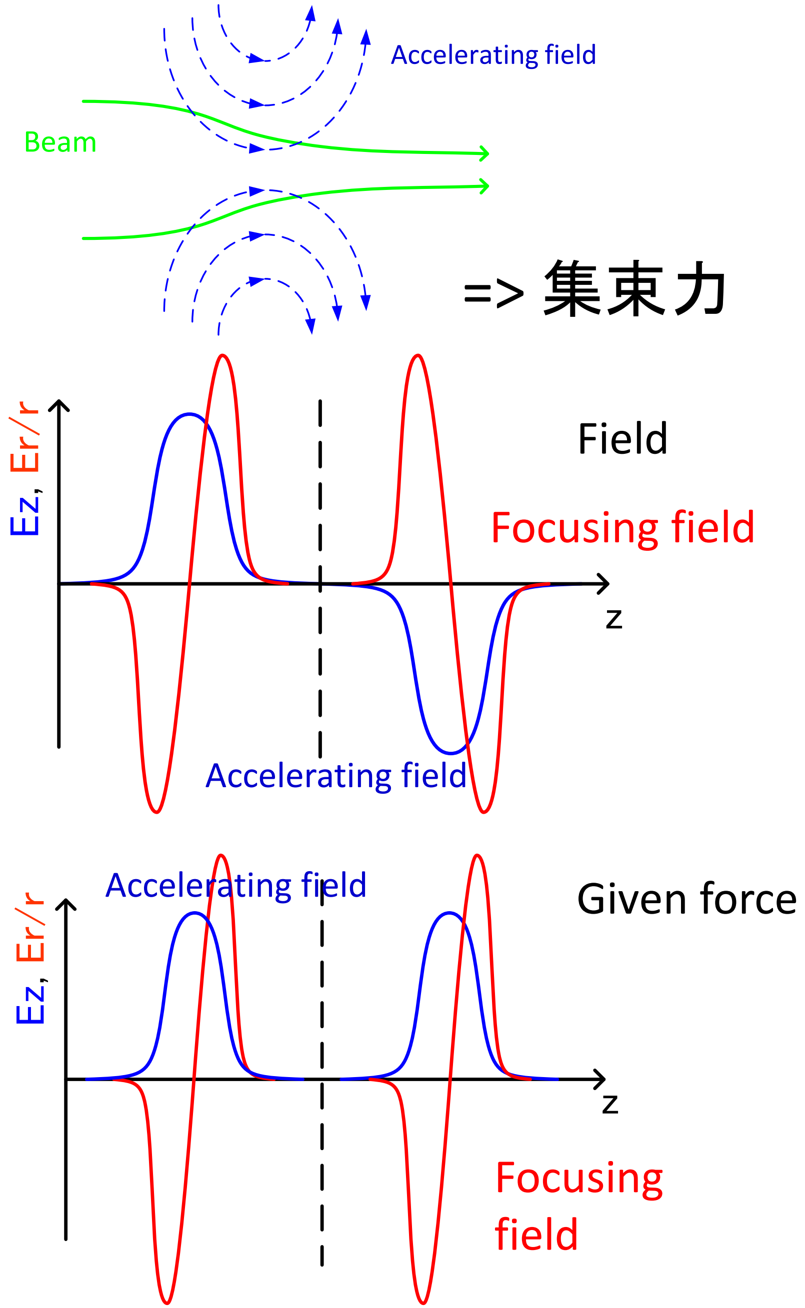
Required laser pulse energy



Pill-box cavity

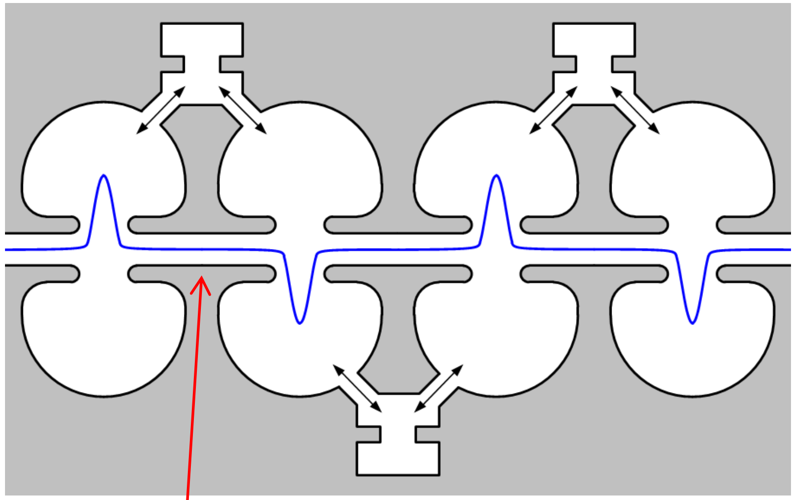


Annular coupled cavity with nose

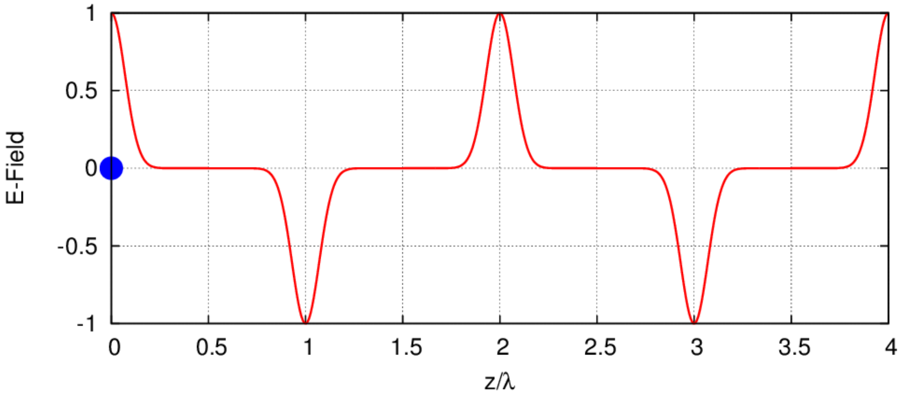


Design of a quasi traveling wave side couple RF gun

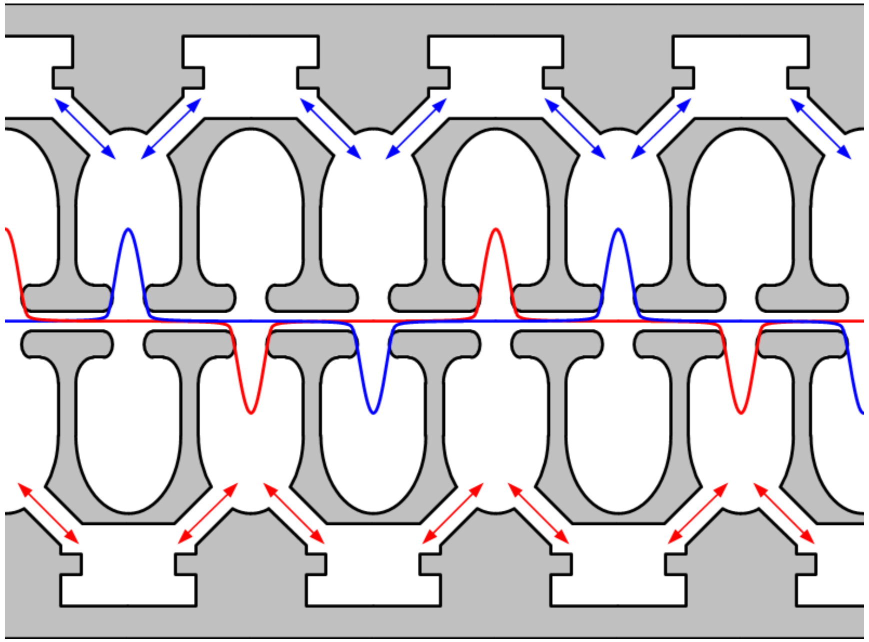
Normal side couple structure

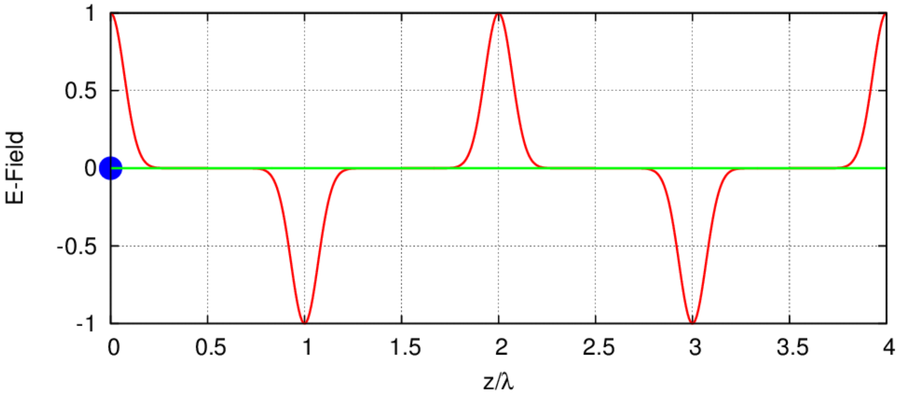


Long drift space is problem.



Quasi traveling wave sidecouple structure

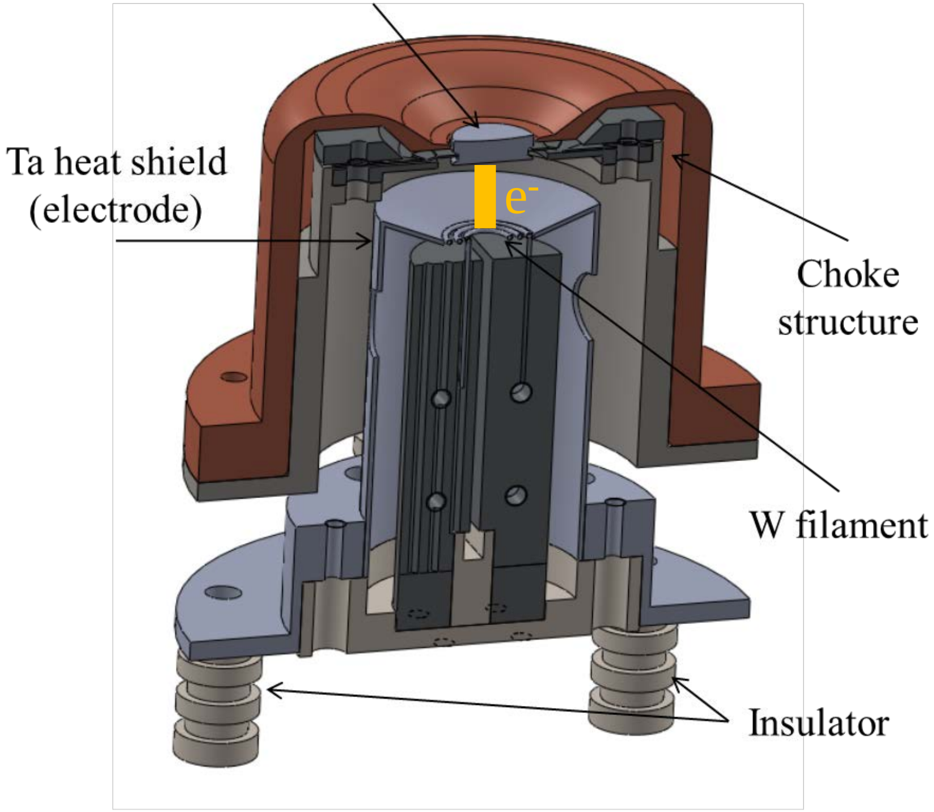




Quasi traveling wave side couple has stronger focusing and accelerated gradient than DAW.

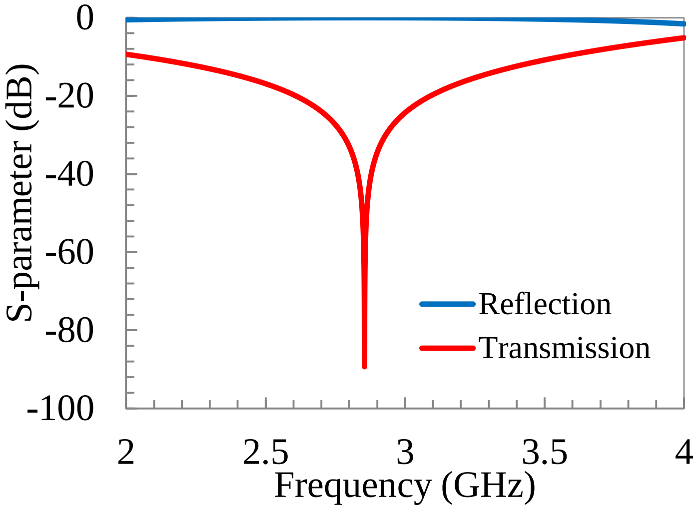
Electron beam (EB) heating type cathode plug

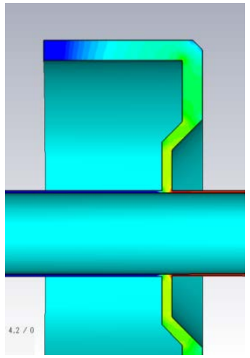
【Design of EB heating type cathode plug】



EB heating is …
a main cathode is bombarded by an accelerated electron beam as a thermal source behind the cathode.

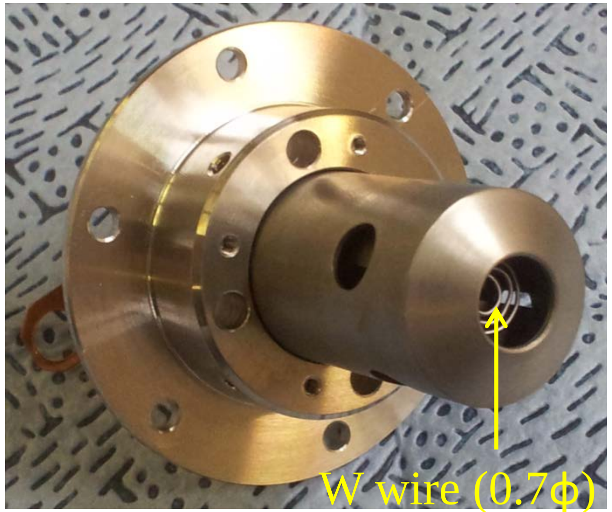
【 RF shielding structure 】

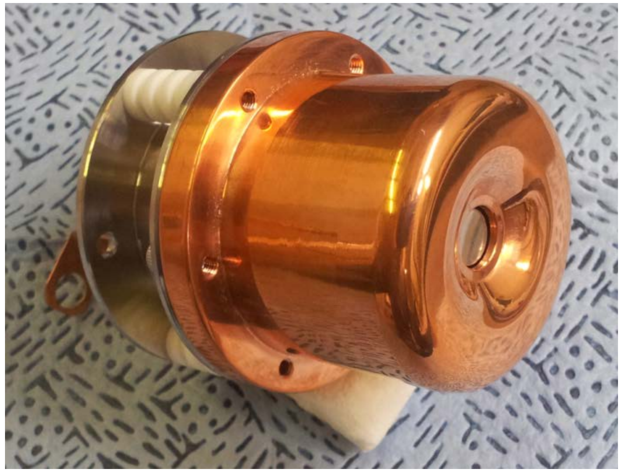




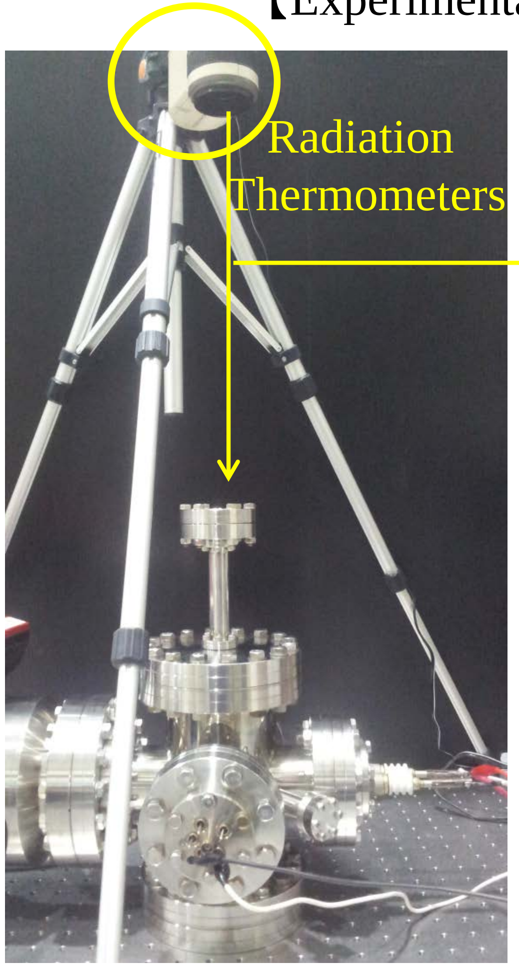
Heating Test

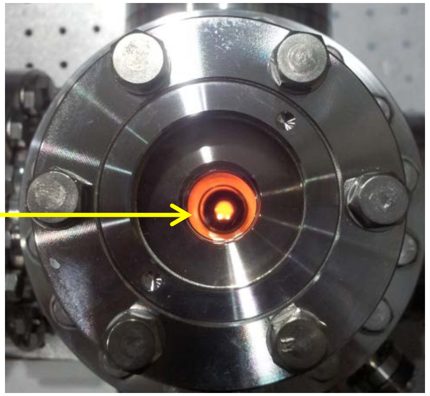
【Cathode plug】





【Experimental Setup & Results】



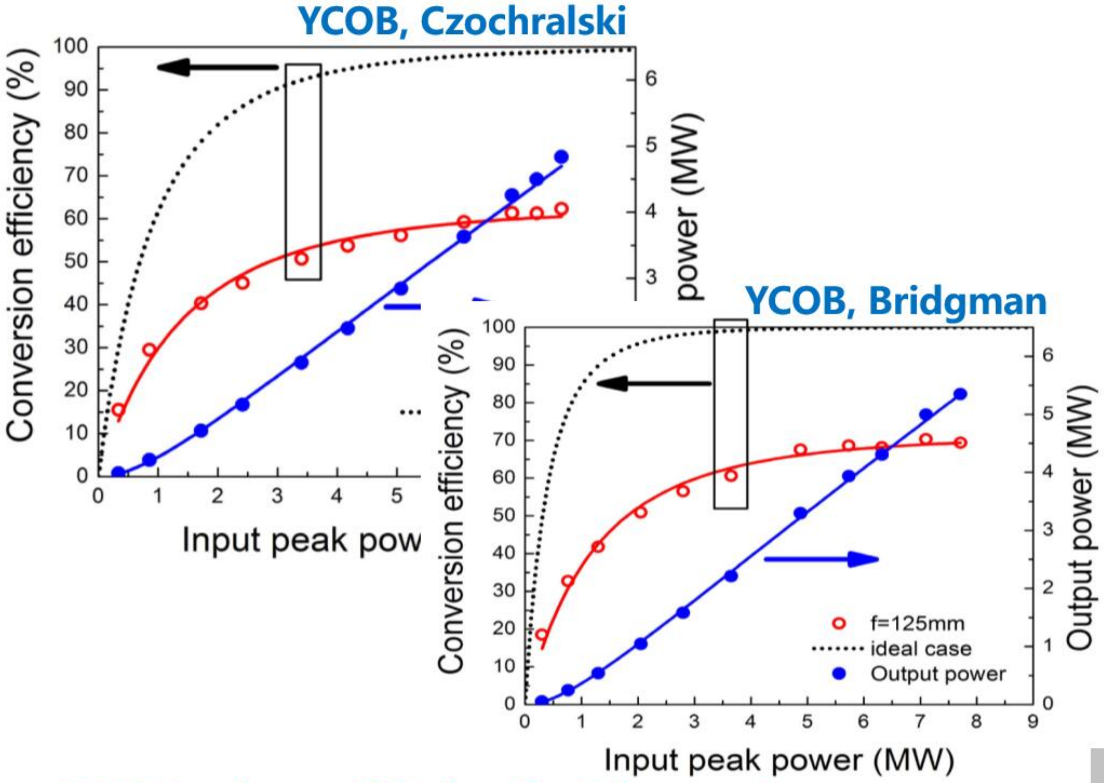


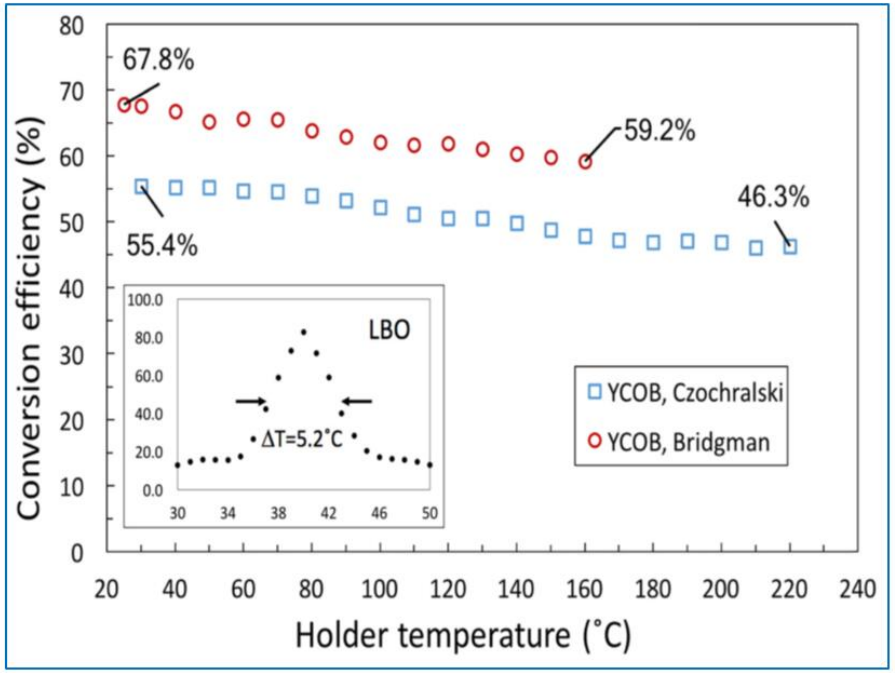
Heater Current (A)	16
Heater Voltage (V)	3.38
Intermediate electrode (V)	-25
High Voltage (kV)	2.3
Beam current (mA)	23
Beam Power (W)	**52.9**
Surface Temperature (degC)	**1029**

Heating a photocathode over 1000°C by EB heating method was succeeded.

3、Characterization

——SHG experiment at IMS





A. Kausas, et al, OE. 25(2017) 6431

- **2017, Institute of Molecular Sciences, Japan**
- Czochralski：5mm×5mm，（31°, 180°）; Bridgman：16mm×16mm，（30.5°, 180°）;
- Efficiency of Cz crystal：62.4%、**Bridgman crystal : 70.2%（1.14 mJ, 223 ps）;**
- Temperature tuning properties of YCOB crystals, the temp. coefficient is -0.057%/℃ and-0.064 %/℃.

Phase II Nd laser module