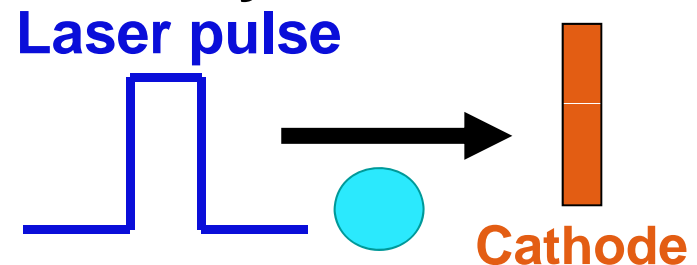


# ALTERNATIVE SCHEME FOR POLARIZED ELECTRON SOURCE WITHOUT USING NEA-SURFACE

Hiromitsu TOMIZAWA  
JASRI/SPring-8

**Background:** The next generation X-ray light sources (**X-FEL**, **ERL**) require electron beams with very low emittance (high brightness source).



**Photocathode:** One of the most reliable candidates for this high-brightness & **polarized electron source (ILC)**

# History of SPring-8 Photocathode RF Gun

1996 Study of photocathode RF guns started.

1999 First beam test with YLF laser system

2001 New Ti:Sapphire laser system installed.

**All concepts of 3D-Laser shaping technologies** were proposed.

2002 Emittance  $2.3 \pi \text{mm mrad}$  @0.1 nC (pulse width: 5 ps) with homogenizing in Spatial profile (using Microlens array)



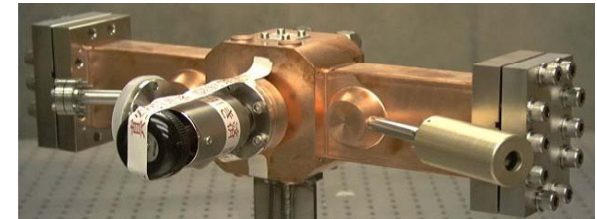
Cartridge type cathode (transparent) development started.

2003 New gun & laser test room (fully environmental control) constructed and an accelerating structure installed.

Fiber Bundle shaping for cathode backward illumination was demonstrated.



2004 Maximum field of  $190 \text{ MV/m}$  at cathode  
Laser was stabilized with 0.2%(rms @0.3TW fundamental), 1.4%(rms @THG; 263 nm), for 1.5 Month.



---

2005 3D-laser shaping system was completed (10 month continuously operated).

2006 Emittance  $1.4 \pi \text{mm mrad}$  @0.4 nC (pulse width: 10 ps) with “Beer can” laser pulse (Flat top SP (DM); Square TP (PS))



2007 Hollow beam incidence system with 3D-laser shaping was developed. Z-pol. gun was proposed (in 2006).



# Present status and future requirements for Photocathode Sys.

## Laser source:

**Compact & without Pulse Shaping**

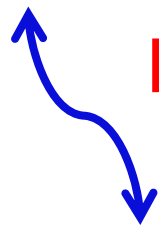
Laser Amplifier for high bunch charge & repetition rate

Large laser complex systems....

3D Laser Pulse Shaping for high brightness

Complicated systems.....

NEA-GaAs cathode: Polarized electron source



**Robust material & Adjustability**

High QE NEA surface cathode

Metal Cathode

It requires the ultra high vacuum ....

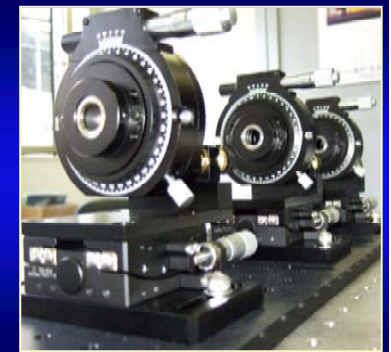
# SPring-8 Photocathode Laser source status

## A. We realized yearlong stable laser system

**Oscillator : 24 hours, 10 months, non-stop**

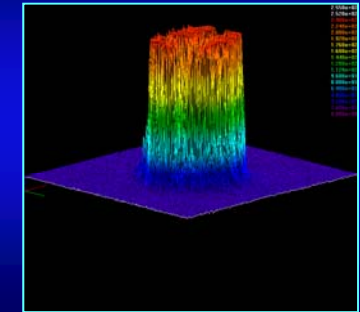
**TW- Amp. : 24 hours, 5 months, non-stop**

## THG: 1.4% rms stability



**B. Automatically shaping Spatial Profile with DM + GA was successful! (Gaussian or Flattop)**

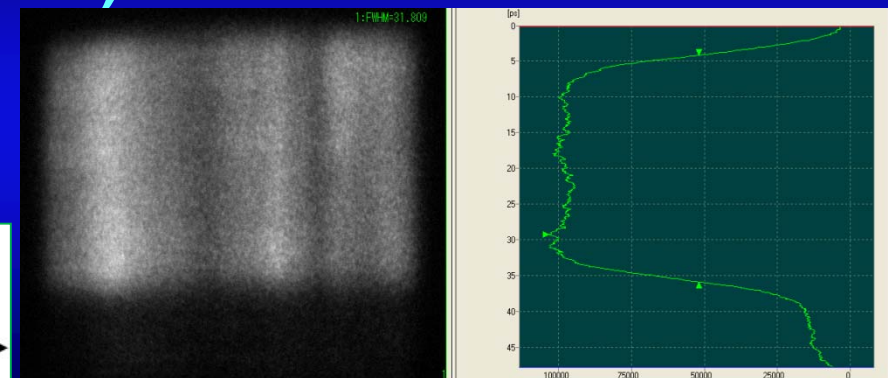
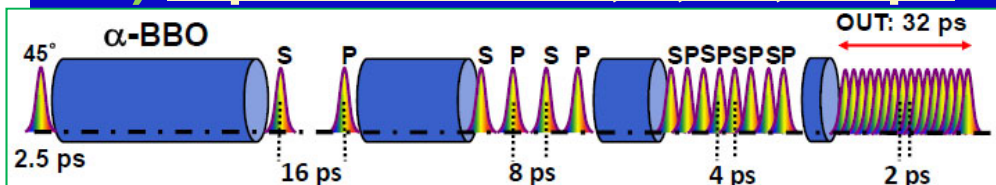
~ However, Laser profiler is damaging for yearlong continuous operation. (Uranium Glass + Camera)



**C. Square pulse generation with UV-pulse stacker (rods) was successful at THG (263 nm) !**

## 1) Square Pulse: 5, 10, 20 ps

## 2) Square Pulse: 4, 8, 16, 32 ps



# Characteristics of SPring-8 RFgun

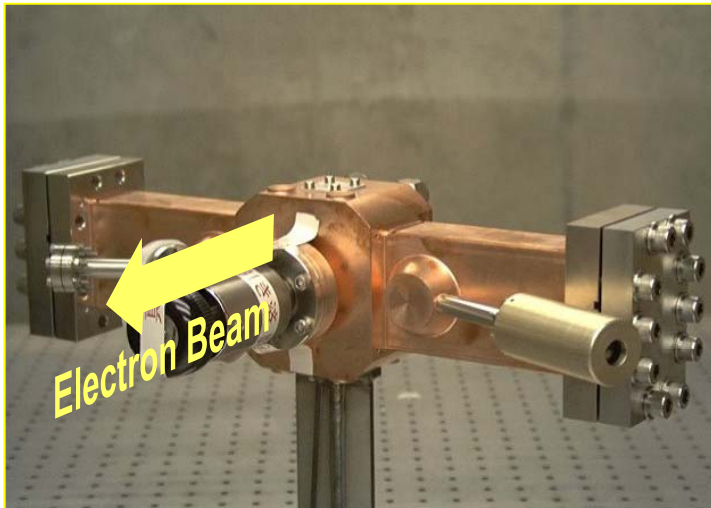
## 1. Laser

- **Spatial** profile control : **Deformable Mirror**
- **Temporal** distribution : **UV-pulse stacker**

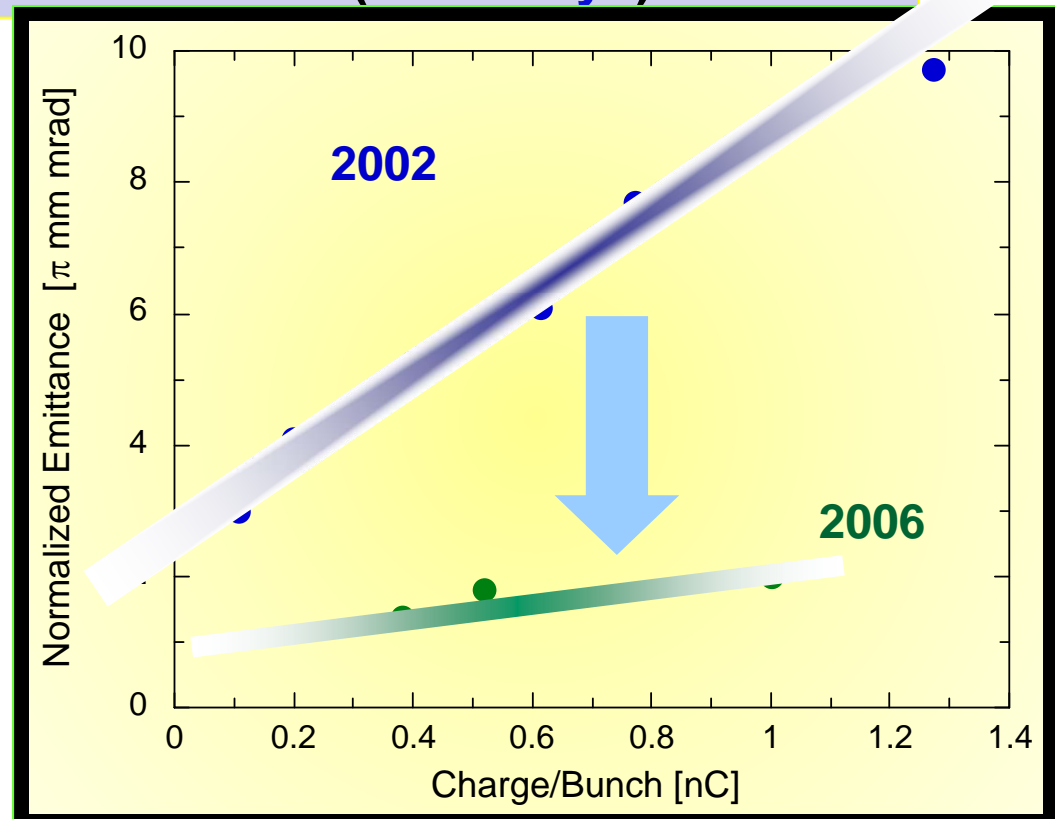


## 2. RF cavity

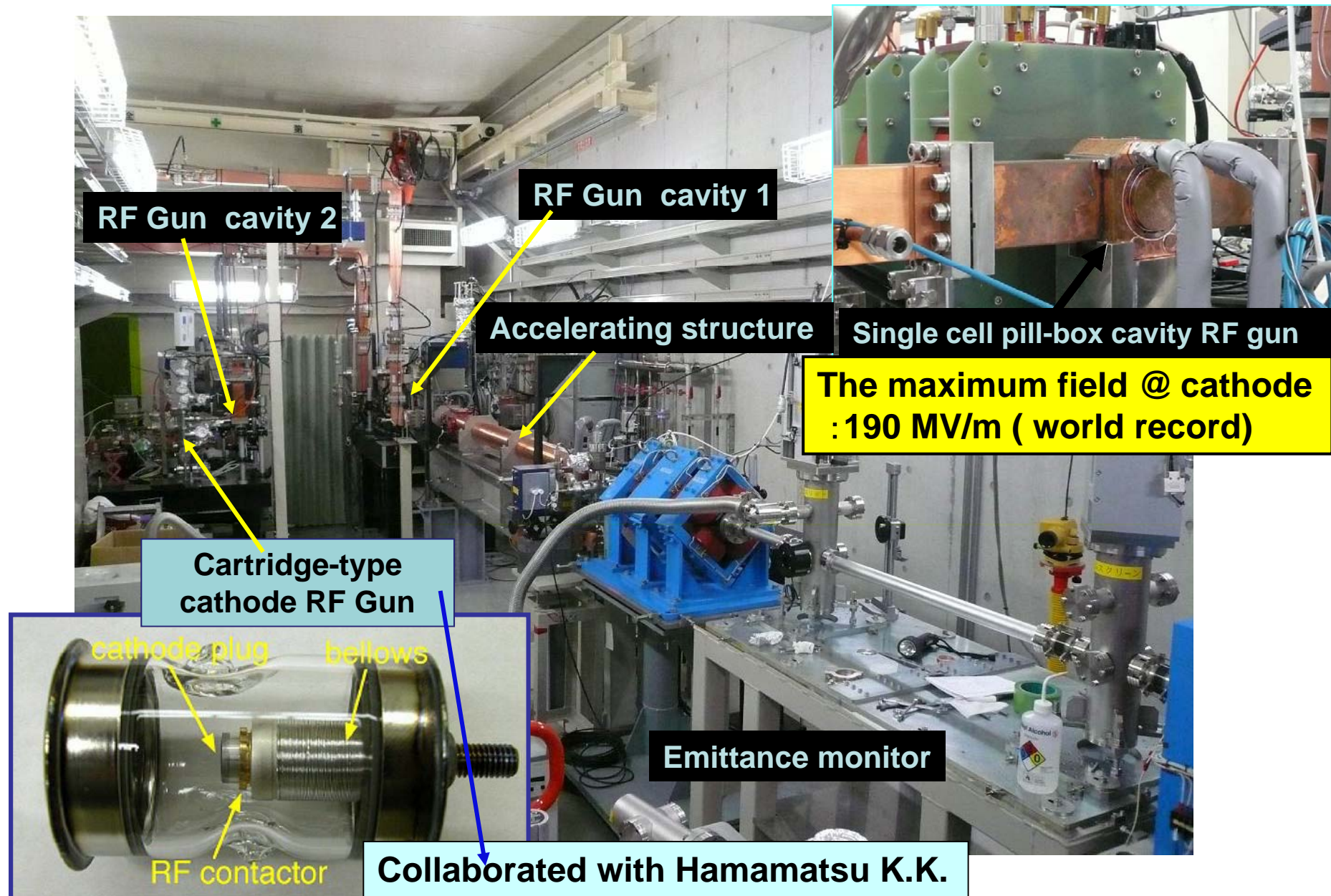
- S-band (2856MHz), Single-cell pill-box type
- Cathode: fixed cavity wall (**RF cavity1**)  
changeable cathode plug with cartridge (**RF cavity2**)
- High electric field on cathode : **190 MV/m (RF cavity1)**



**SPring8-type RF gun cavity**  
**190 MV/m**



# SPring-8 Photocathode RF gun test facility

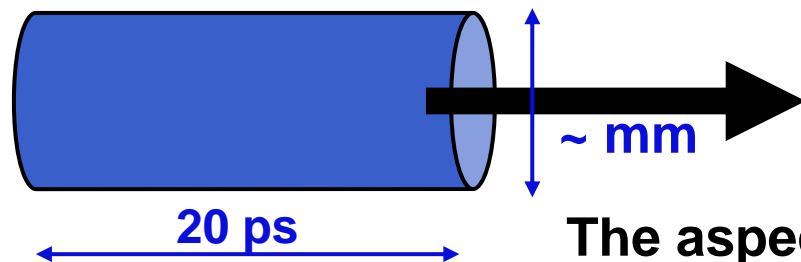


# Physical background of ideal laser profile

$$\sigma = \sqrt{\sigma_{SC}^2 + \sigma_{RF}^2 + \sigma_{Th}^2}$$

**Space charge effect** consists of:

1. **Linear** term in radial direction  
.....possible to compensate with **Solenoid Coils**
2. **Non-linear** term in radial direction  
.....possible to suppress non-linear effects  
with optimization of **ideal Laser Profile**



**Note that, in real case ideal 3D-shape can be different!**

**The aspect ratio of the Laser Profile is important!**

# “Beer can” UV-laser pulse shaping system

UV- Laser source (yearlong stability!)

Laser Pulse Energy : 1.4% @THG

Timing Jitter < 0.3 ps

Cylindrical

Spatial Profile:

Distribution: Flattop

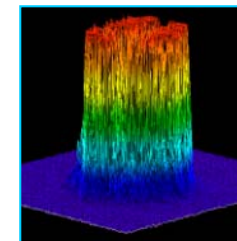
Deformable Mirror

Gaussian



Deformable Mirror

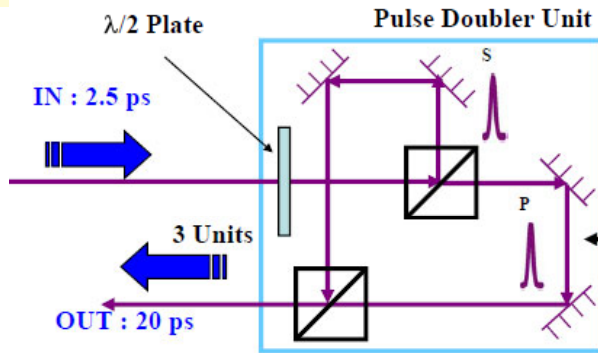
Flattop



Temporal Profile:

Pulse duration: 4 ~ 32 ps

UV- Pulse Stacker

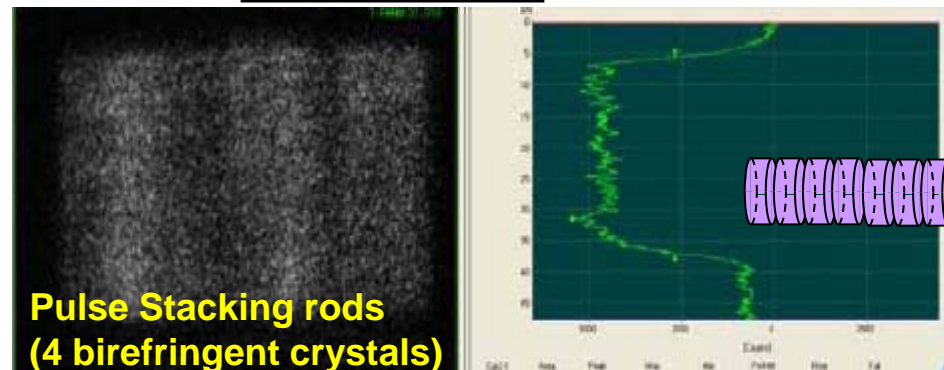
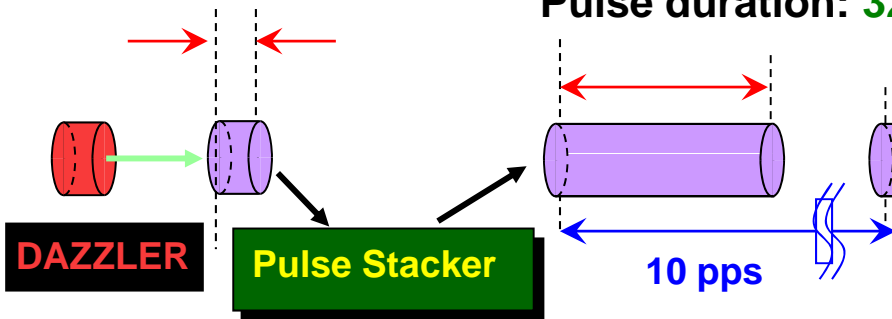


Pulse duration: 2.5 ps

Pulse duration: 32 ps

Diameter: 1 mm

Deformable Mirror

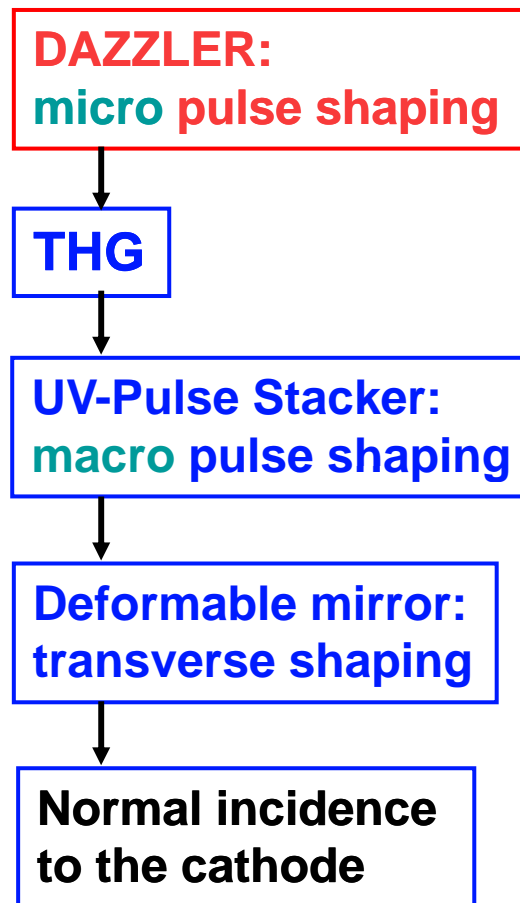


Pulse Stacking rods  
(4 birefringent crystals)

# Present 3D-laser pulse shaping @ SPring8

Cylindrical

“Beer can”



# Optimization of laser profiles and schemes

~ Spatial & Temporal ~

## History of Ideal Beam Shape Evolution

our contributions for following requirements



“Beer can”

### Spatial Shaping

Deformable Mirror (Wave Front Control, also!)

### Pulse (Temporal) Shaping

SLM (Spatial Light Modulator)

UV- Pulse Stacker (birefringence  $\alpha$ -BBO)



Ellipsoid

K-V distribution

**3D-pulse shaping** (uniformly filled **ellipsoidal**)

*Linear space charge fields in each direction* (Lorenz invariant).

Fiber Bundle with backward illumination



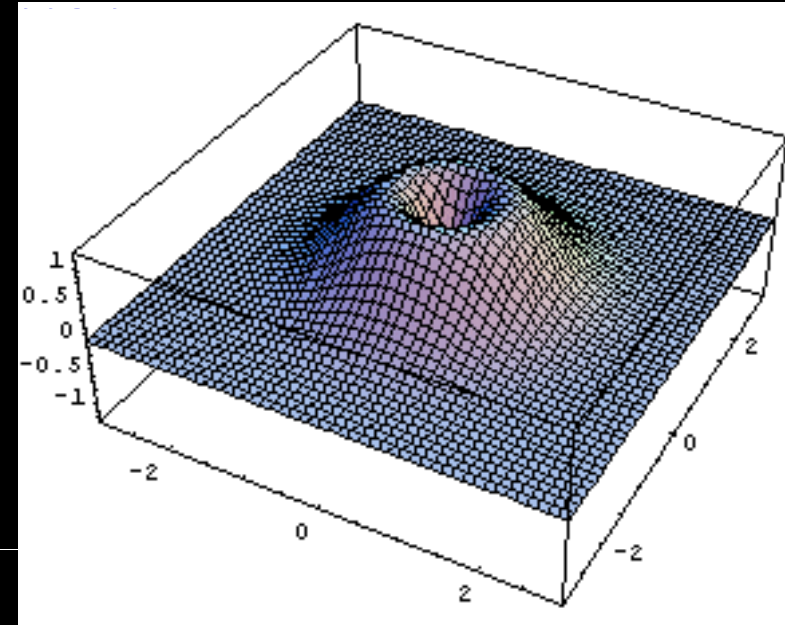
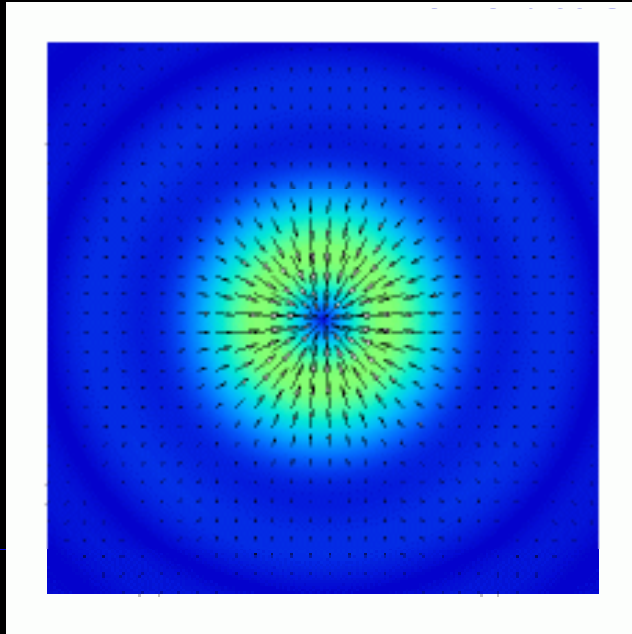
Luiten scheme (2004)

**Start from femtosecond pulse**

Z-polarization with Schottky effect

How to utilize the laser coherency....  
Laser-field can be used: Radial Polarization

**No requirements of laser shaping for  
high-brightness electron beam**

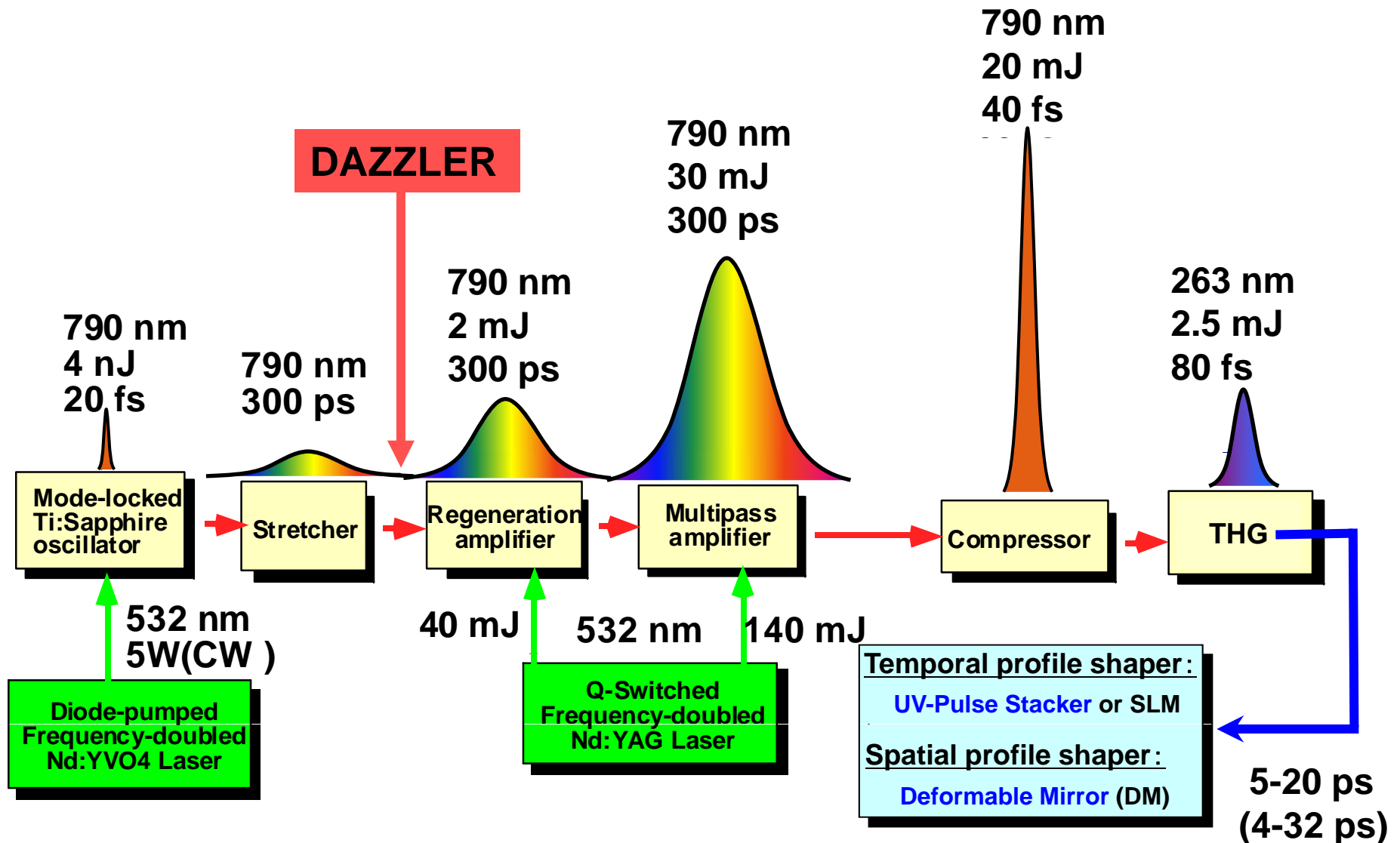


Luiten scheme (2004)

**Start from femtosecond pulse**

**Z-polarization with Schottky effect**

# Spring-8 Photocathode Laser System Configuration

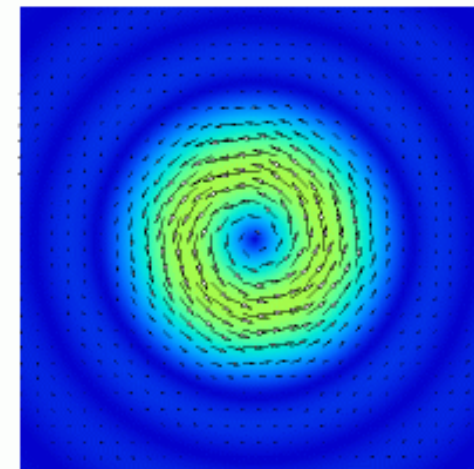
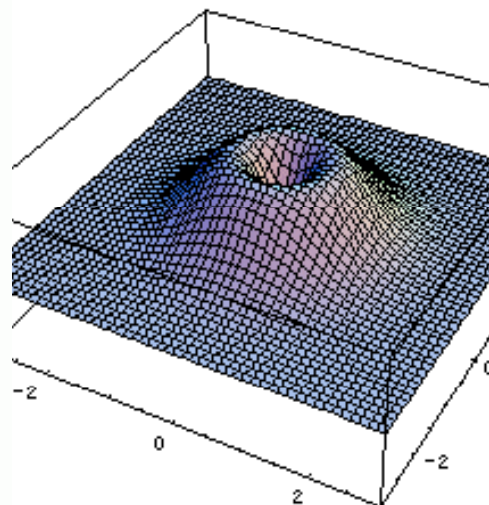
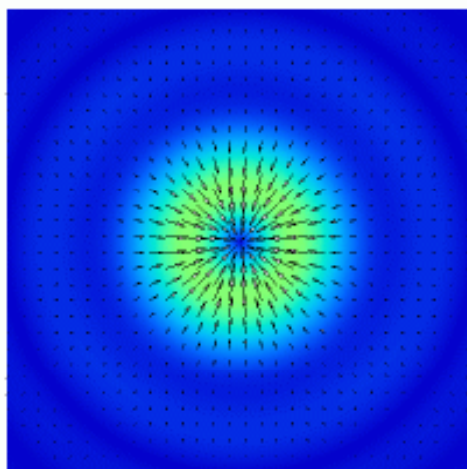
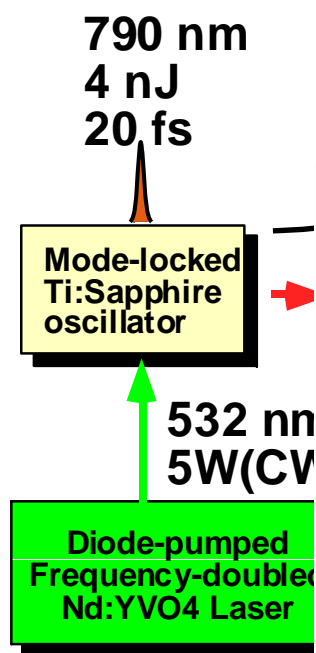


# Spring-8 Photocathode Laser System Configuration

Is it possible to assist electron emission with laser-field ?

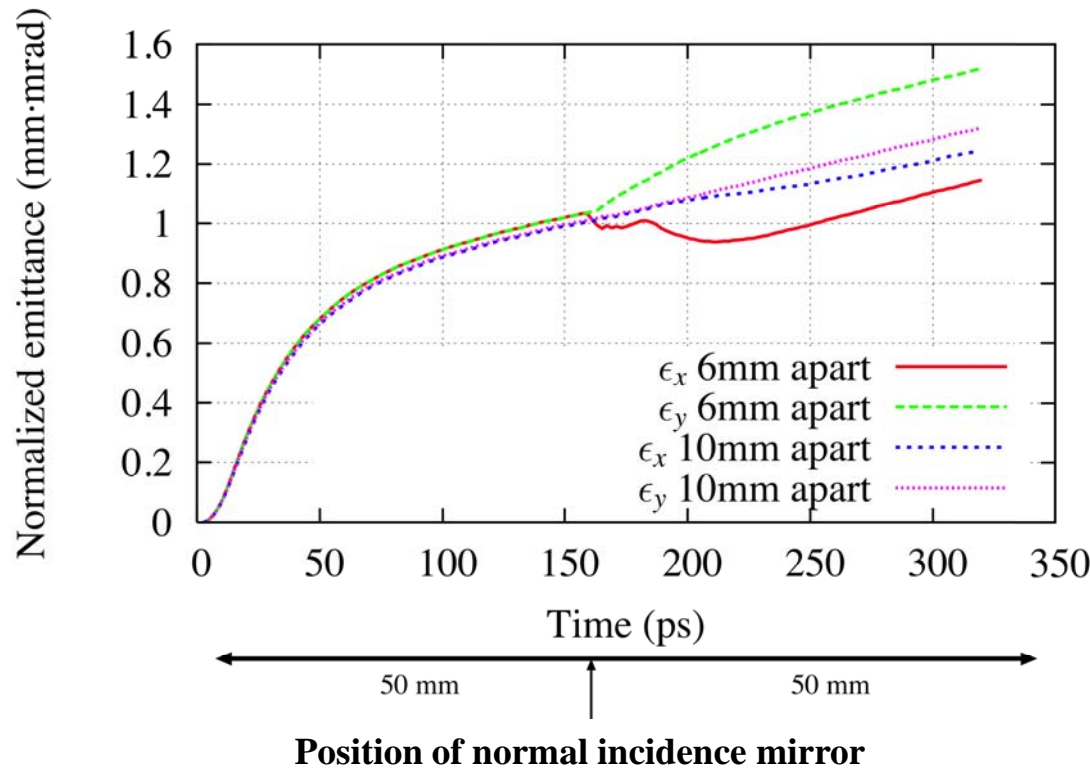
..... Z-polarization

*If Z-pol. Gun is feasible, just laser oscillator is required!!*



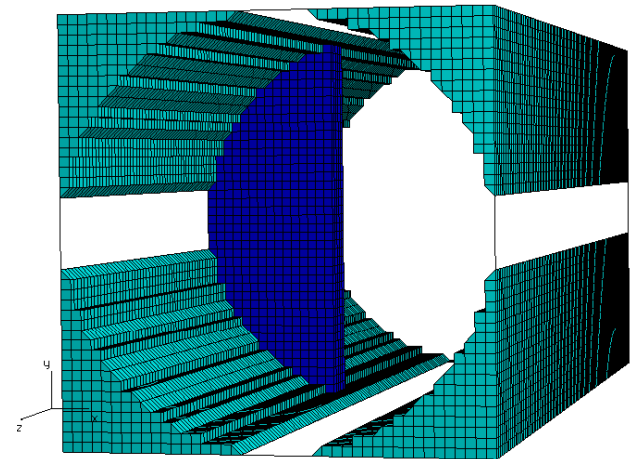
# Simulation results of emittance growth under influence of normal incidence mirror installed in horizontal (x-axis)

(Behavior near by mirror in vacuum)



## Beam Conditions

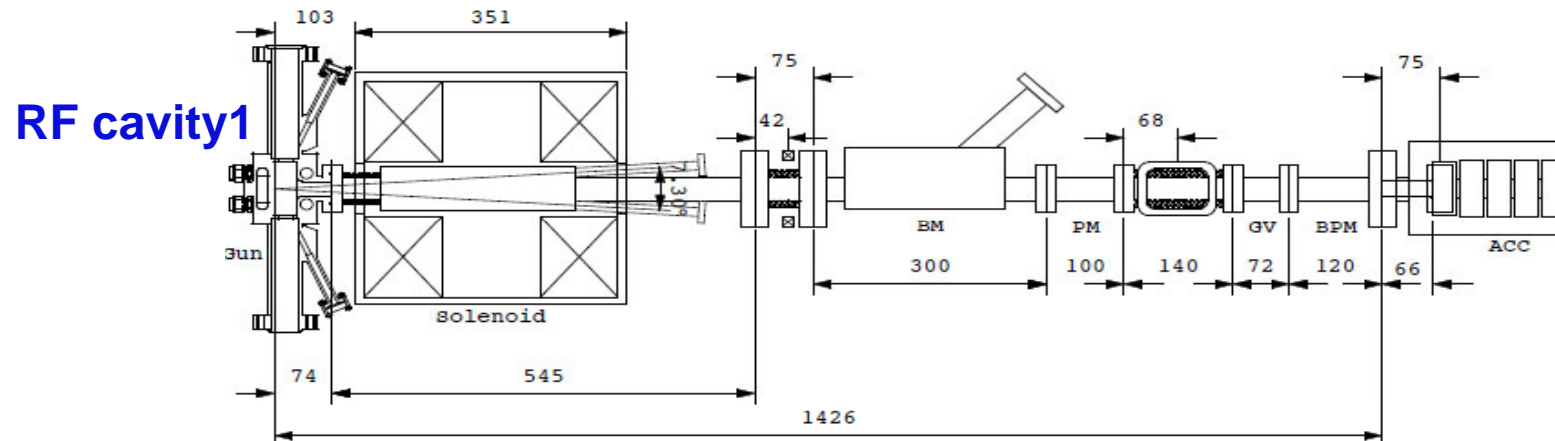
bunch charge = 0.83 nC  
bunch length = 4.5(1 $\sigma$ )ps( $\pm 3\sigma$ )  
beam size = 3.5(1 $\sigma$ )ps( $\pm 3\sigma$ )  
beam energy = 3.6 MeV  
initial emittance = 0 m·rad



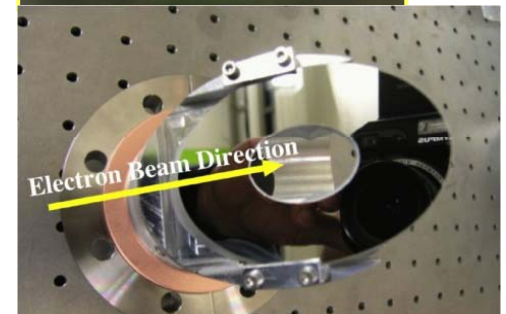
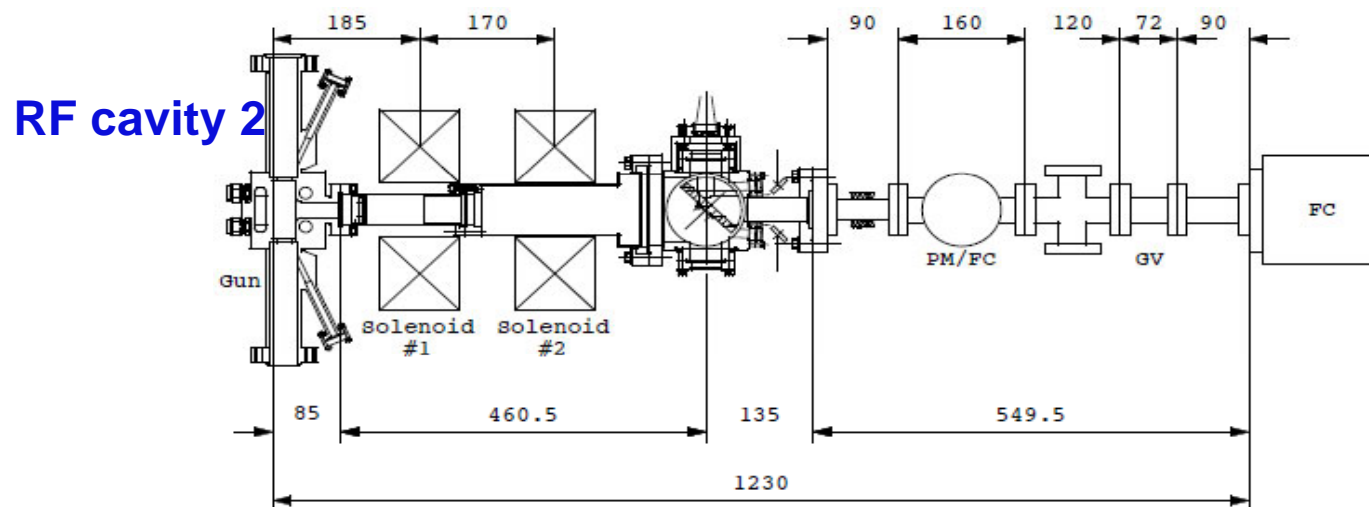
- Simulation results reproduce that Y- emittance growth is larger than X- .  
 $\Rightarrow$  Normal incidence mirror is the cause of emittance asymmetry.
- When the mirror installs 10mm apart from beam axis, emittance symmetry is improved enough.

# New laser incidence schemes

- A. Quasi-normal incidence (**No mirror in Vacuum**)



- B. Hollow mirror incidence (**Z-polarization gun**)



# A. Quasi-normal incidence

(No mirror in Vacuum)

Improvement of emittance

symmetry

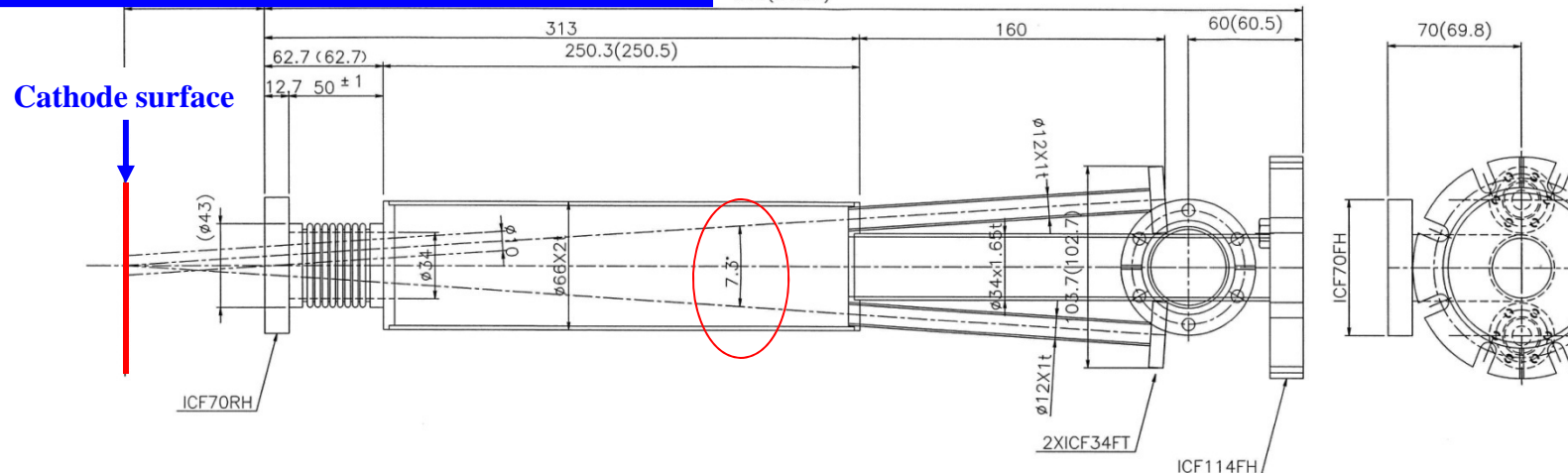
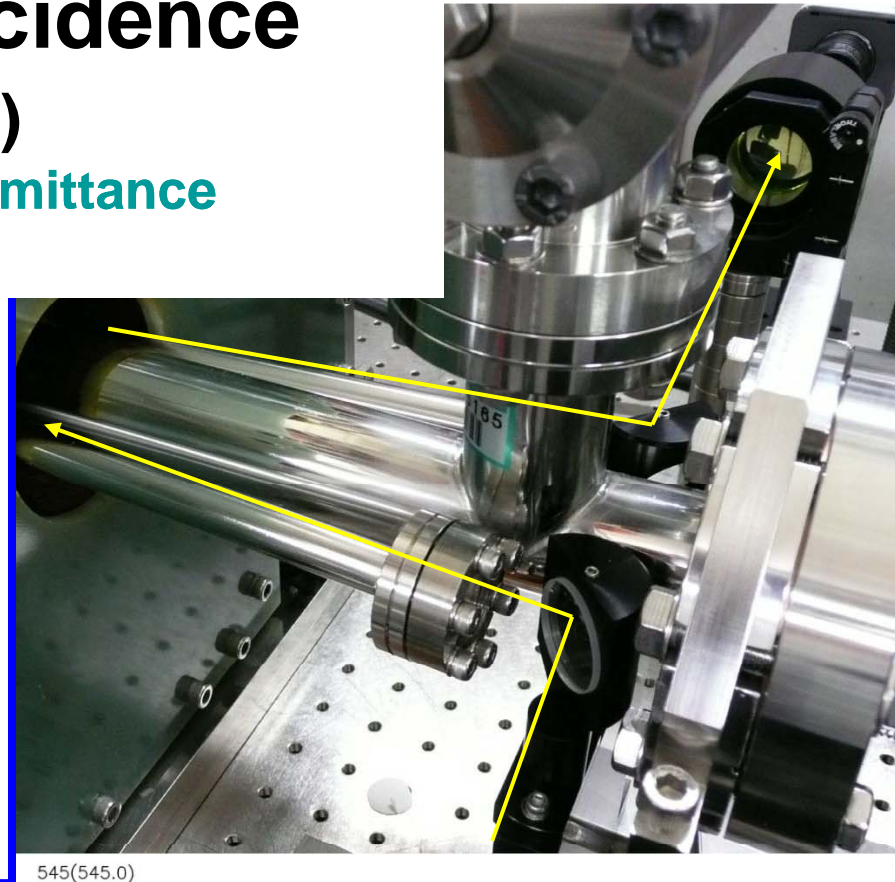
## New Oblique Incidence:

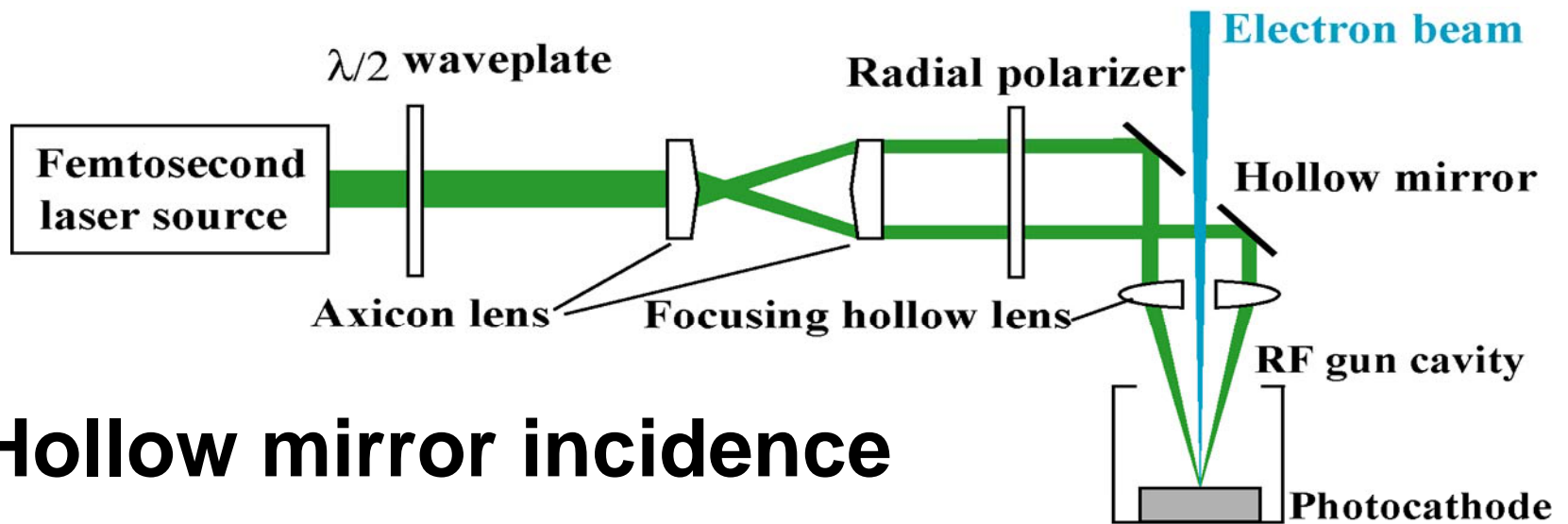
**4 degrees (3.65 degrees) incidence**

- a little larger incident angle than normal incidence (1.4 degrees)

**Final transport mirror to the cathode installs out of Vacuum**

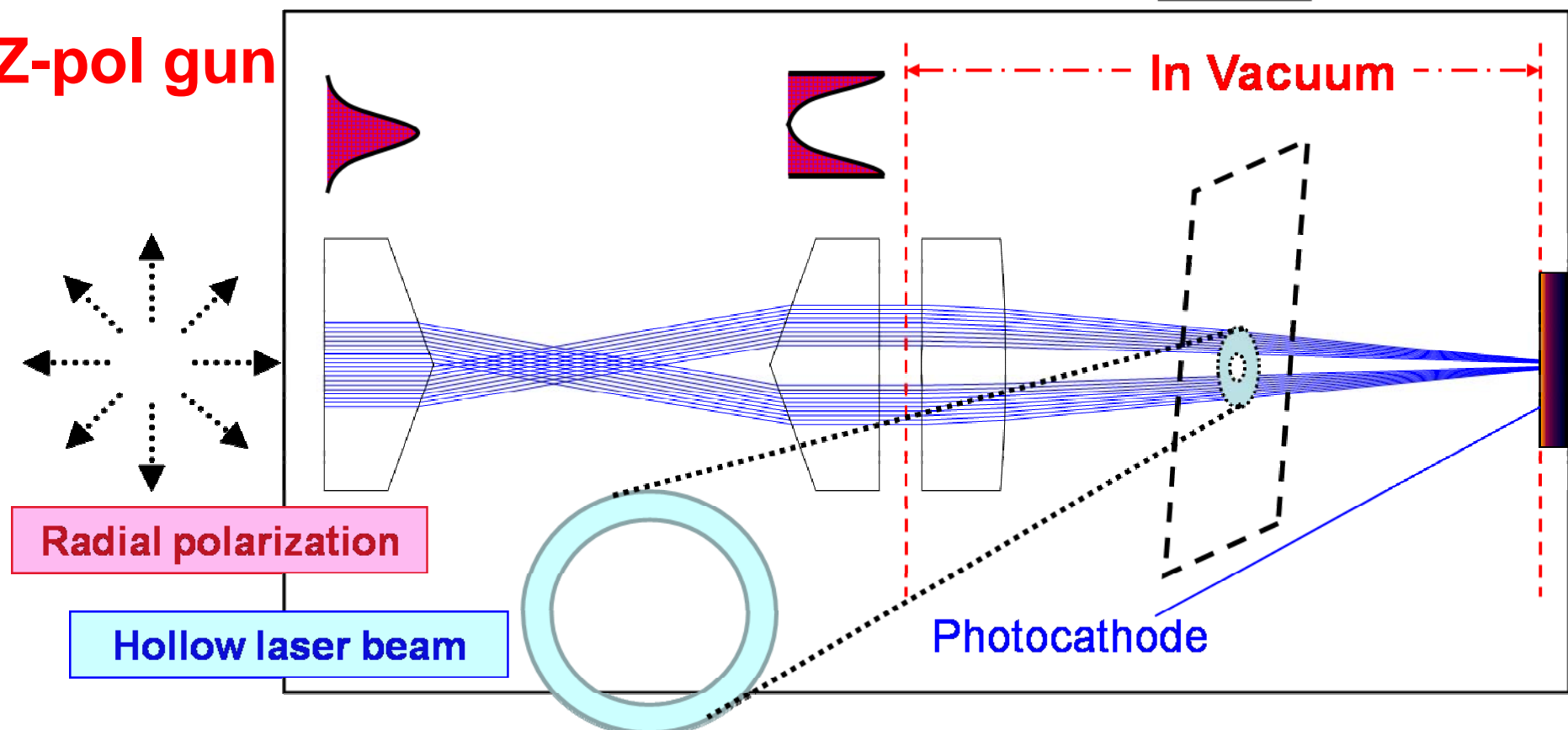
- Laser illuminating spot is monitored with a reflection from the cathode.






- **B. Hollow mirror incidence**

**Z-pol gun**

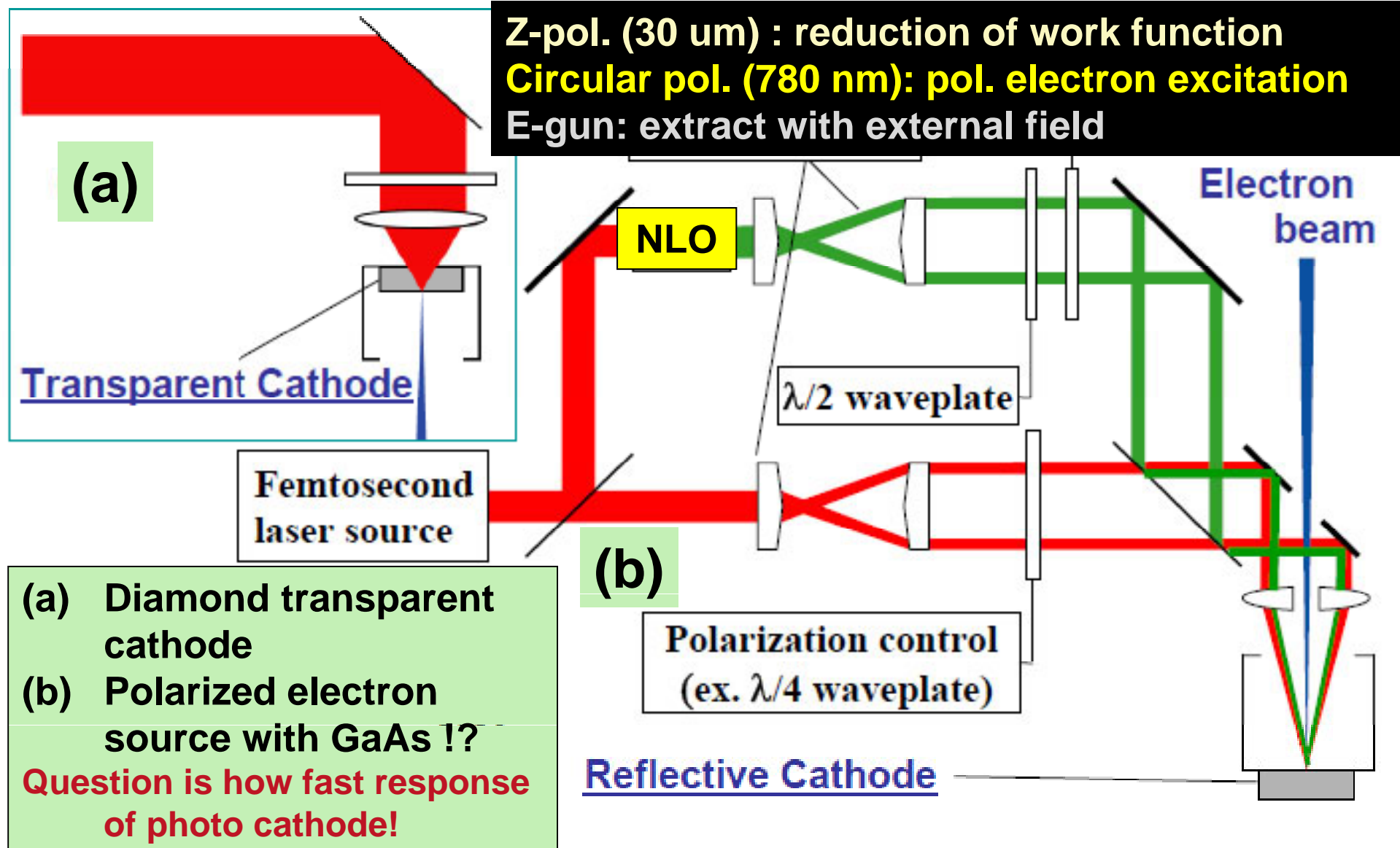




# How should we make deal with Laser's coherency?

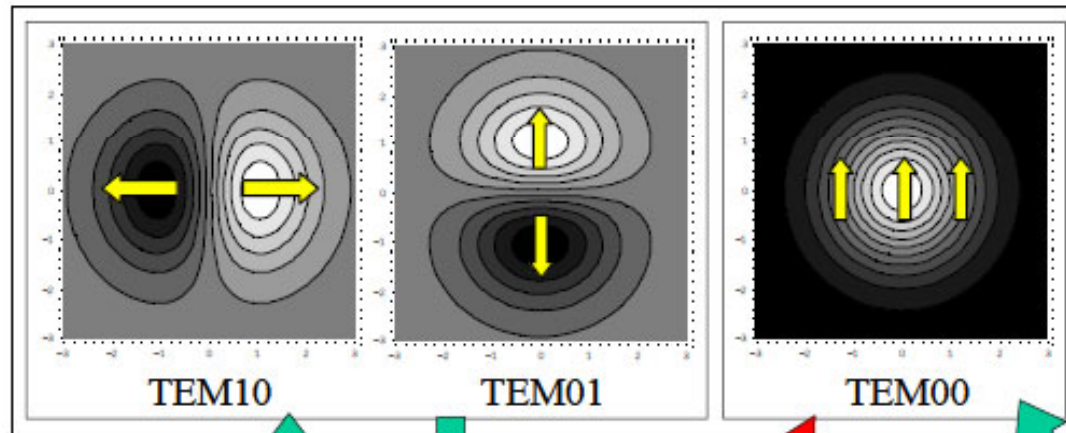
- 1. State-of-the-art photocathode guns have never utilized laser coherency!!
- 2. Utilize coherency with laser Z-polarization with hollow laser beam incidence  
(Optical Schottky effect on the metal cathode)
- 3. If it is possible to use this scheme, it will be an alternative technology for NEA surface

# Variation of Z-polarization RF gun with laser –induced field gating (plane field emitter)



# Special laser Polarizations

Hermite Gaussian

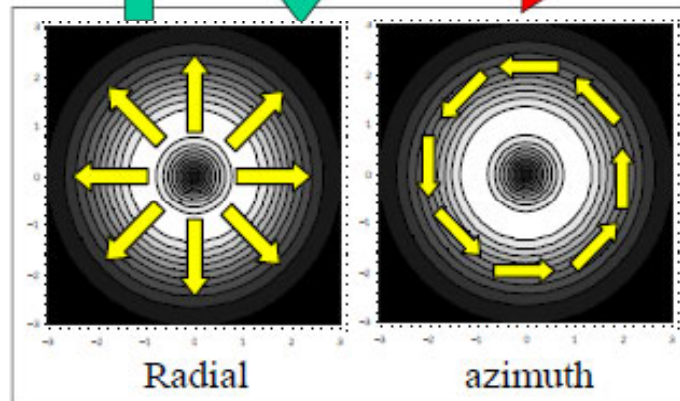


Polarizer

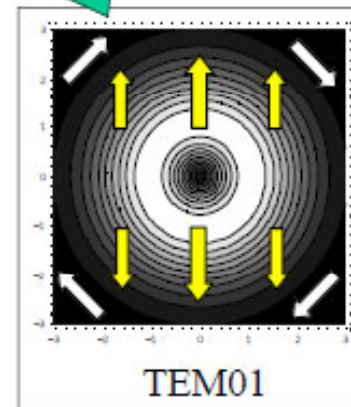
Sum

Twisted Nematic Cell  
or Divided Wave Plate

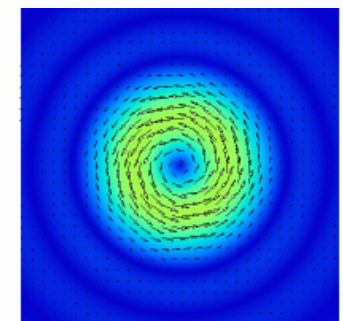
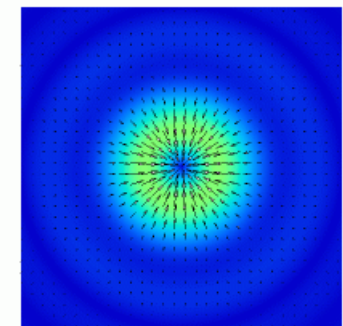
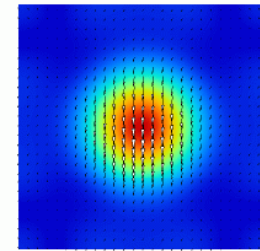
Spiral Phase Delay Plate



Radial and azimuth polarization



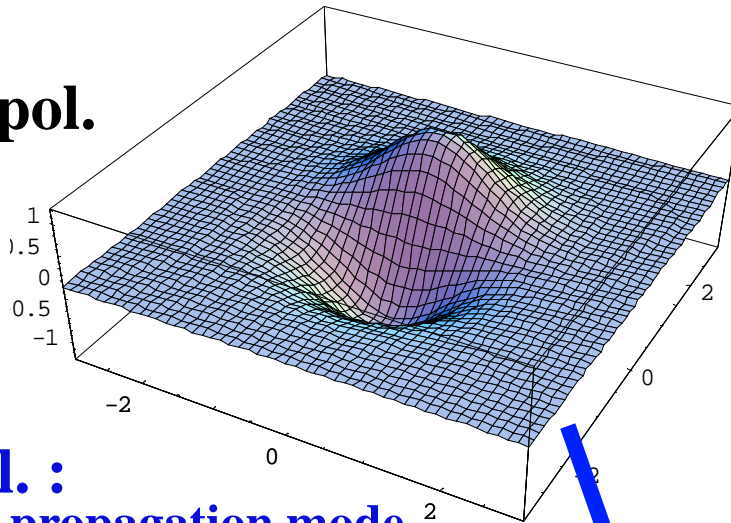
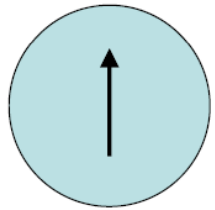
Laguerre Gaussian



# Radial Polarization laser beam

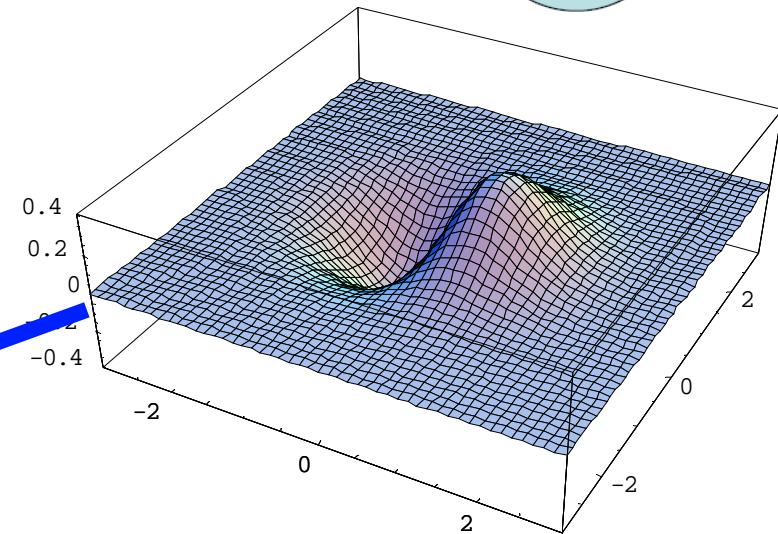
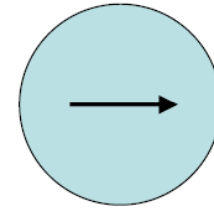
TEM01

S-pol.

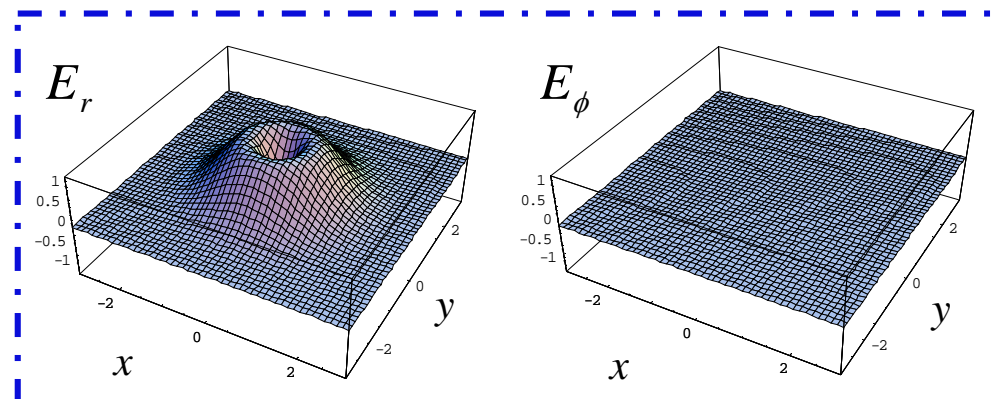
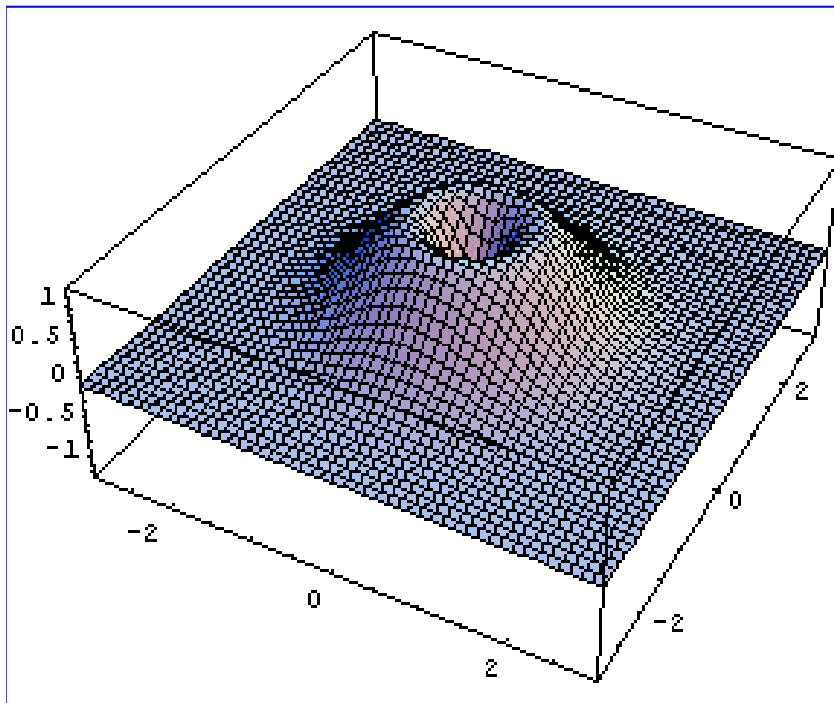
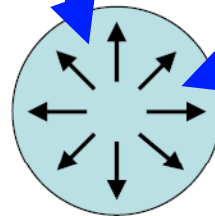


TEM10

P-pol.

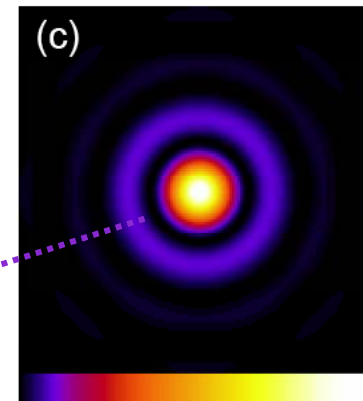
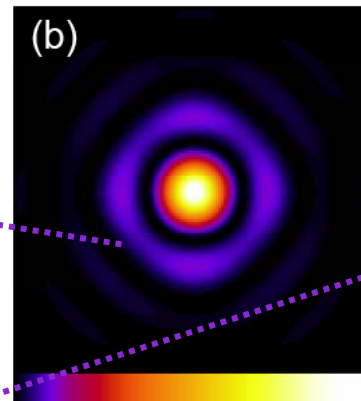
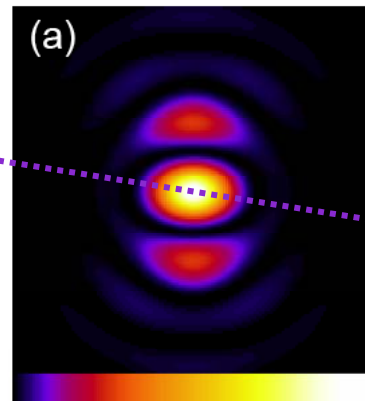
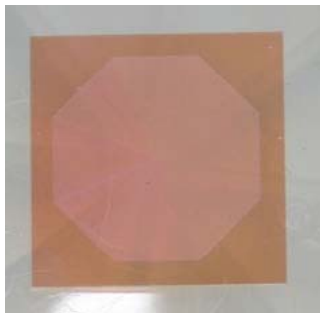
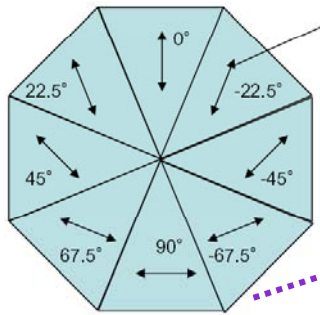
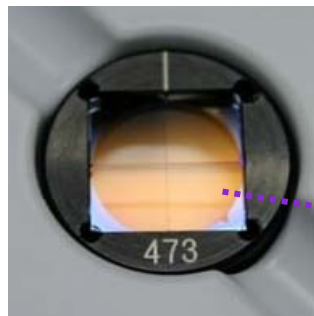


**Radial Pol. :**  
propagation mode

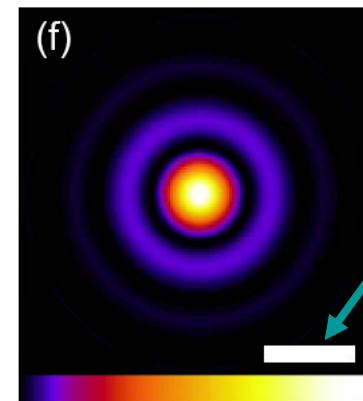
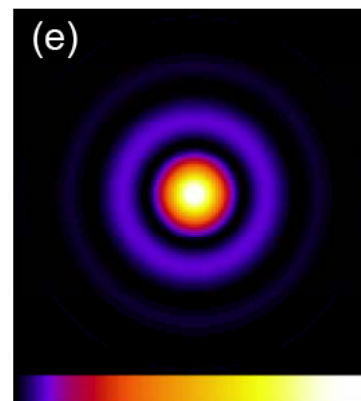
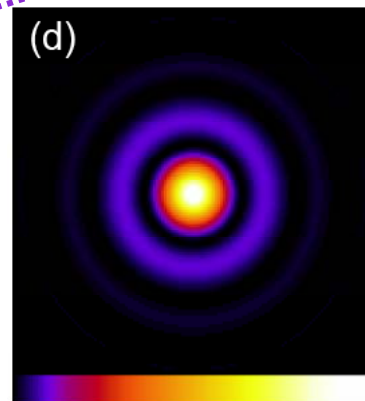


# Z-polarization field on the cathode:

## Divided number(2~32) dependence



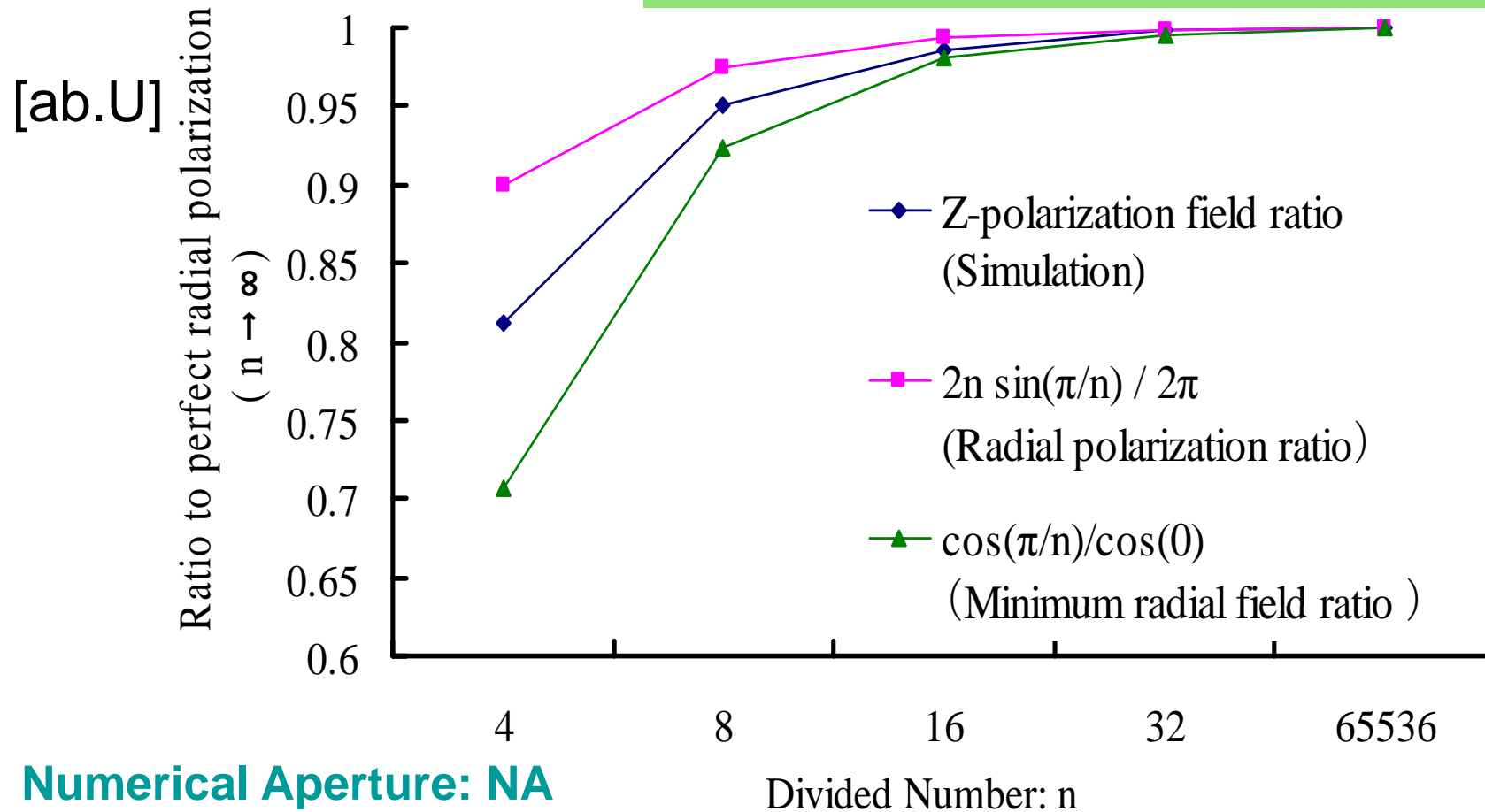
Scale bar is 7.5 $\mu$ m @790nm, NA=0.1 (Flatop incidence)



Using divided waveplate, the distribution of strength of Z-polarization field  $|E|^2$ : (a)2-divided, (b)4-divided, (c)8-divided, (d)16-divided, (e)32-divided, (f) perfect radial polarization (n: infinity)

# Z-polarization ratio with divided waveplate

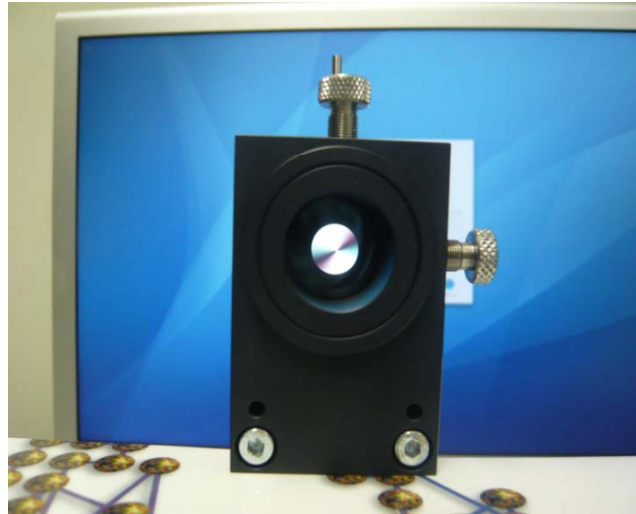
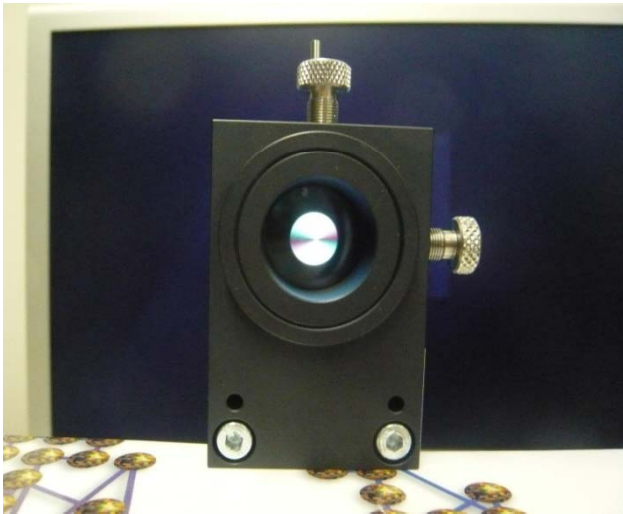
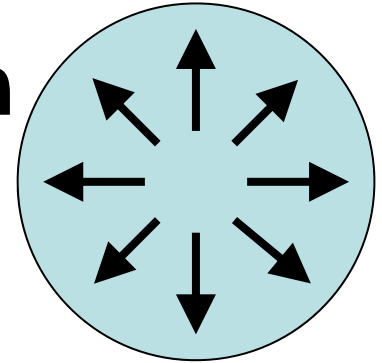
More than  $n=8$ , ideal radial polarization



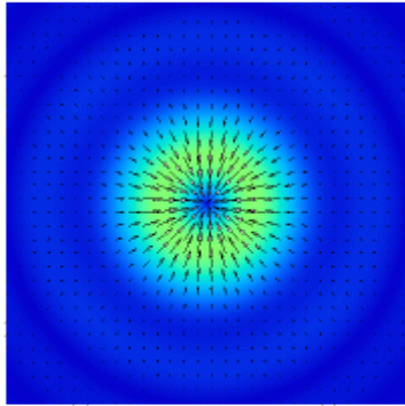
Numerical Aperture: NA

- The strength of Z-polarization field  $\propto 1/(\text{Wavelength}:\lambda)^2$
- The strength of Z-polarization field  $\propto (\text{NA})^2$   
 $\propto 1/(\text{Focus length})^2$

# Demonstration of Radial polarization with rotation of polarizer

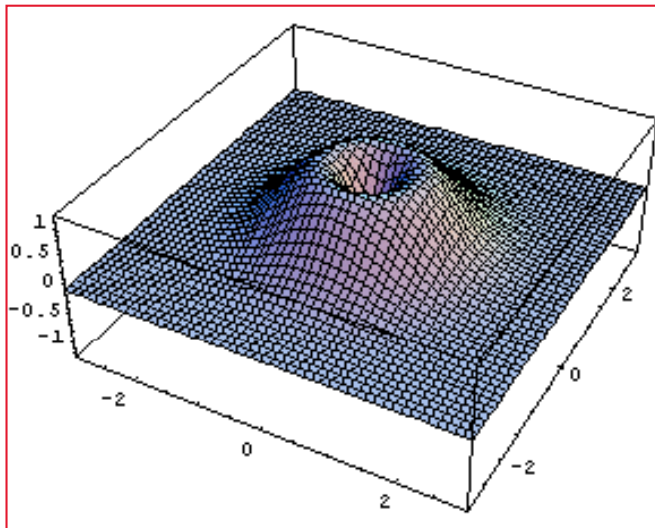


# Z-polarized laser on the cathode & field emission with Schotkky effect **(It's not proved yet!)**



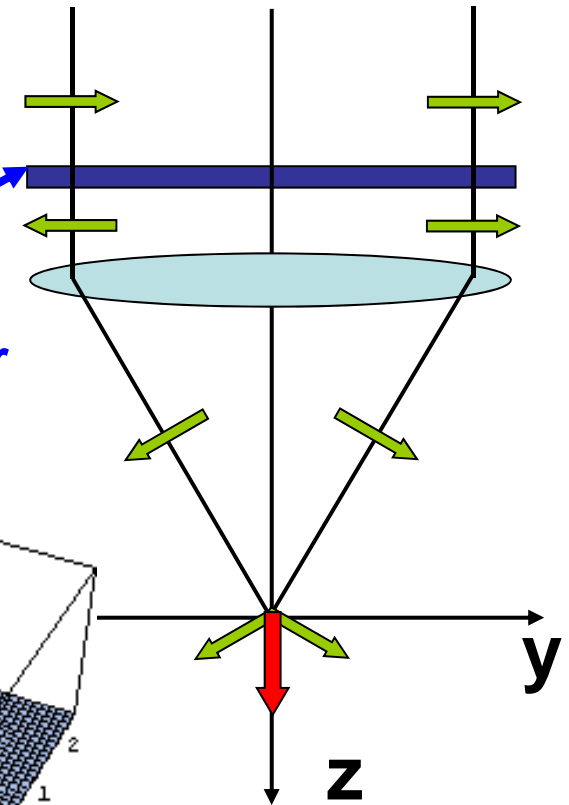
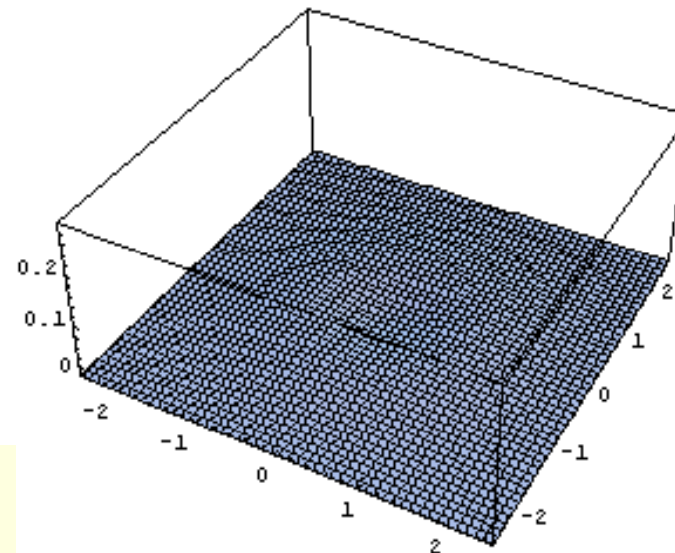
At the focus point, laser electrical field is reinforced in its propagating direction

**Radial polarization :**



With 1GV/m field,  
Work function reduces  $\sim 2\text{eV}$ .

Radial polarizer

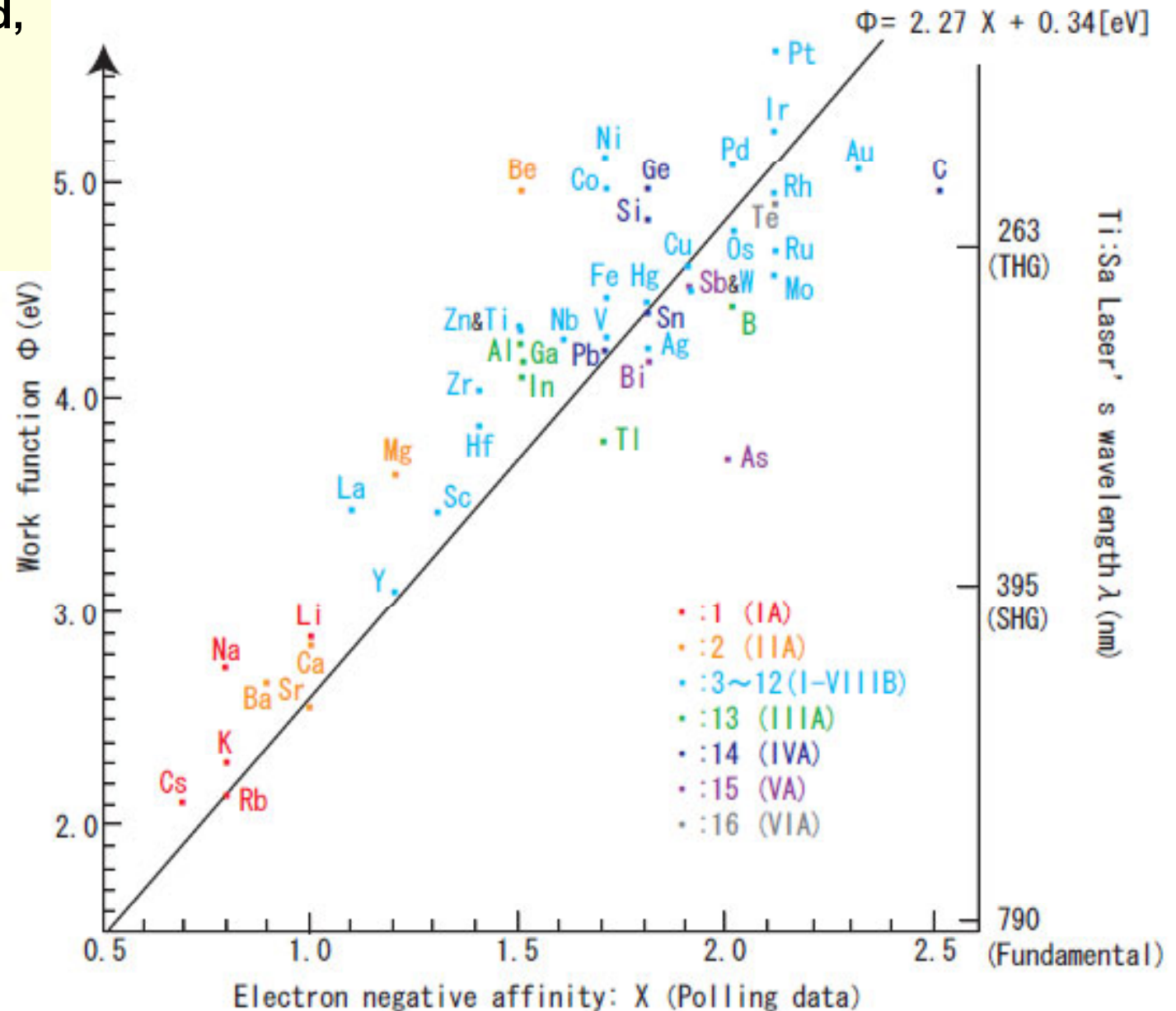
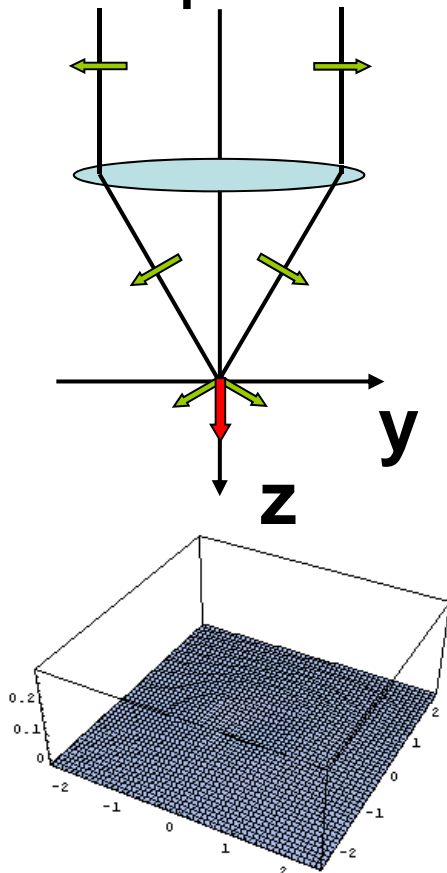


# Work function of various metal cathode

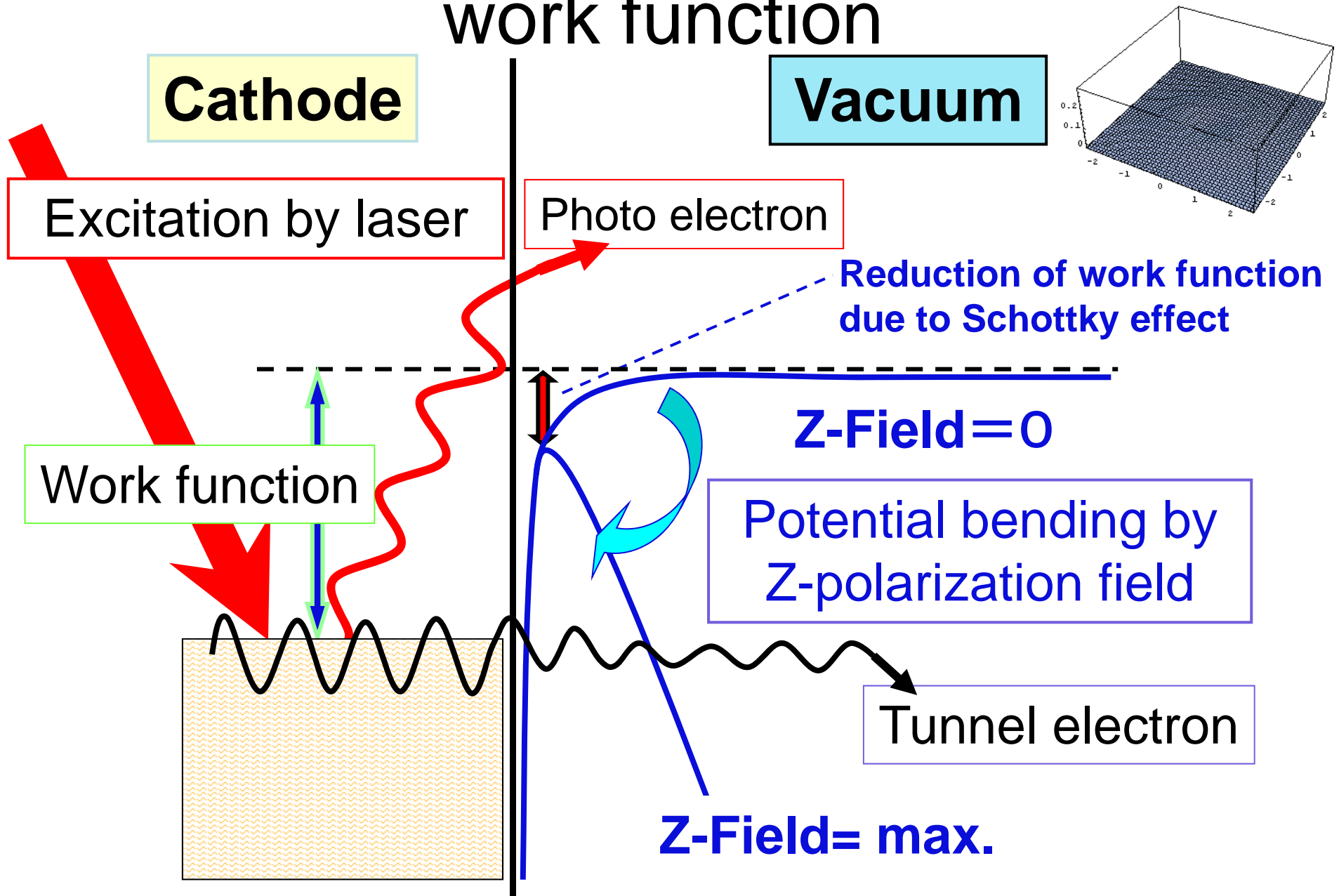
With 1~2GV/m field,  
Work function  
reduces ~2eV.

Drive Laser wave-  
length can be IR.

Radial polarization



# Z-field on the cathode surface reduces work function



# ***No Pulse shaping optics!!: Luiten scheme***

**If it works, we can generate ultra-low emittance.**

Idea: Use “pancake” laser pulse, allow beam to self-evolve to ideal ellipse  
Proposed by Serafini in 1997; again by Luiten in 2004.

**We can start from femtosecond pulse at the cathode.**

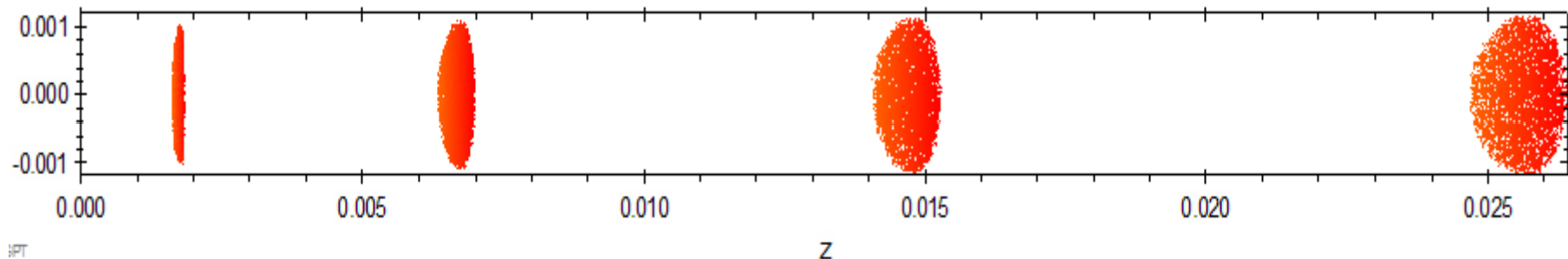


Luiten, “How to realize uniform 3-dimensional ellipsoidal electron bunches”, Phys. Rev. Letters 93, 094802 (2004)

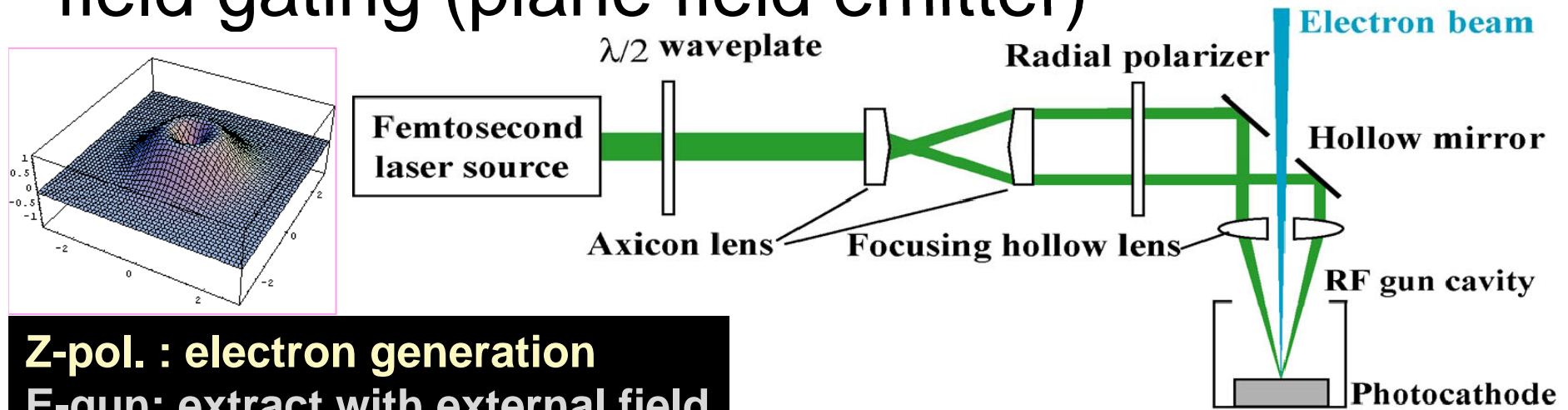
**Laser: 100 fs with parabolic transverse distribution with 1 mm radius**

Luiten scheme, 80 pC, 5 MV/m

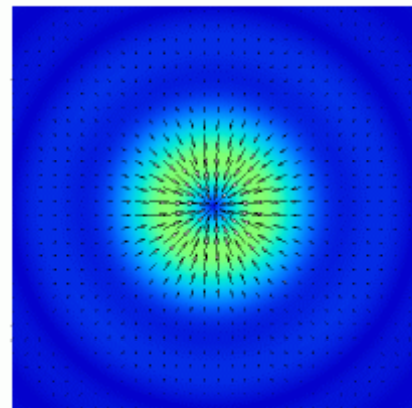
Cornell DC gun with 500 kV, peak 5MV/m  
Bazarov, PRST-AB 8, 034202(2005)



# Z-polarization RF gun with laser-induced field gating (plane field emitter)

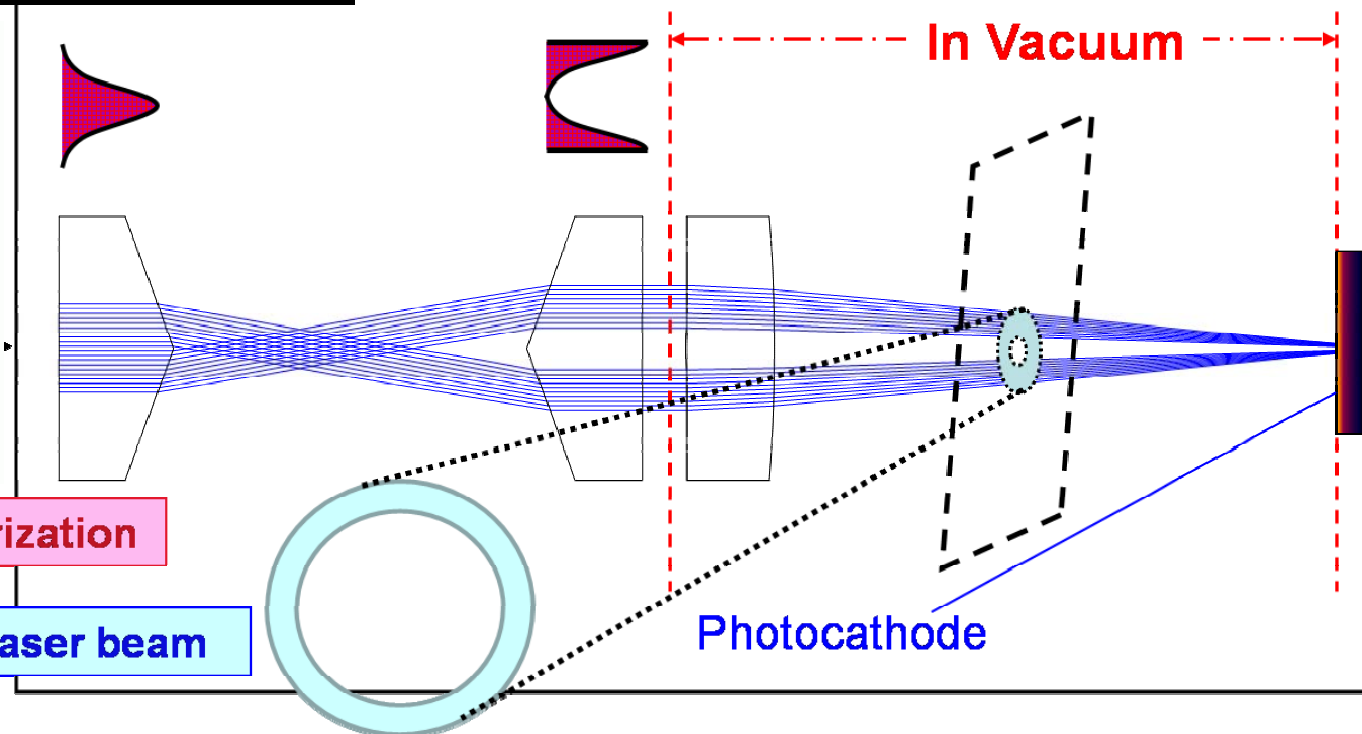


**Z-pol. : electron generation**  
**E-gun: extract with external field**

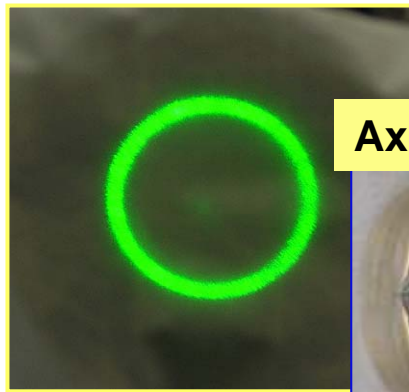


**Radial polarization**

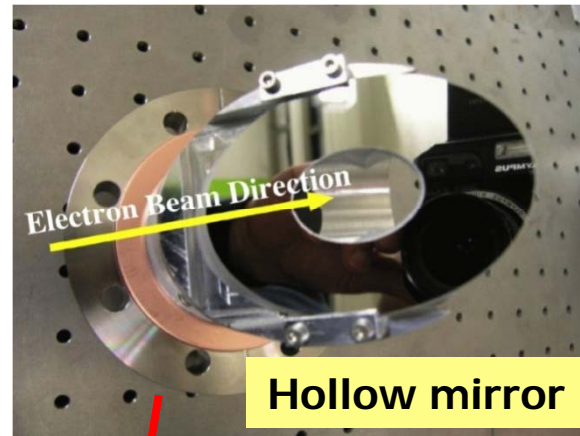
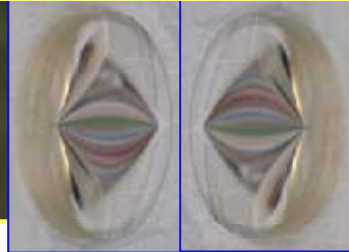
**Hollow laser beam**



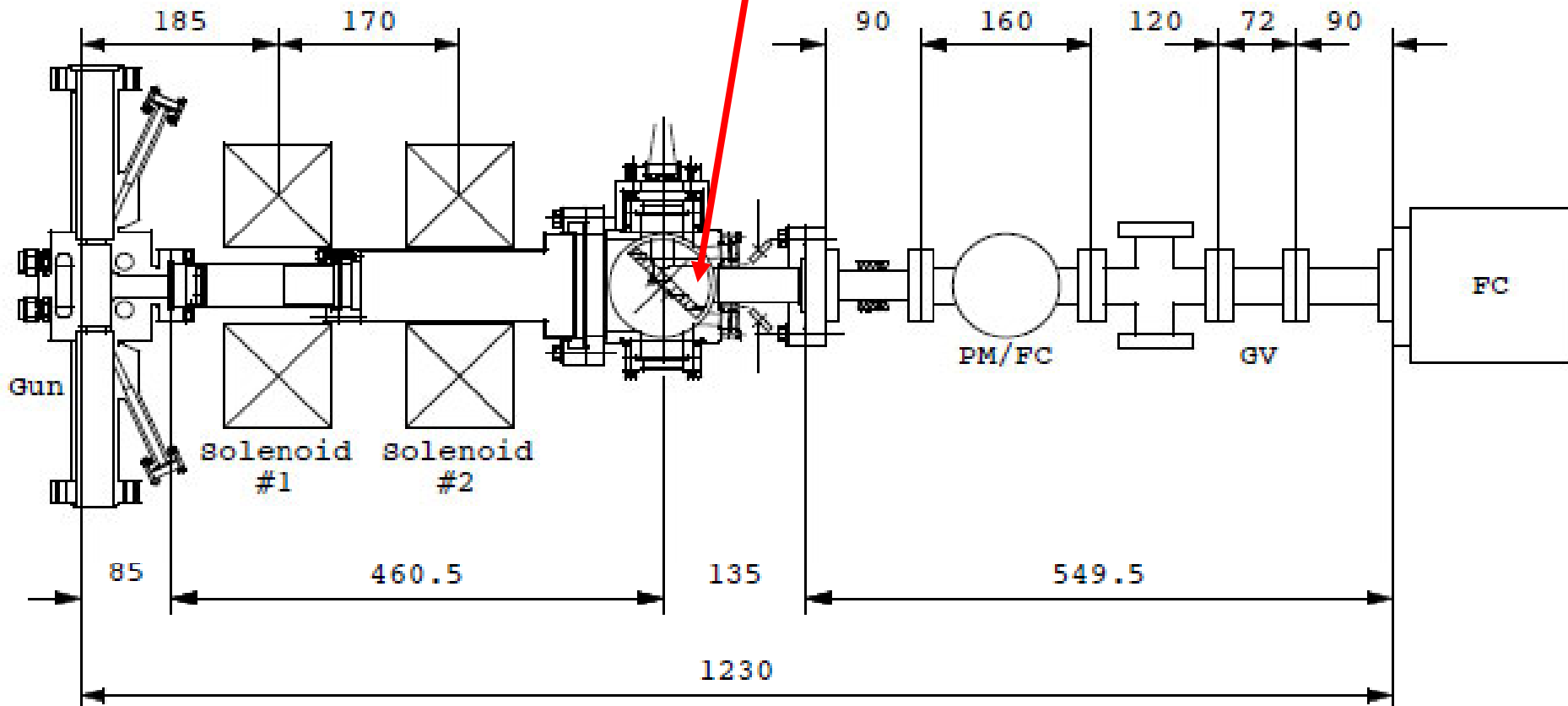
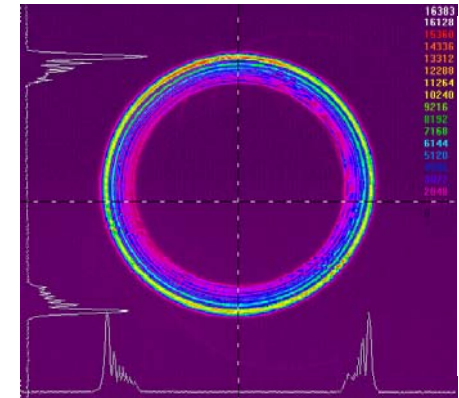
# The hollow laser beam incidence

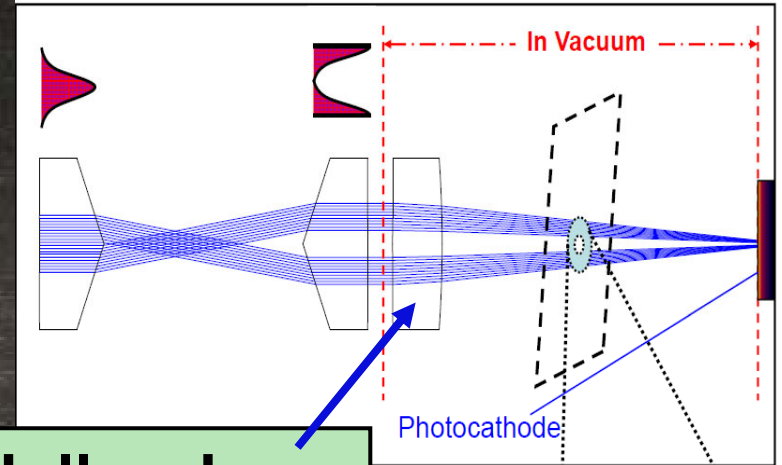
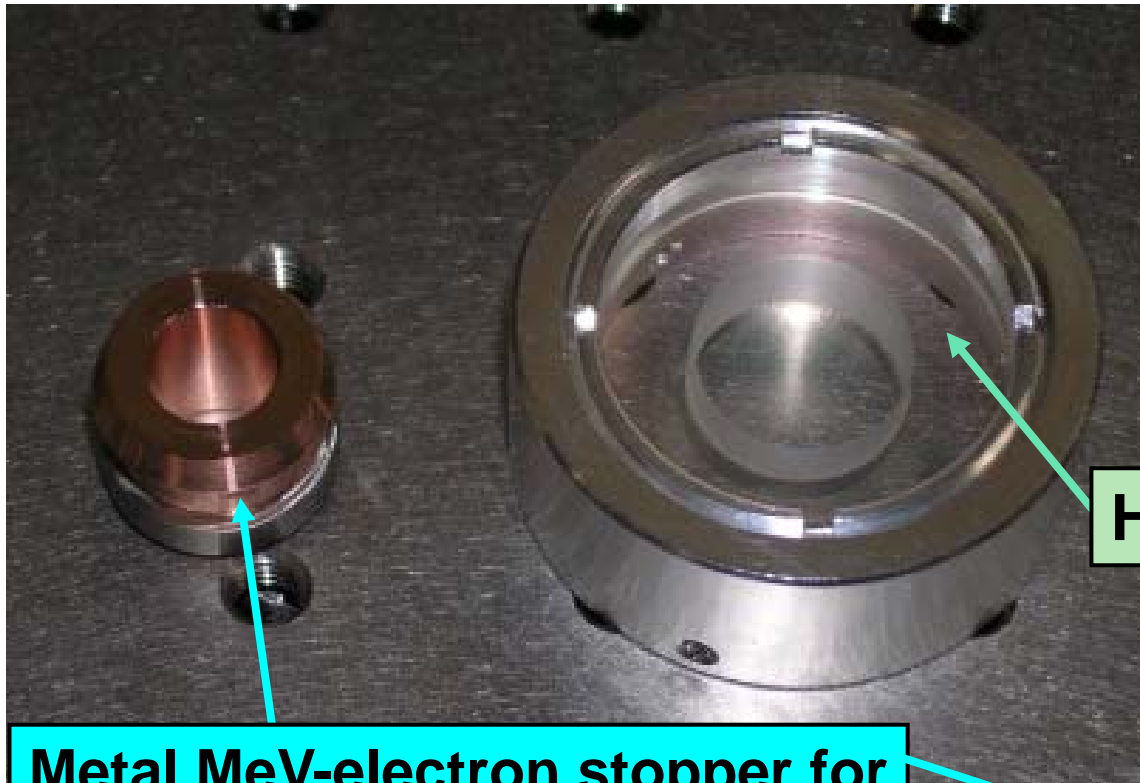


**Axicon lens pair**



**Hollow mirror**

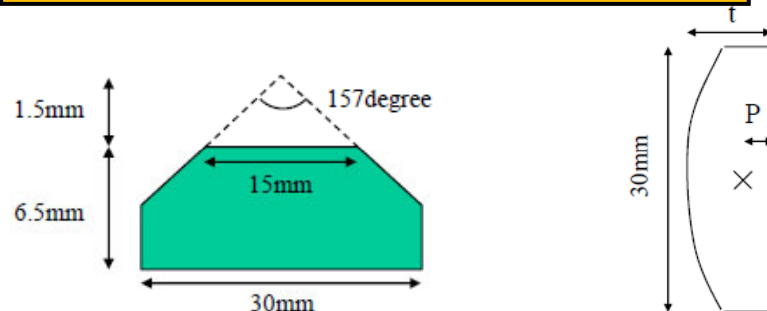




**Hollow Lens**

**Metal MeV-electron stopper for Lens protection**

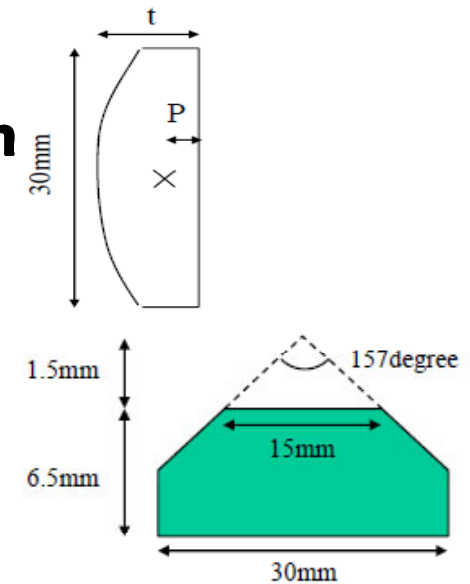
**2 type of focusing lens:  
Axicon lens & convex lens**



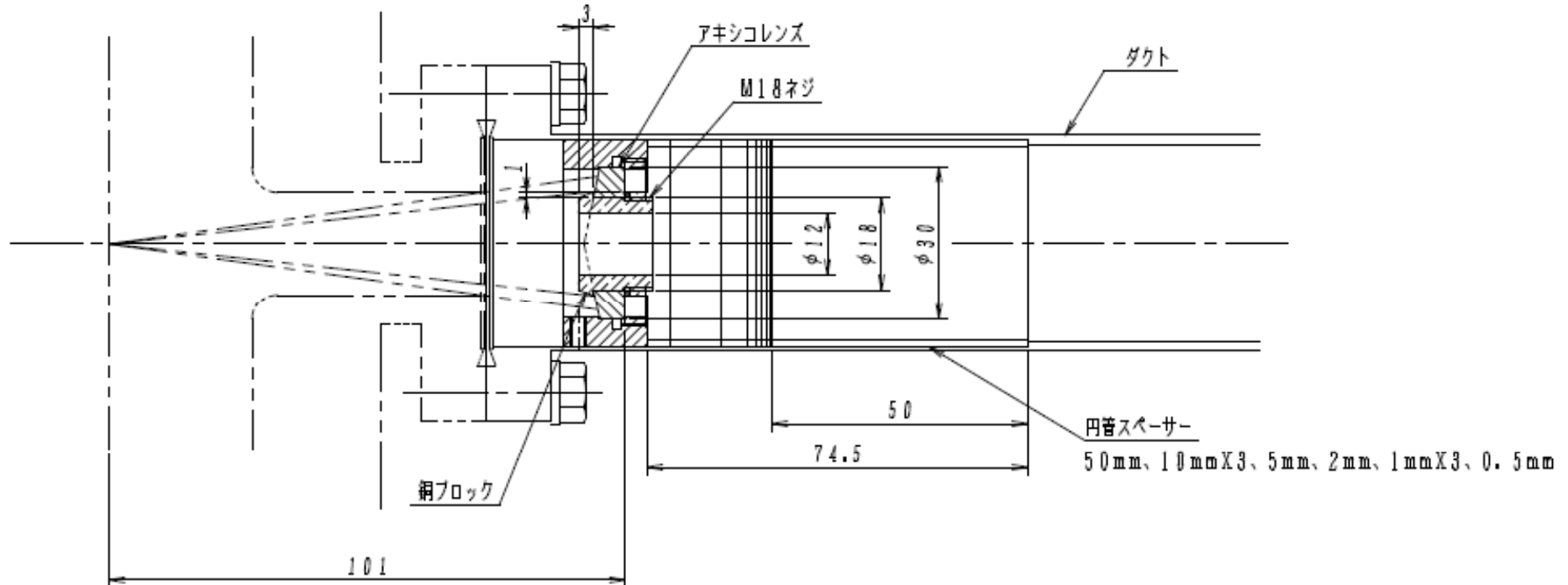
⇒ **Charge-up issue is also considered in this metal cover for the wall of glass lens hole.**

**Type1: Convex focusing lens:** ~< 10~100 $\mu$ m spot size  
for **very low** bunch charge generation

**Type2: Axicon focusing lens:** ~< mm spot size  
for **higher** bunch charge generation



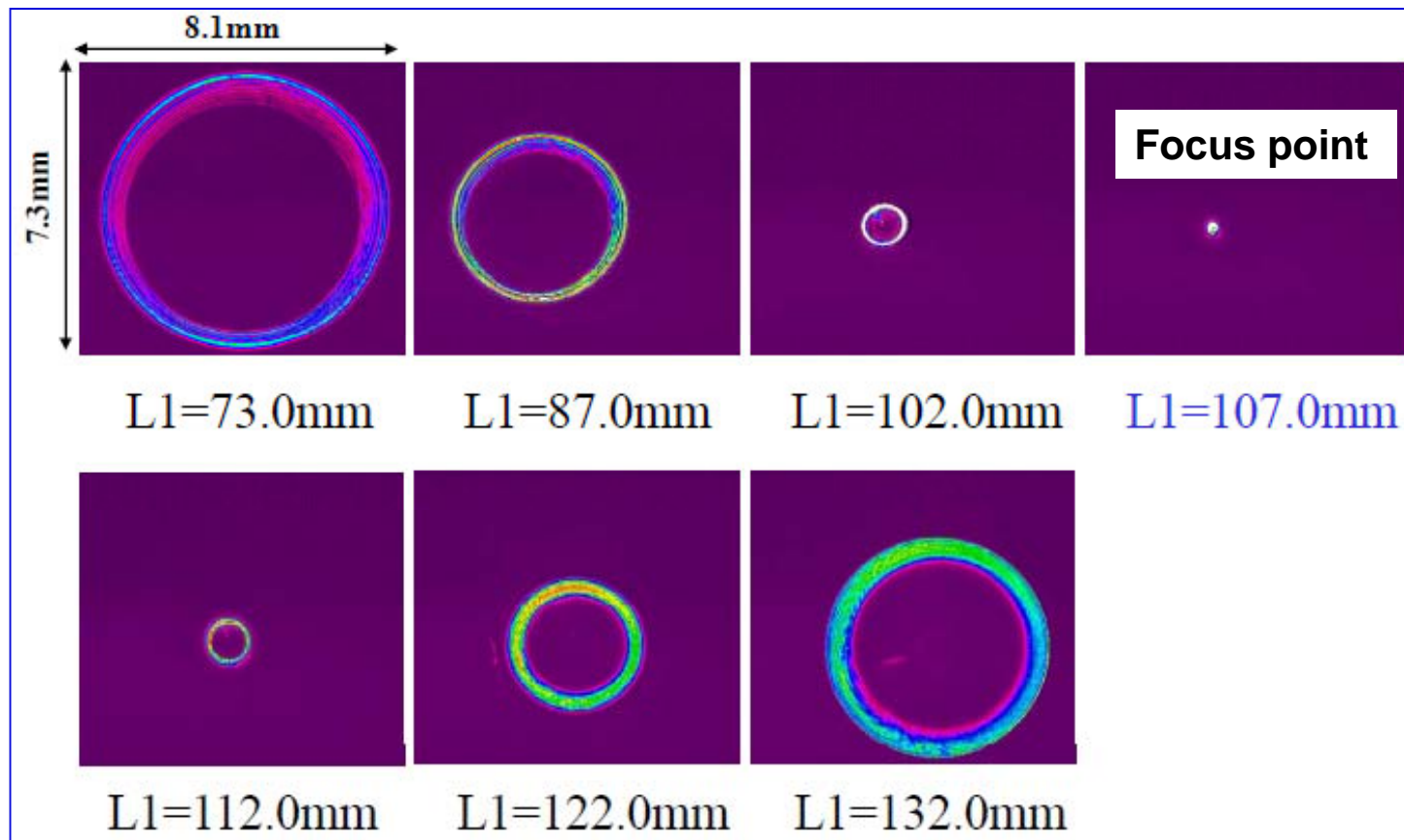
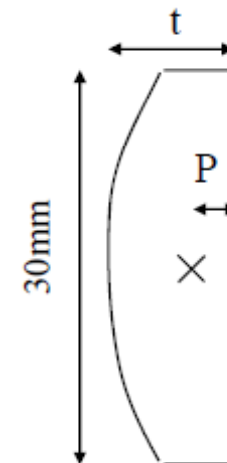
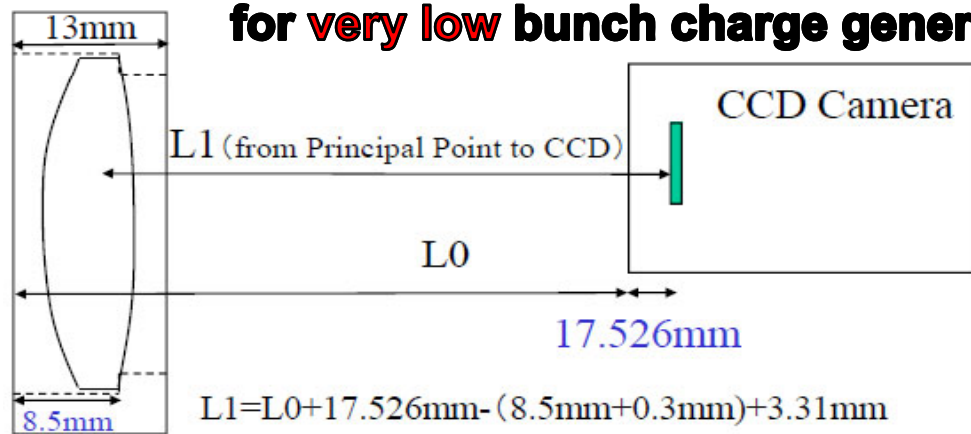
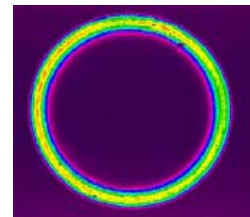
**5mm-copper cover to stop 3MeV electron for lens protection**



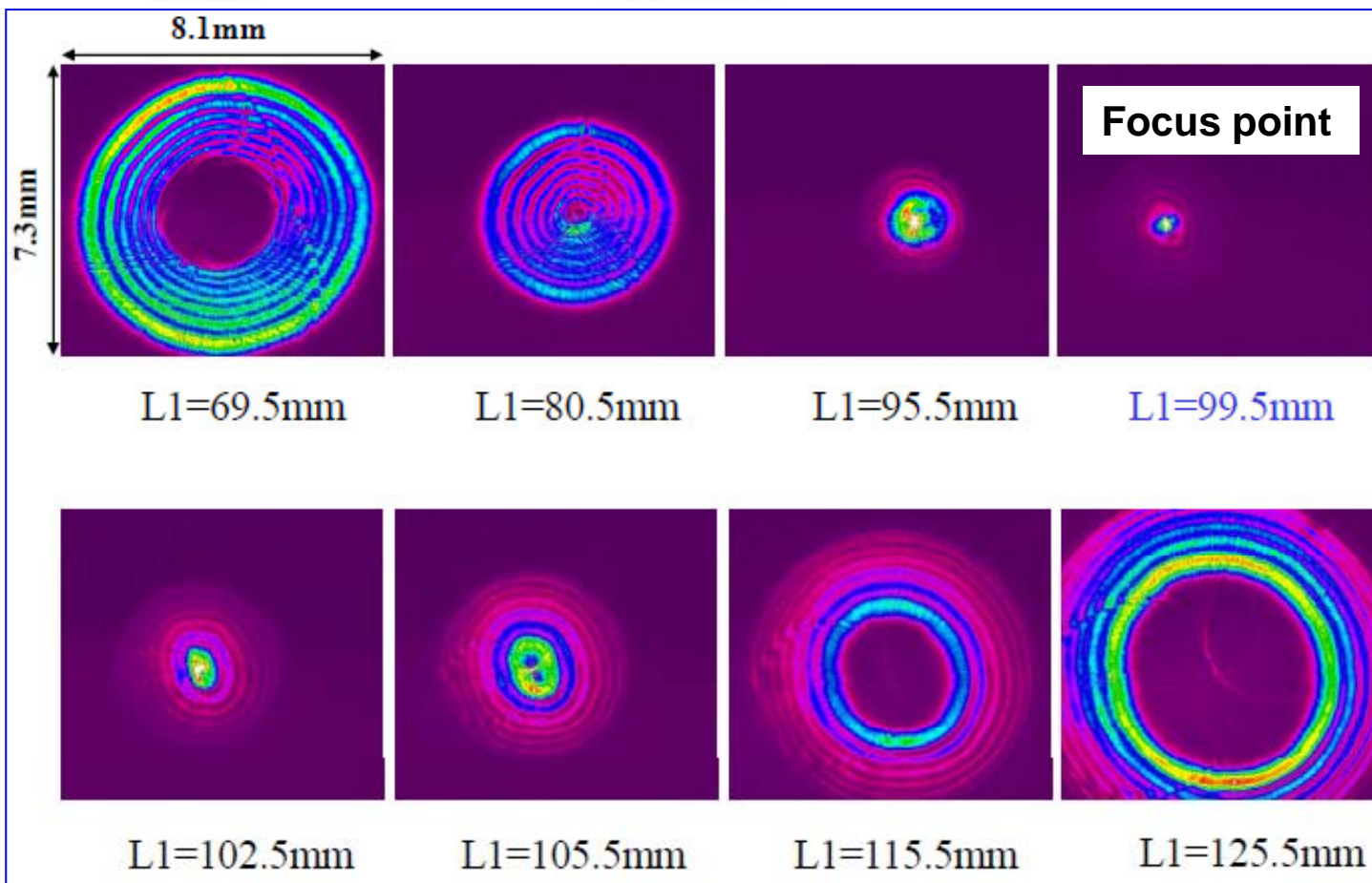
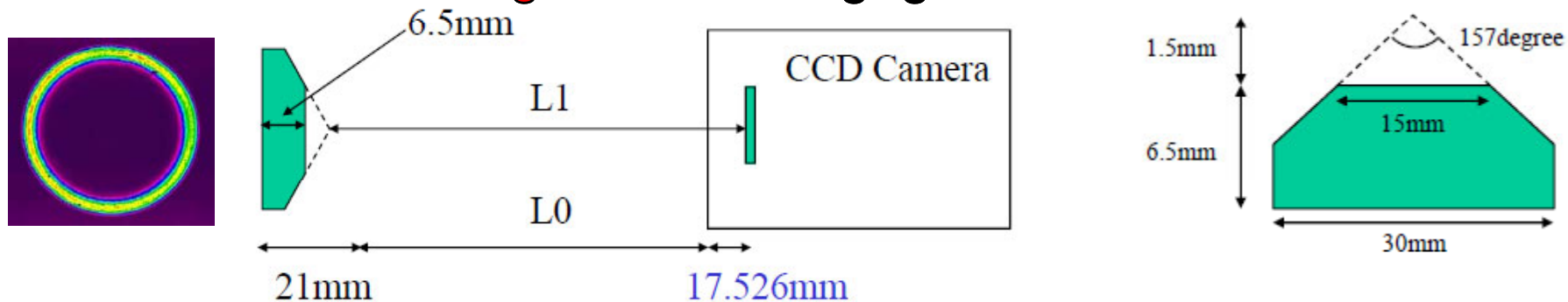
# Type1: Convex focusing lens:

~< 10~100μm spot size

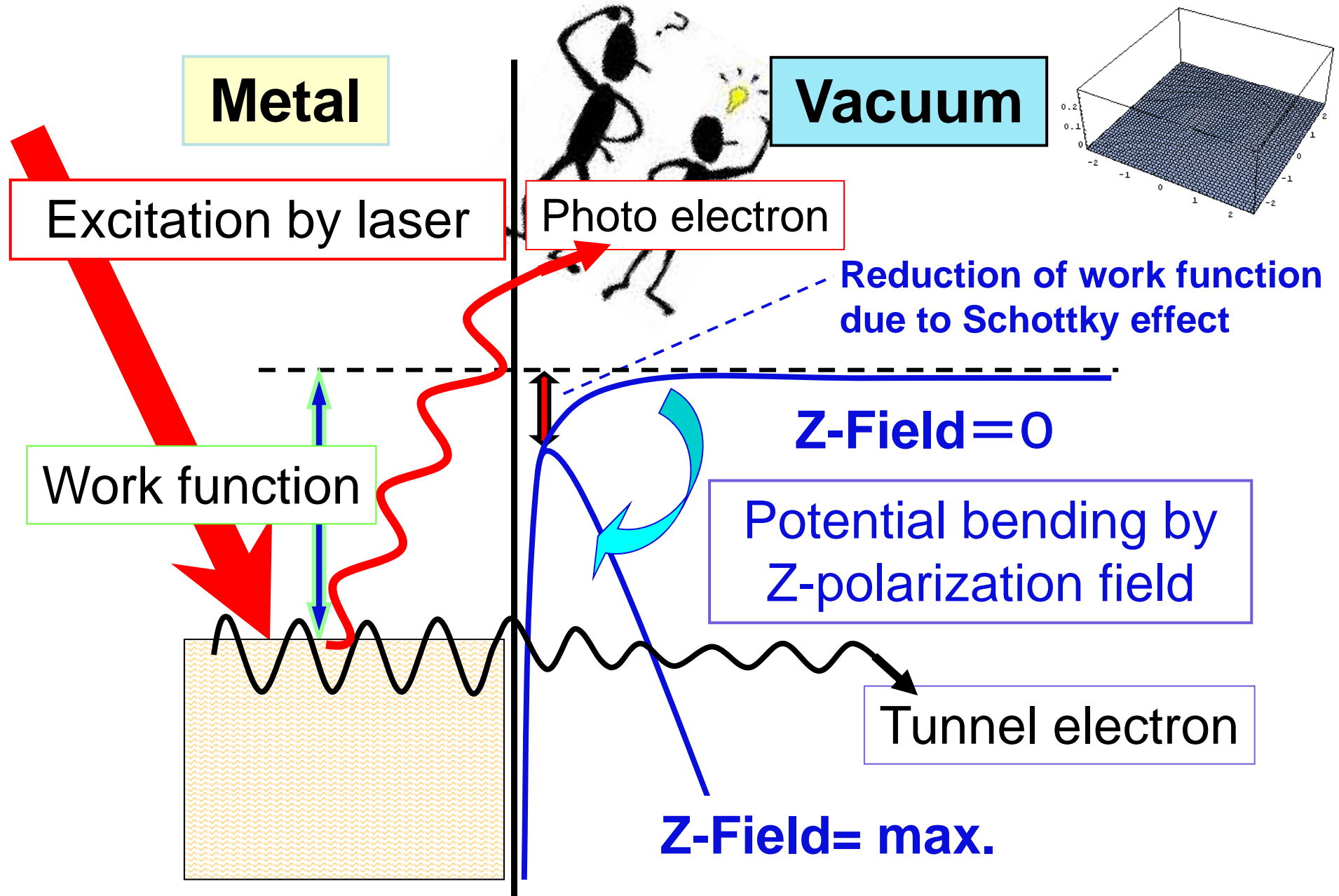
for **very low** bunch charge generation



**Type2: Axicon focusing lens:** ~< mm spot size  
**for higher bunch charge generation**

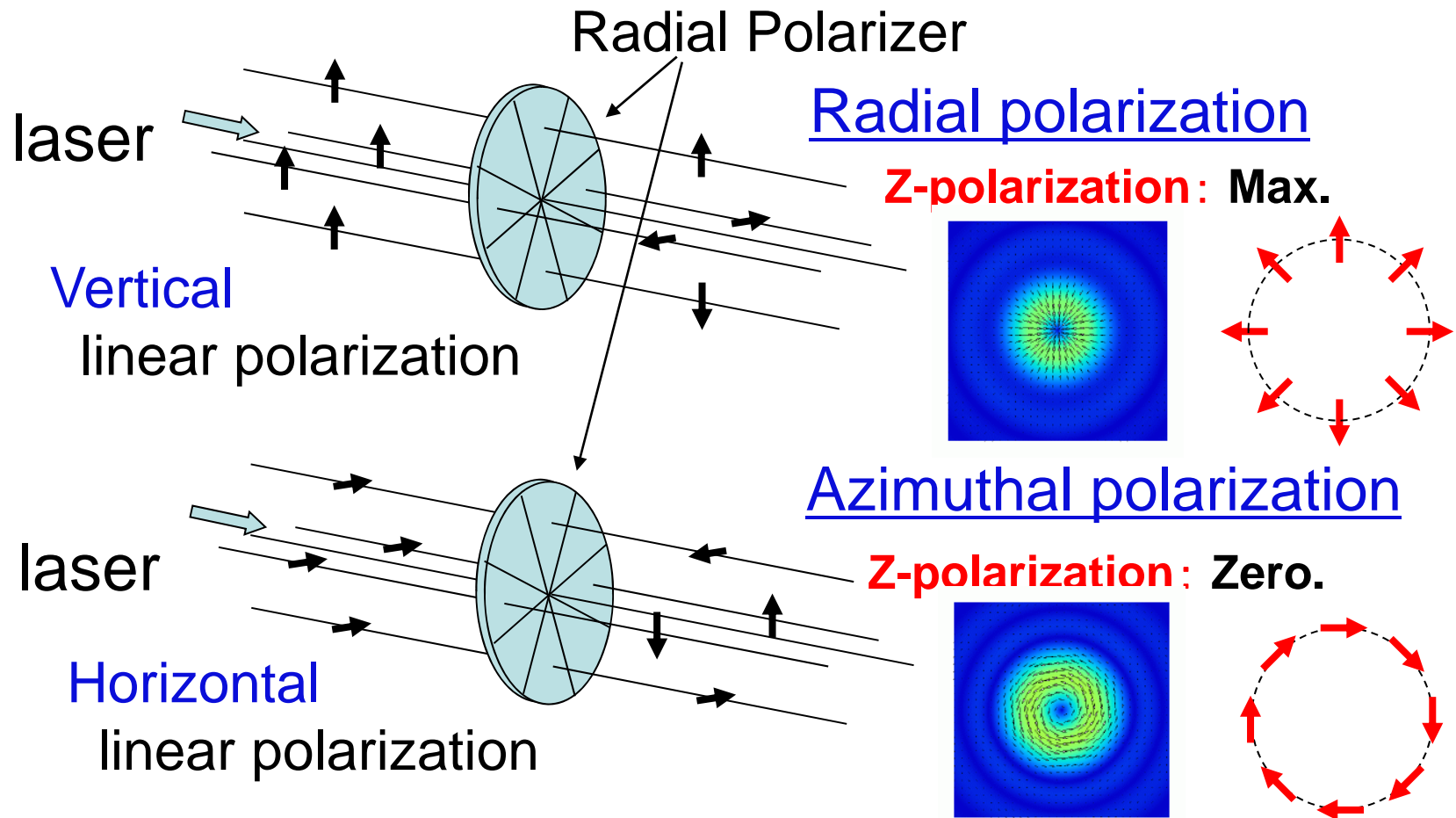


# Is the response of metal cathode femtosecond ?



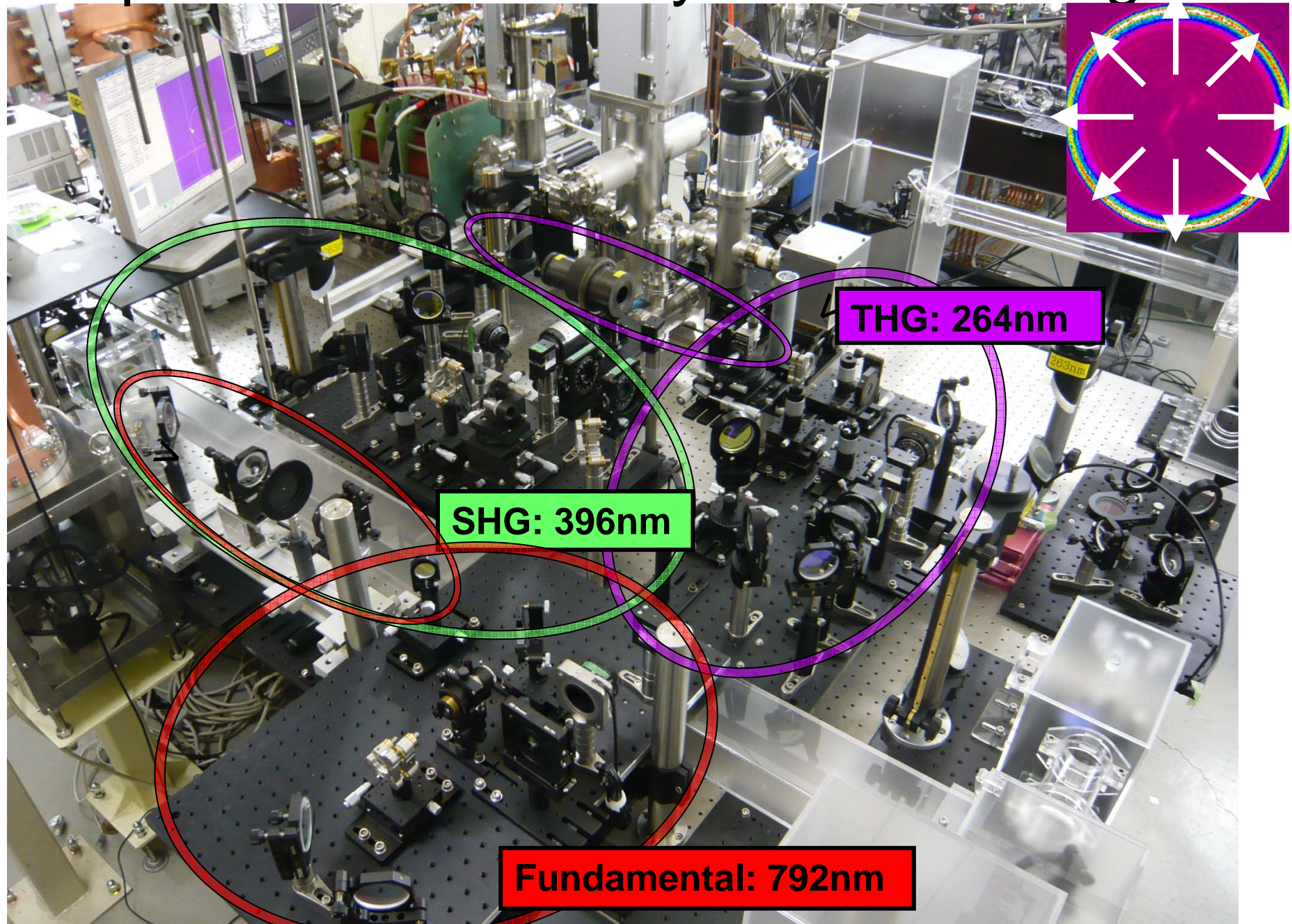
# Feasibility test for Z-polarization effect

(Comparison between radial & azimuthal polarization)

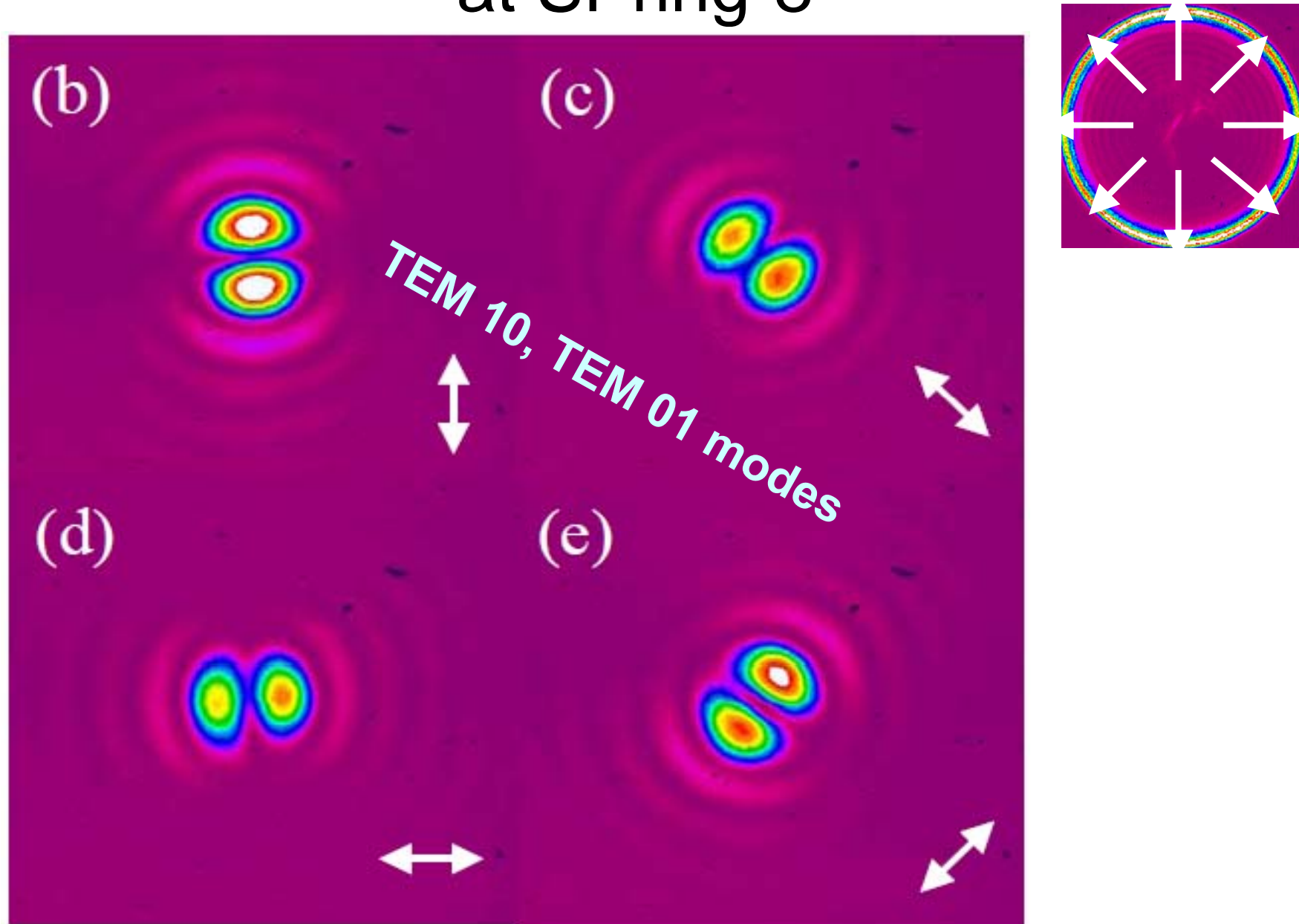


- (1) We can switch radial to azimuthal with rotating half waveplate!
- (2) Comparison between radial and azimuth polarization can tell Z-polarization effect on the cathode (**spot size** & **photon density**).

# Z-polarization Gun System at SPring-8



# Radial polarization laser test with a polarizer at SPring-8



# Cathode candidates for UV Z-polarization

Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni



1

1.0079

H

HYDROGEN

3

6.941

Li

LITHIUM

11

22.990

Na

SODIUM

19

39.098

K

POTASSIUM

37

85.468

Rb

RUBIDIUM

55

132.91

Cs

CAESIUM

87

(223)

Fr

FRANCIUM

2

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He

HELIUM

4

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Be

BERYLLIUM

12

24.305

Mg

MAGNESIUM

20

40.078

Ca

CALCIUM

38

87.62

Sr

STRONTIUM

56

137.33

Ba

BARIUM

88

(226)

Ra

RADIUM

13

10.811

B

BORON

5

10.811

B

BORON

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BORON

14

28.086

Si

SILICON

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30.974

P

PHOSPHORUS

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32.065

S

SULPHUR

17

35.453

Cl

CHLORINE

18

39.948

Ar

ARGON

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69.723

Ga

GALLIUM

49

114.82

In

INDIUM

67

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Tl

THALLIUM

83

208.98

Bi

BISMUTH

101

(209)

Po

POLONIUM

115

(289)

Uuq

UNUNQUADIUM

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12.011

C

CARBON

6

12.011

C

CARBON

14

28.086

Si

SILICON

32

72.64

Ge

GERMANIUM

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118.71

Sn

TIN

68

196.967

Au

GOLD

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Po

POLONIUM

102

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At

ASTATINE

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NITROGEN

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PHOSPHORUS

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ARSENIC

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ANTIMONY

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GOLD

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CHLORINE

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BROMINE

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IODINE

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ARGON

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KRYPTON

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Xe

XENON

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178.49

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SEABORGIUM

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POTASSIUM

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Rb

RUBIDIUM

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Cs

CAESIUM

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YTTRIUM

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BARIUM

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RHENIUM

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54

131.29

Xe

XENON

72

178.49

Hf

HAFNIUM

90

(223)

Fr

FRANCIUM

108

(277)

Hs

HASSIUM

142

(272)

Uuu

UNUNUNIUM

156

(285)

Uub

UNUNBIUM

47

107.868

Ag

SILVER

55

132.91

Cs

CAESIUM

73

180.95

Ta

TANTALUM

91

(223)

Fr

FRANCIUM

109

(268)

Mt

MEITNERIUM

143

(272)

Uuu

UNUNUNIUM

157

(285)

Uub

UNUNBIUM

48

112.41

Cd

CADMIUM

56

137.33

Ba

BARIUM

74

183.84

W

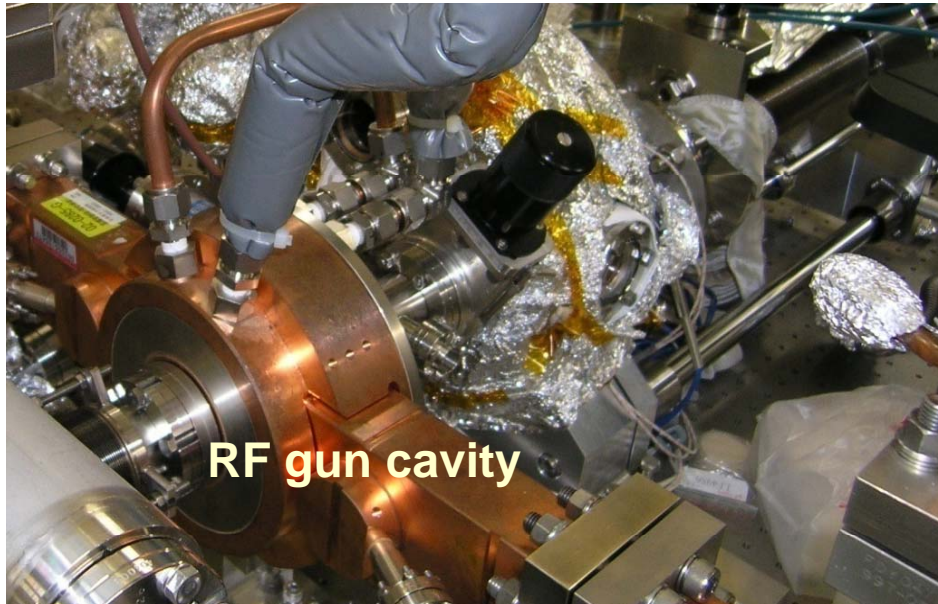
TUNGSTEN

<

# Experiment setup for different cathode test

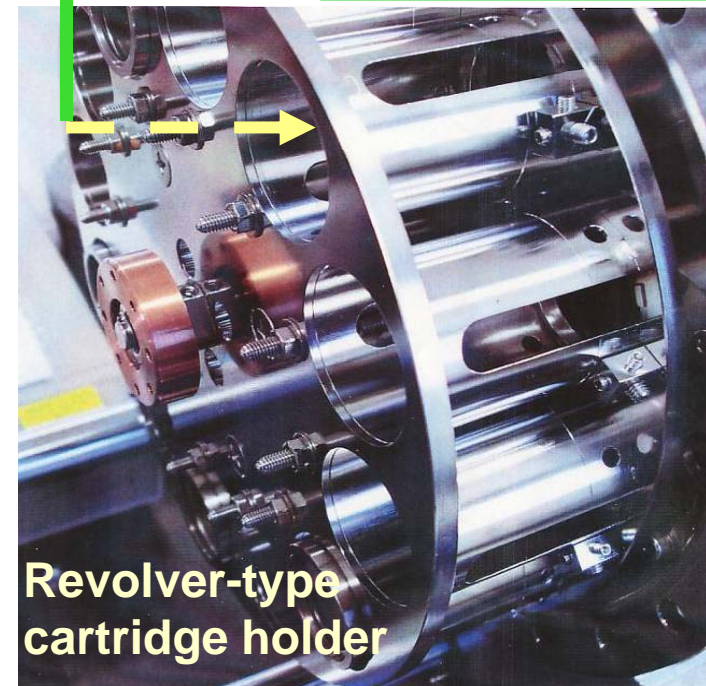
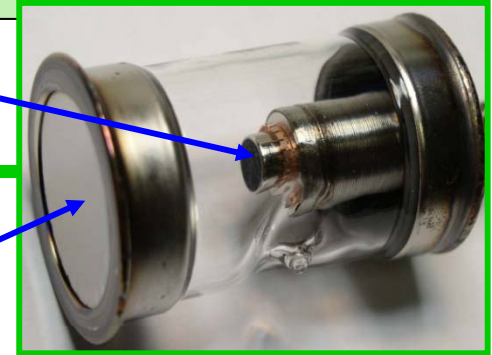
Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni

Cartridge type cathode holder accommodates up to 12 cartridges



Cathode plug

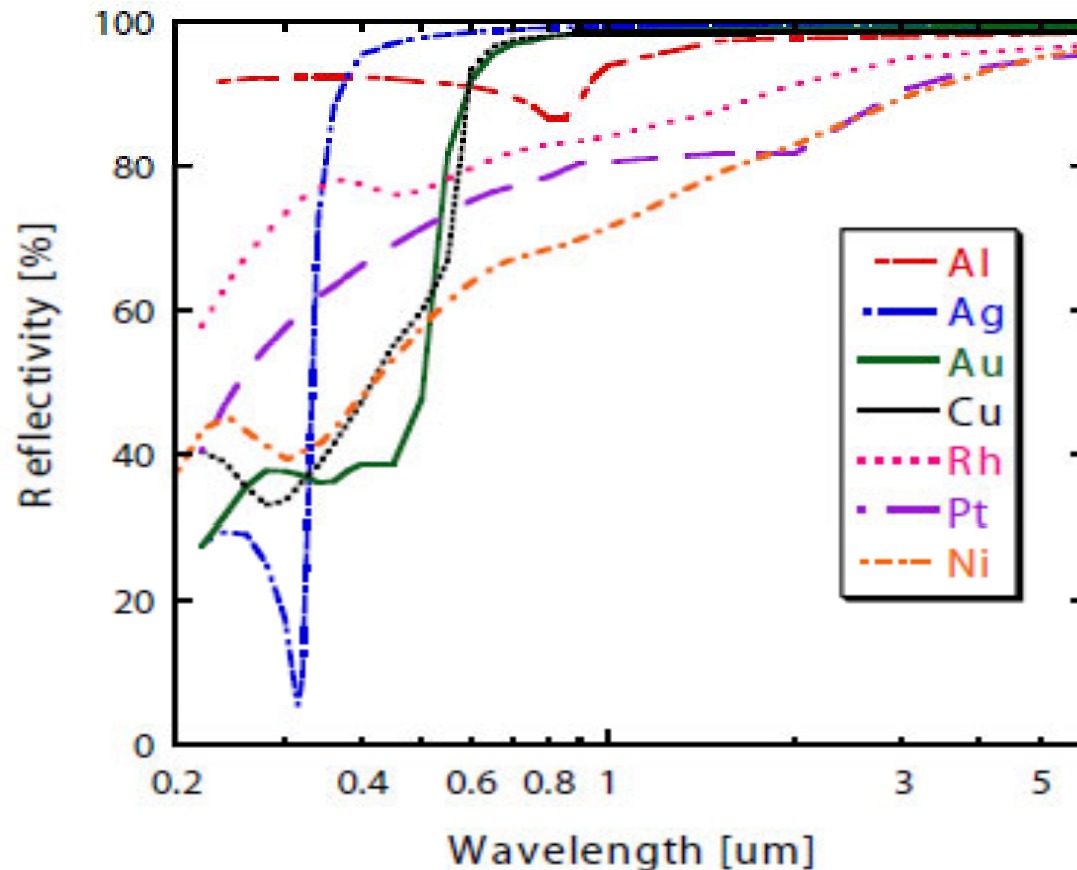
Kovar Foil



# Metal cathode candidates in cartridge tubes



Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni



The question is how fast electron move coherently with laser wake Z-field.

Uncertainty Principle:

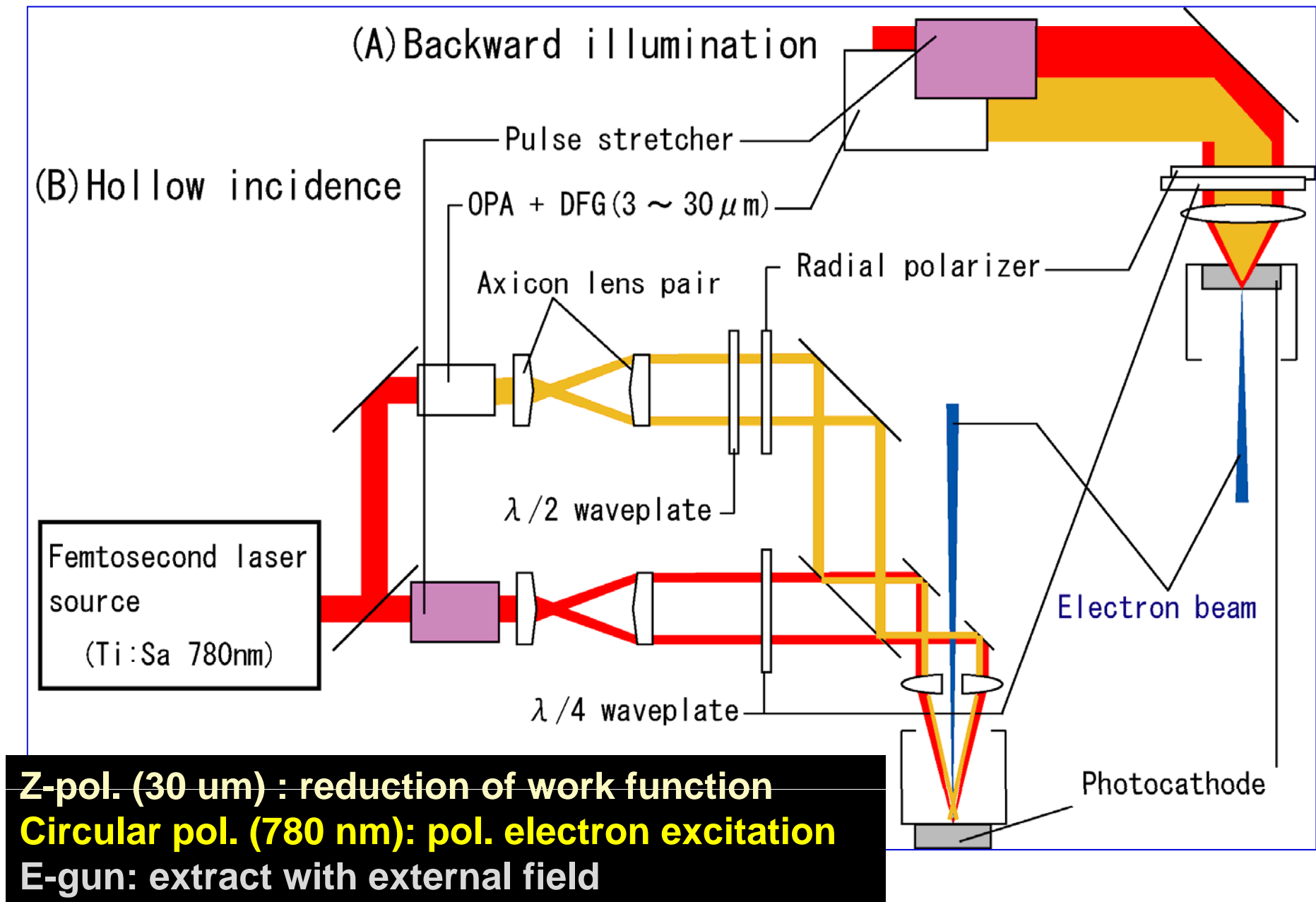
$$h/2\pi \sim [\text{fs}] [\text{eV}]$$

(Dirac's constant)

Skin depth:

$$\text{Metal} \sim \lambda/20$$

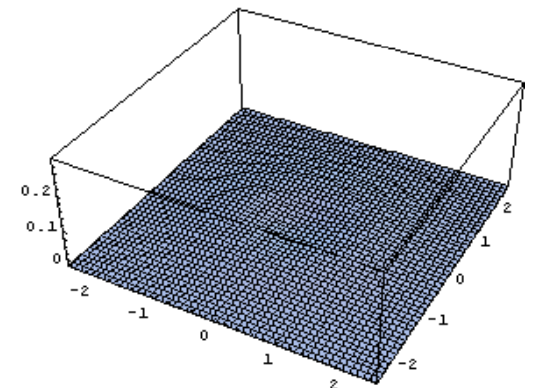
# Polarized electron RF gun (laser-induced field gating)




# Summary

- The generated Z-polarization can exceed an electrical field of 1 GV/m easily with fundamental wavelength from femtosecond laser oscillator (with long cavity). In the case of  $NA=0.15$ , the Z-field of 1GV/m needs **1.2 MW** at peak power for **fundamental (790 nm)** and **0.31 MW** for **SHG**. In the field of 1~2GV/m, the work function of Cu cathode reduces ~2 eV.
- This concept of **laser-induced Schottky emission** can be applied for photo-cathode DC gun.
- For polarized electron source, **Mid-IR** laser is used as a Z-field gate pulse, circular pol. **fundamental** used as a photo-excitation source.

~ **Optical rectification** ~



# History & future plan of Z-polarization gun

- 
- 2006 1. **Z-polarization** gun & **Hollow** beam incidence method were proposed.
- 2007  
~2008 2. **Radial Polarizer**, **Axicon lens pair** & their **Optical coatings** were developed & tested.  
Feasibility test of **Hollow incidence**
- 2009 3. Electron emission with **Z-polarization**.  
& selection of ideal cathode material.
- 2010  
~2011 4. Feasibility test of **Polarized** e-beam generation; Cathode study with T. Nishitani
- Preparing Optics
- Feasibility study