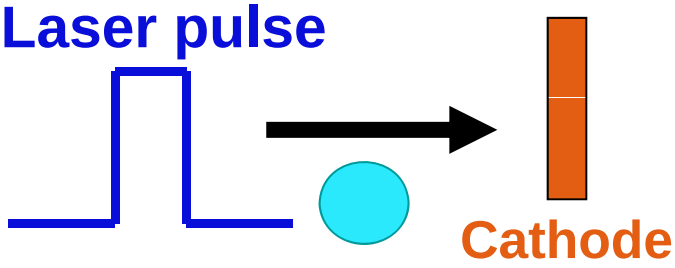
ALTERNATIVE SCHEME FOR POLARIZED ELECTRON SOURCE WITHOUT USING NEA-SURFACE

Hiromitsu TOMIZAWA

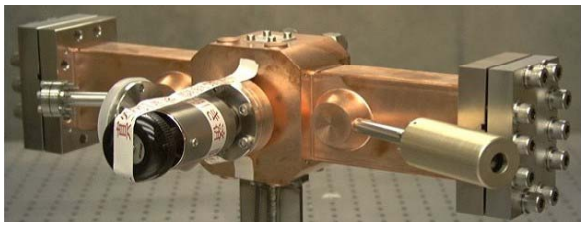
JASRI/SPring-8

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 πmm 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 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 πmm mrad @0.4 nC (pulse width: 10 ps) with "Beer can" laser pulse (Flattop 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

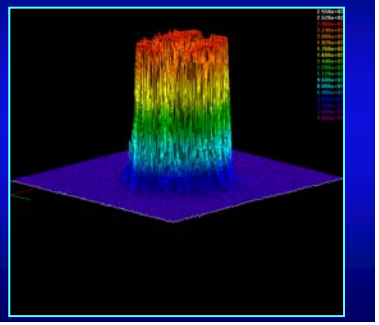
It requires the ultra high vacuum ….

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)

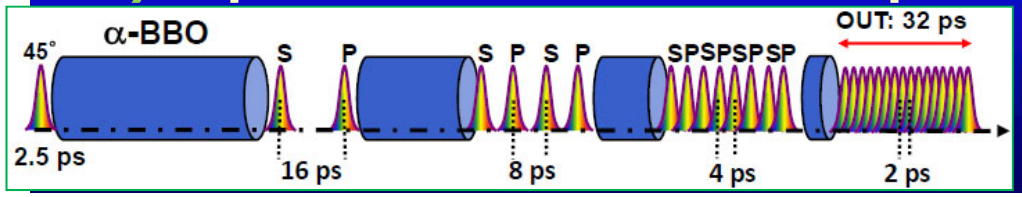


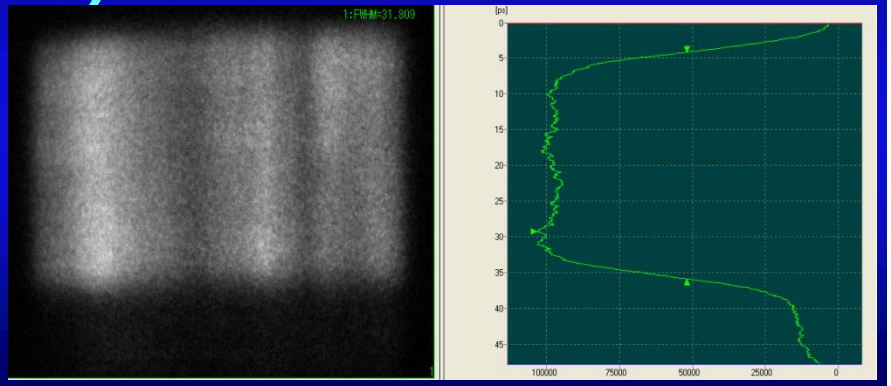
~ However, Laser profiler is damaging for yearlong continuous operation. (Uranium Glass + Camera)

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

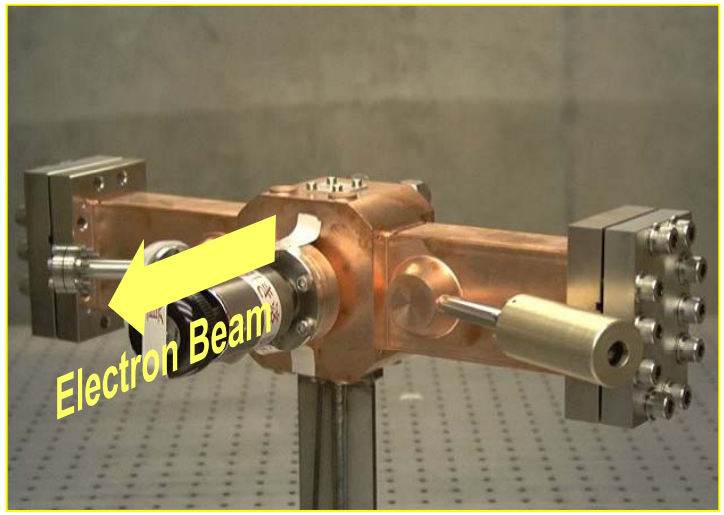




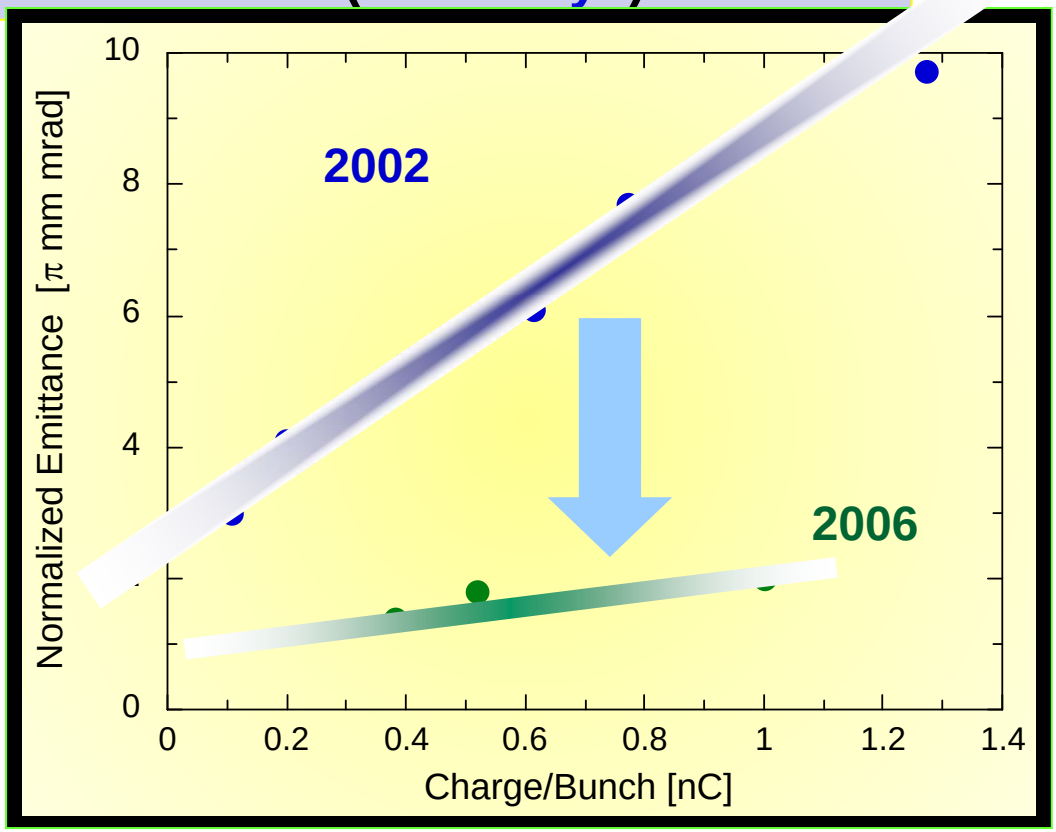
Characteristics of SPring-8 RFgun

1. Laser
   - Spatial profile control : Deformable Mirror
   - Temporal distribution : UV-pulse stacker

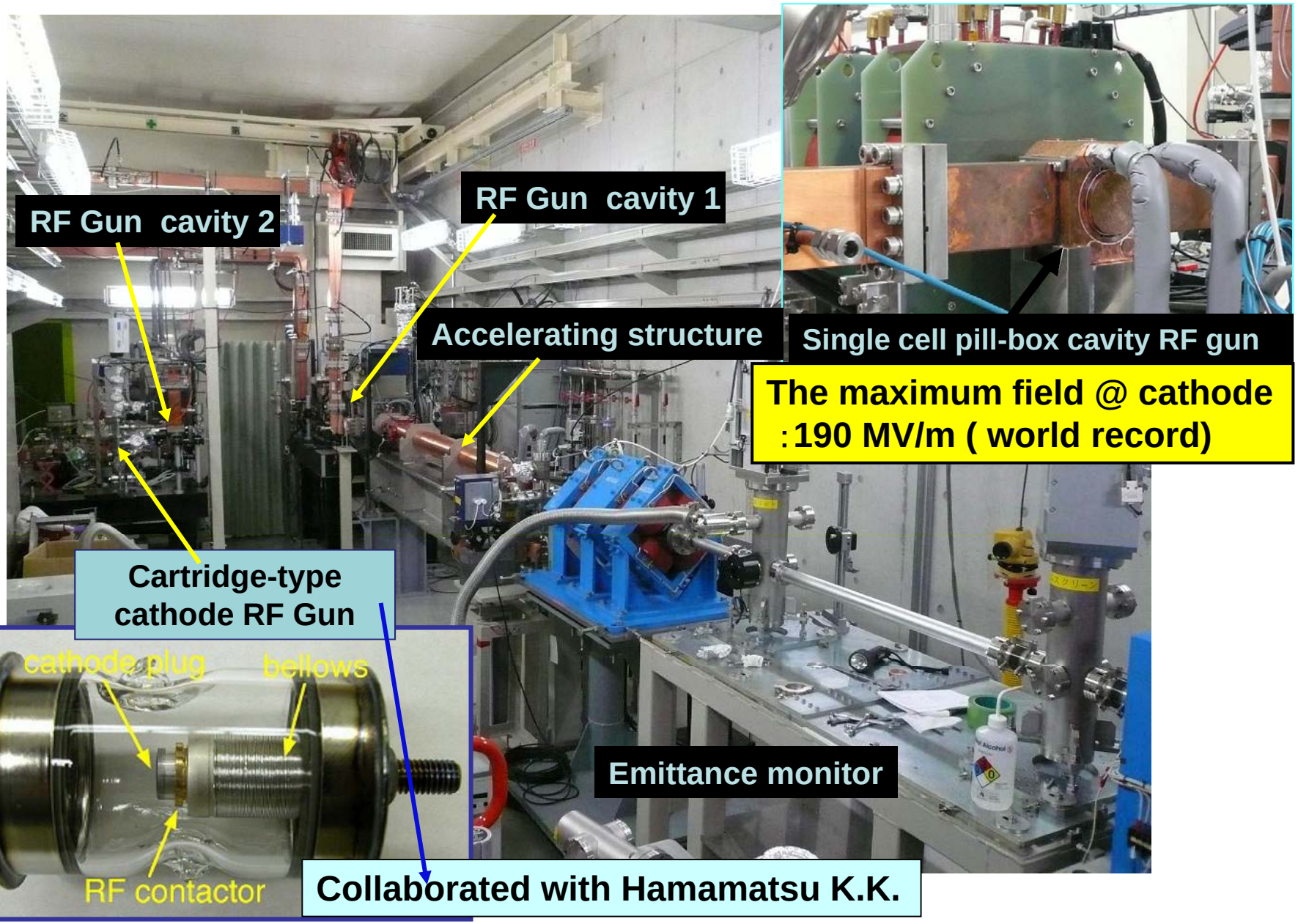
2. RF cavity
   - S-band (2856MHz), Single-cell pill-box type
   - Cathode: fixed cavity wall (RF cavity1)
     changeable cathode plug with cartridge (RF cavity2)
   - High electric field on cathode : 190 MV/m (RF cavity1)



SPring8-type RF gun cavity
190 MV/m



SPring-8 Photocathode RF gun test facility



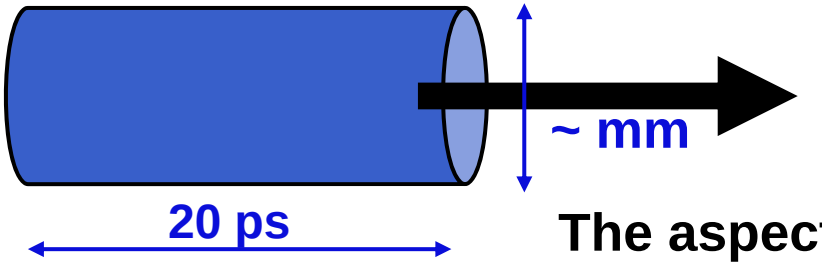
Physical background of ideal laser profile

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

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!

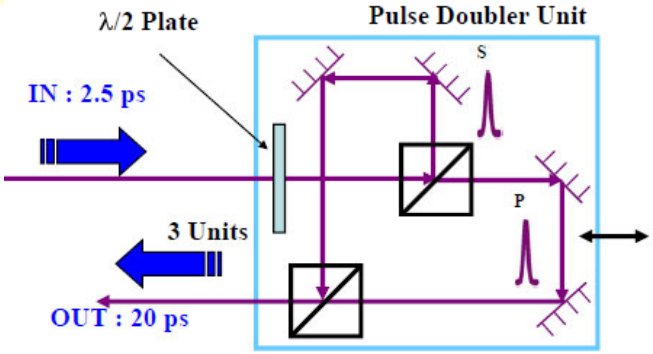
“ Beer can” UV-laser pulse shaping system

UV- Laser source (yearlong stability!)

Laser Pulse Energy : 1.4% @THG

Timing Jitter < 0.3 ps

Cylindrical



Pulse duration: 2.5 ps

Temporal Profile:

Pulse duration: 4 ~ 32 ps

UV- Pulse Stacker

Pulse duration: 32 ps

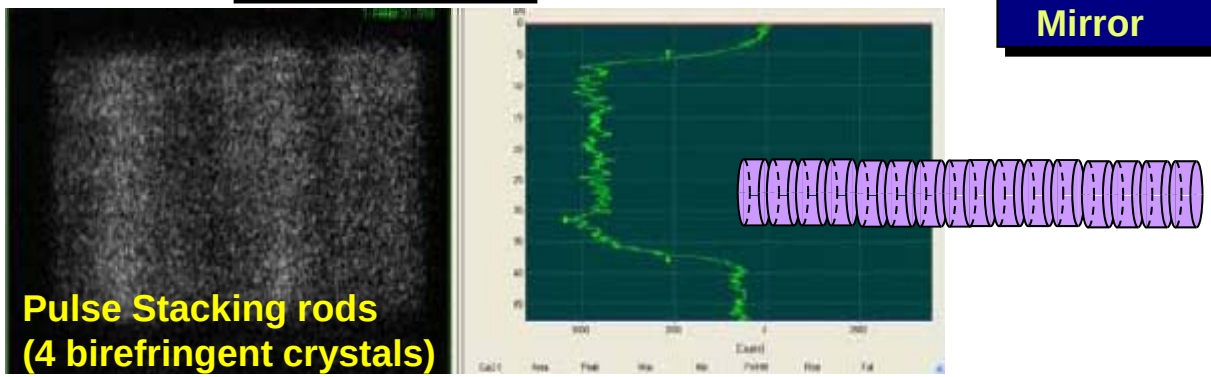
DAZZLER

Pulse Stacker

10 pps

Diameter : 1 mm

Deformable Mirror

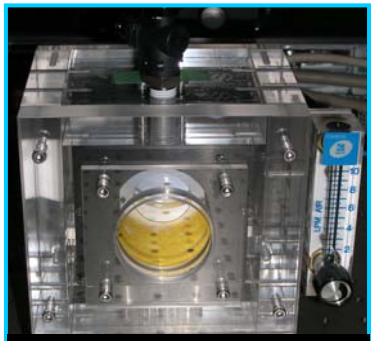


Spatial Profile:

Distribution: Flattop

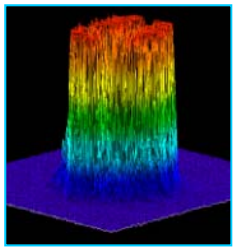
Deformable Mirror

Gaussian



Deformable Mirror

Flattop



Present 3D-laser pulse shaping @ SPring8

Cylindrical

“Beer can”

DAZZLER:
micro pulse shaping

↓

THG

↓

UV-Pulse Stacker:
macro pulse shaping

↓

Deformable mirror:
transverse shaping

↓

Normal incidence to the cathode

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)

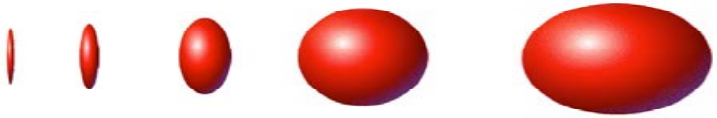
UV- Pulse Stacker (birefringence α-BBO)

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)

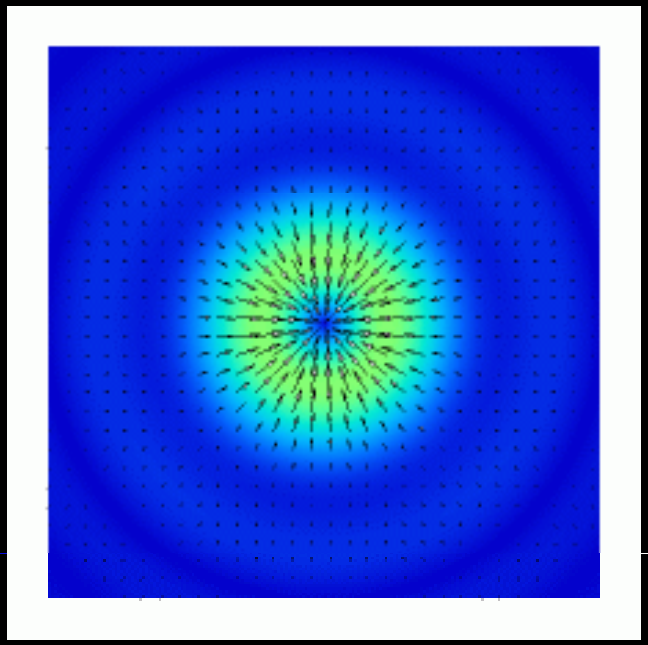
Start from femtosecond pulse

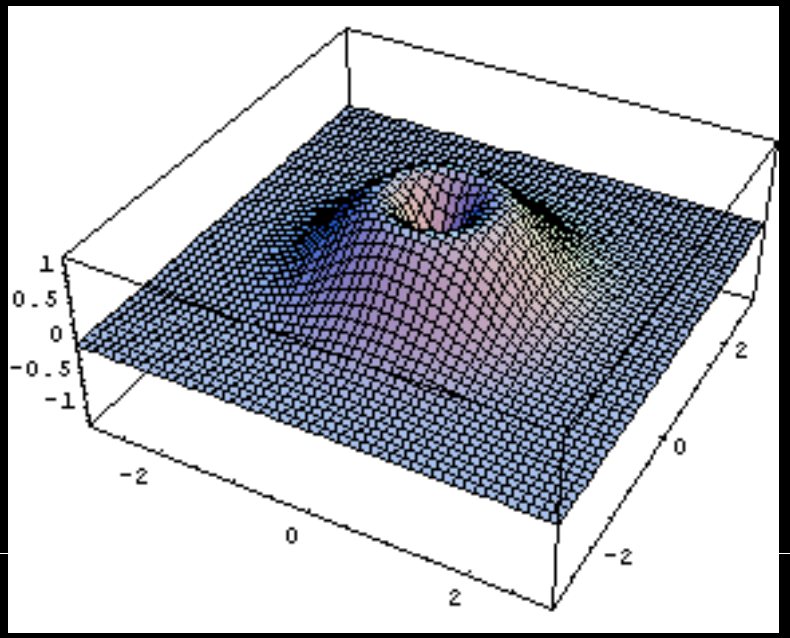
Z-polarization with Schottky effect

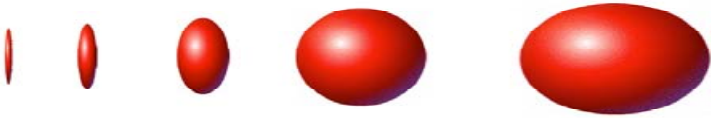
How to utilize the laser coherency….

Laser-field can be used: ***Radial Polarization***

No requirements of laser shaping for high-brightness electron beam





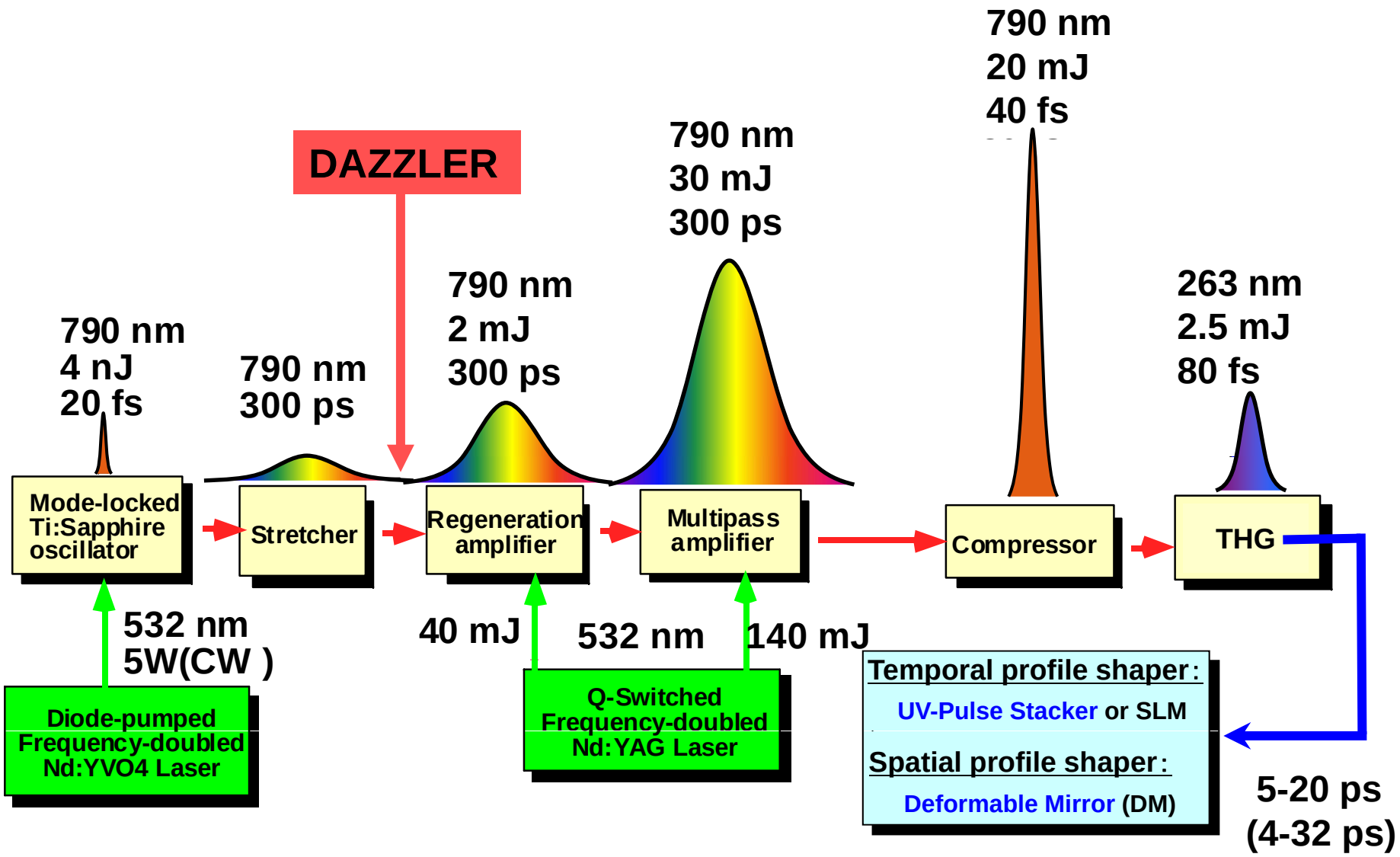


Start from femtosecond pulse

Luiten scheme (2004)

Z-polarization with Schottky effect

Spring-8 Photocathode Laser System Configuration

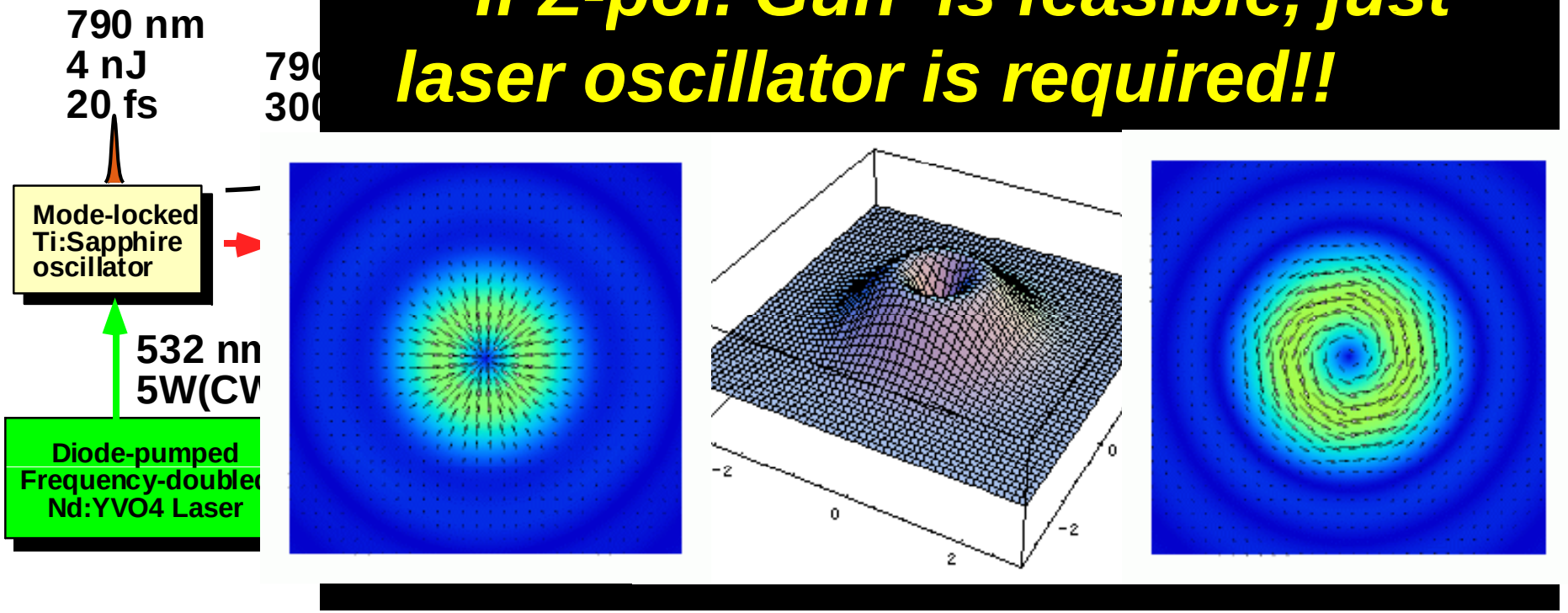


Spring-8 Photocathode Laser System Configuration

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

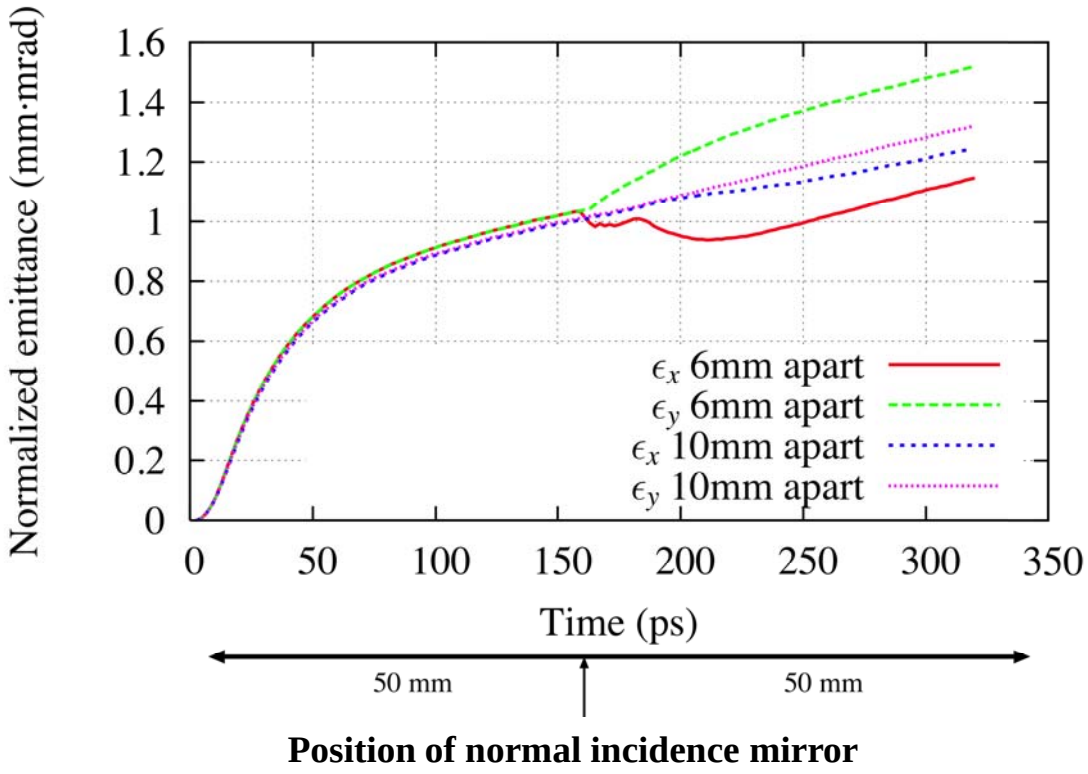
…… Z-polarization

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

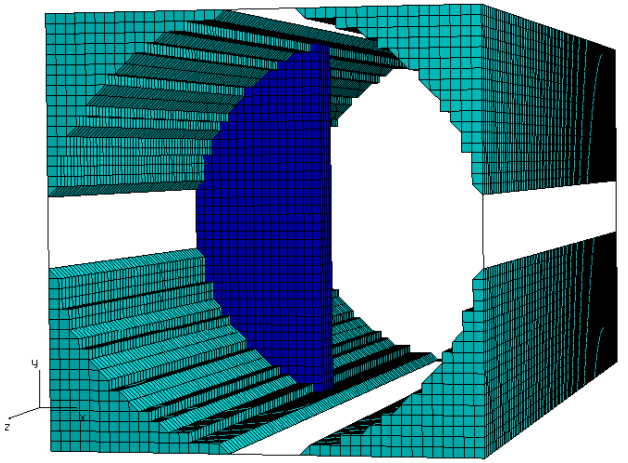


Simulation results of emittance growth under influence of normal incidence mirror installed in horizontal (x-axis)

(Behavior near by mirror in vacuum）



Beam Conditions
bunch charge = 0.83 nC
bunch length = 4.5(1σ)ps(±3σ)
beam size = 3.5(1σ)ps(±3σ)
beam energy = 3.6 MeV
initial emittance = 0 m·rad



- **Simulation results reproduce that Y- emittace growth is larger than X- .**

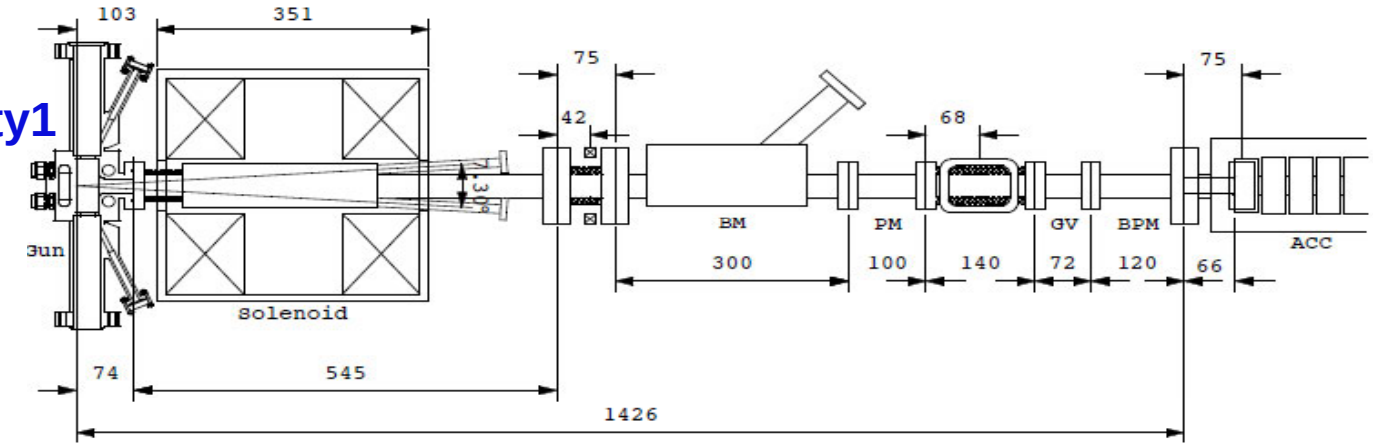
  ⇒ **Normal incidence mirror is the cause of emittance asymmetry.**

- **When the mirror installs 10mm apart from beam axis, emittance symmetry is improved enough.**

New laser incidence schemes

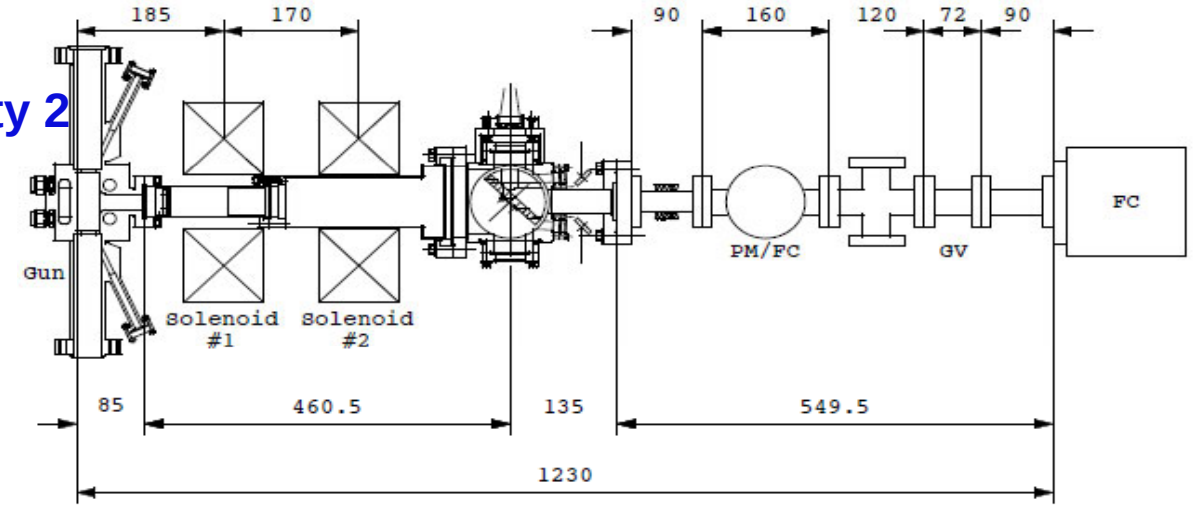
- **A. Quasi-normal incidence (No mirror in Vacuum)**

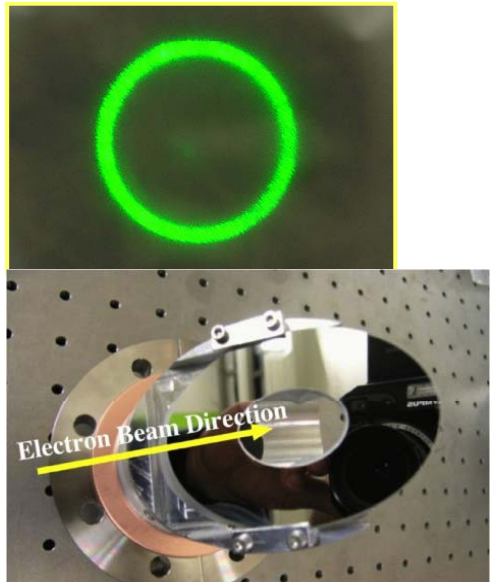
RF cavity1



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

RF cavity 2





A. Quasi-normal incidence

(No mirror in Vacuum)

Improvement of emittance

symmetry

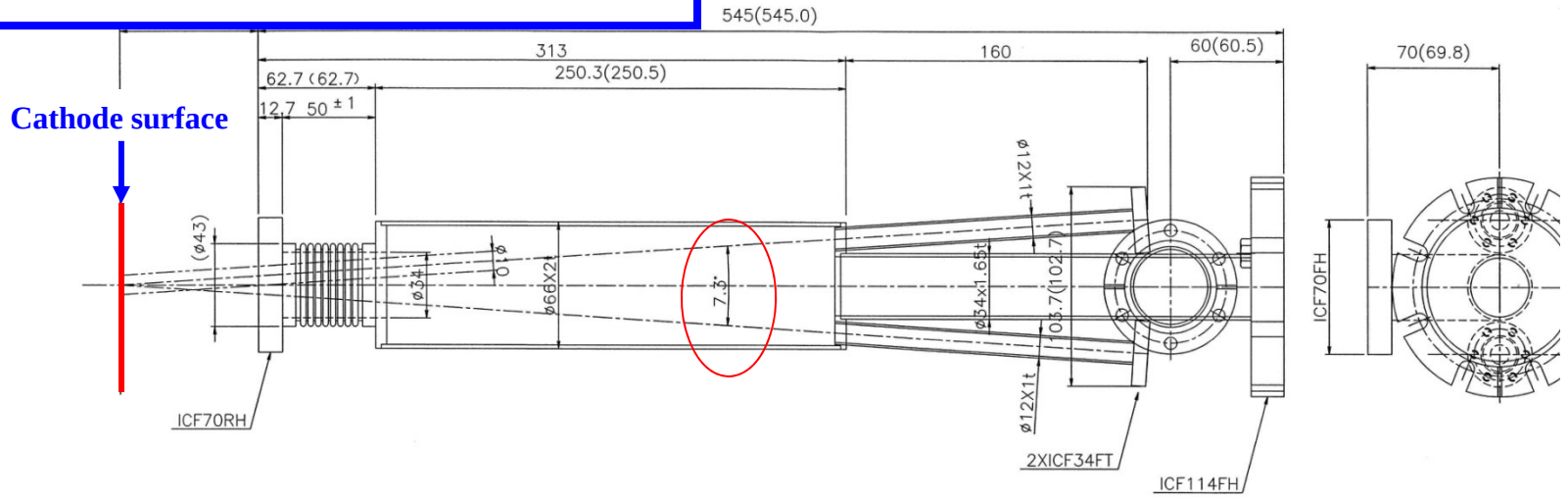
New Oblique Incidence:

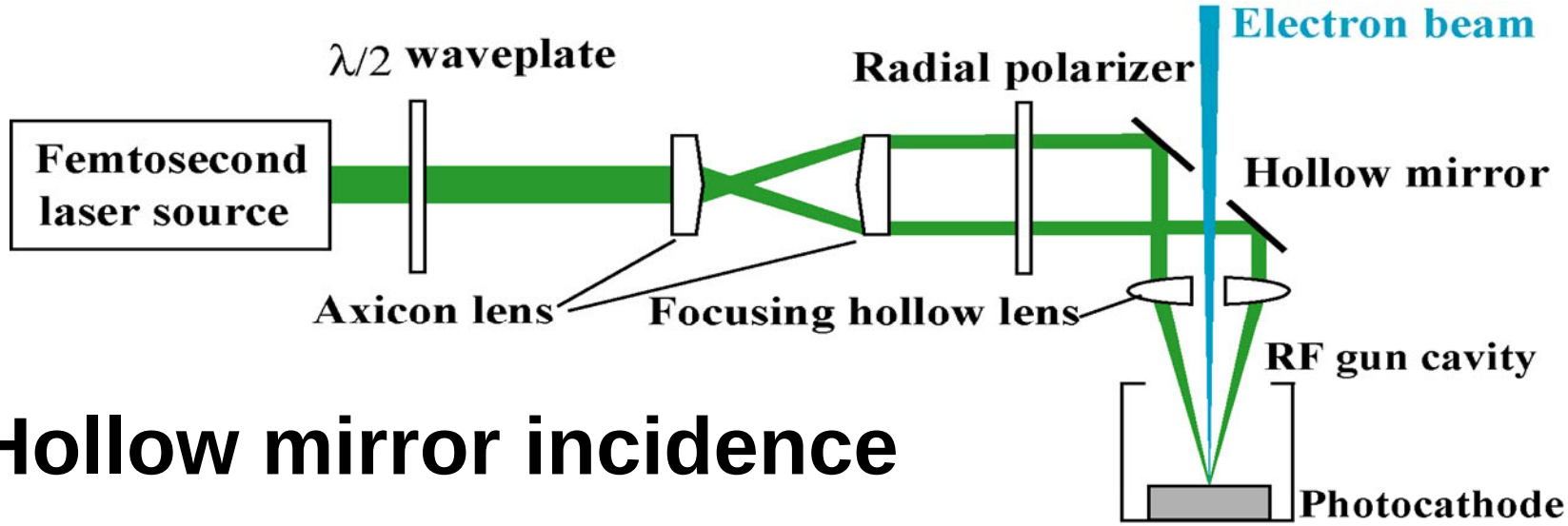
4 degrees (3.65 degrees) incidence

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

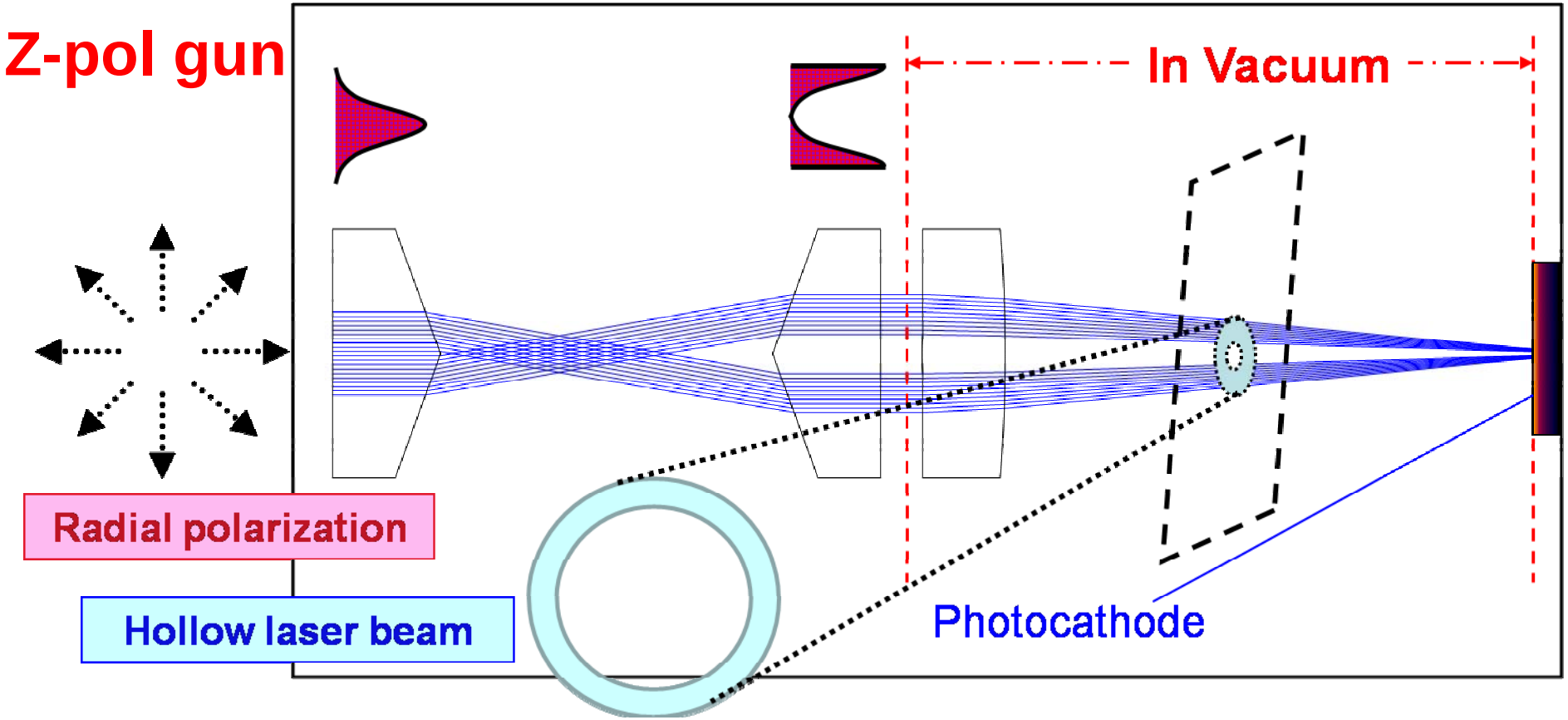
Final transport mirror to the cathode installs out of Vacuum

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





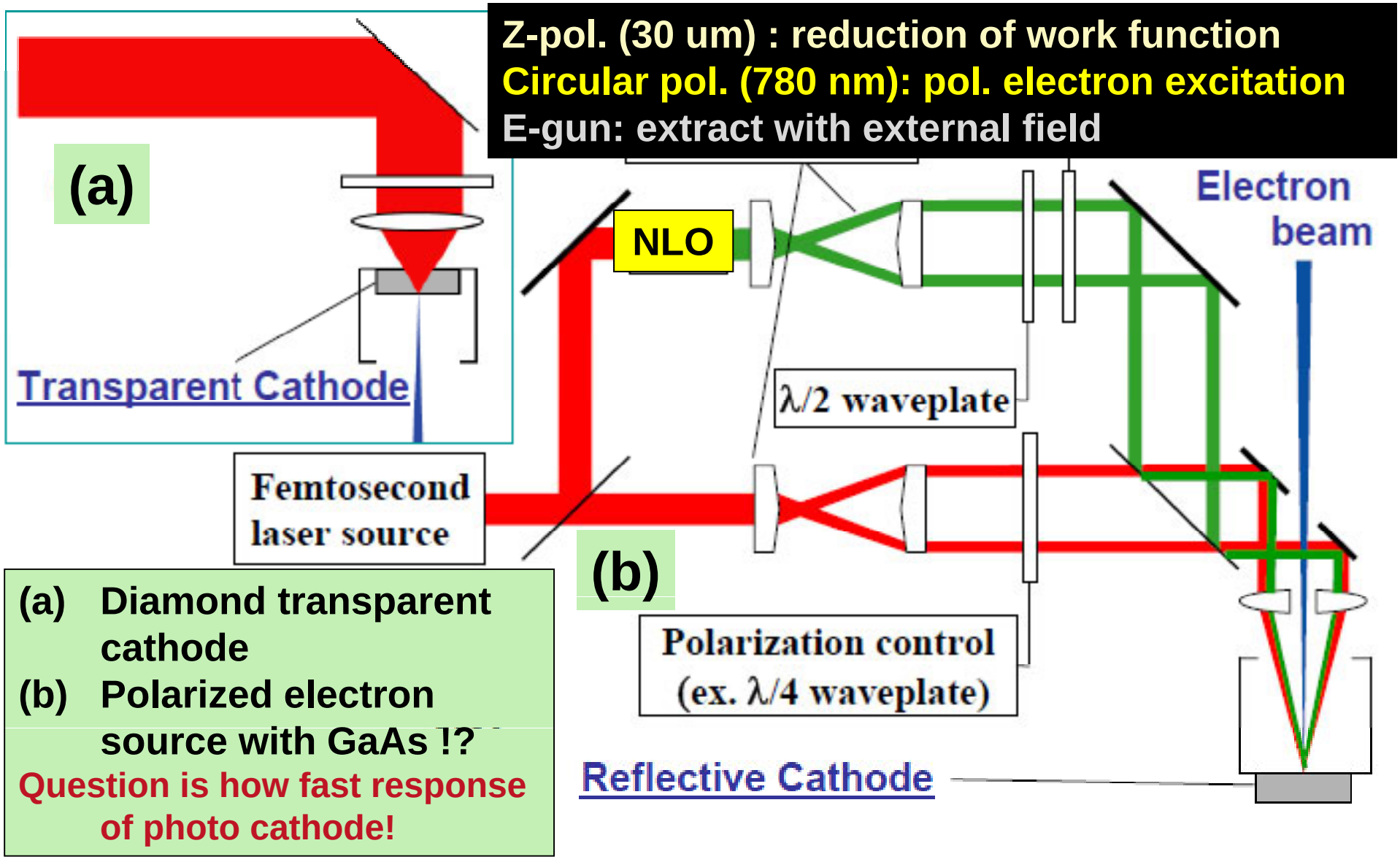
- **B. Hollow mirror incidence**



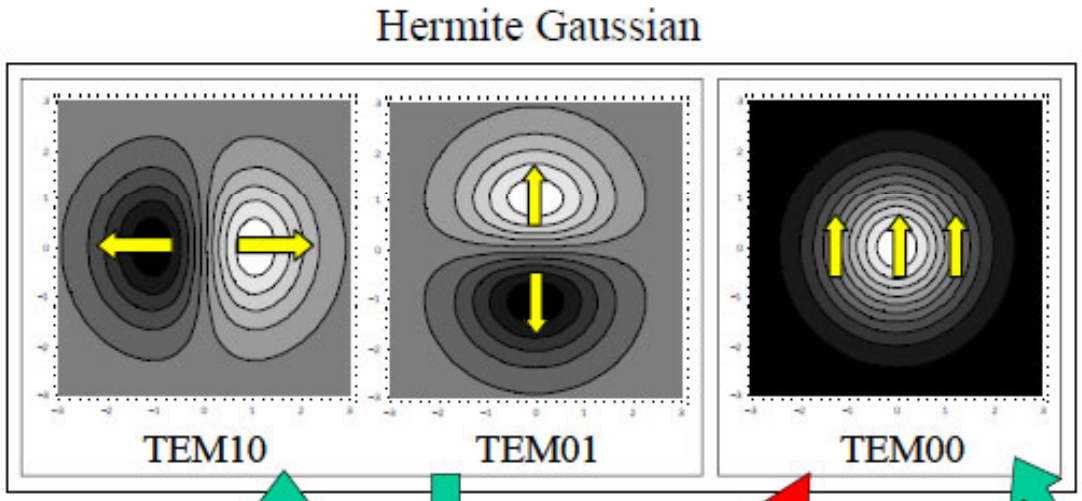
How should we make deal with Laser's coherency?

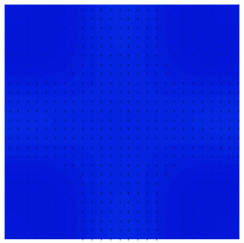
- 1. State-of-the-art photocathode guns have never utilized laser coherency!!
- 2. Utilize coherency with laser Z-polarization with hollow laser beam incidence
  (Optical Schottky effect on the metal cathode)
- 3. If it is possible to use this scheme, it will be an alternative technology for NEA surface

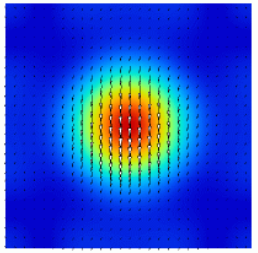
Variation of Z-polarization RF gun with laser –induced field gating (plane field emitter)

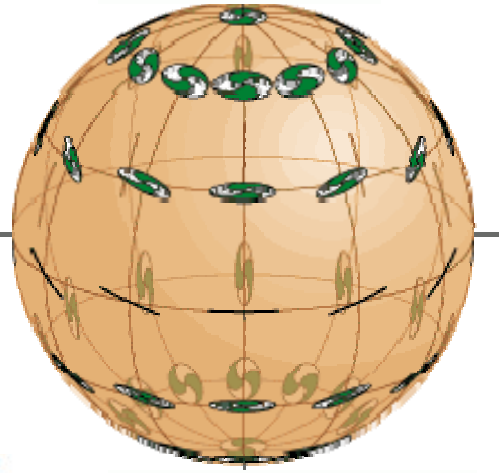


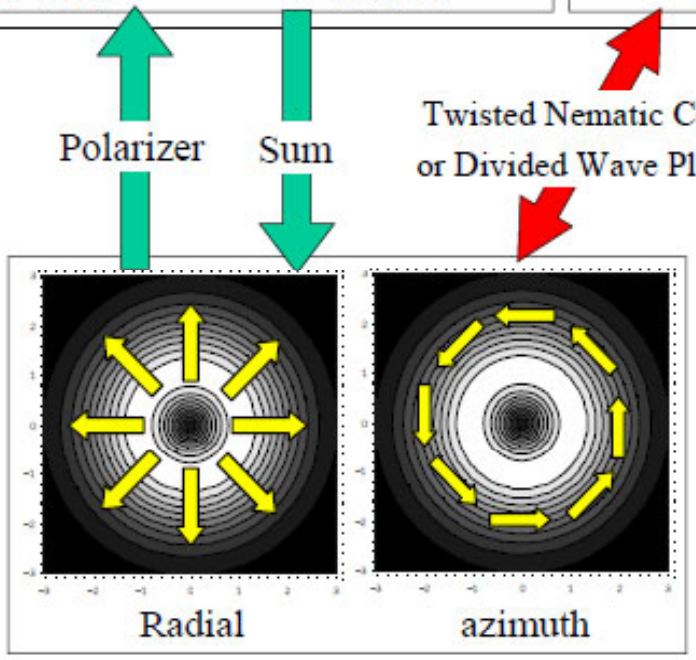
Special laser Polarizations



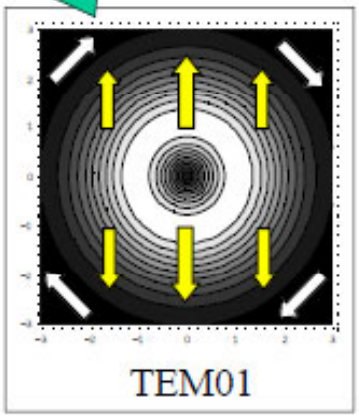




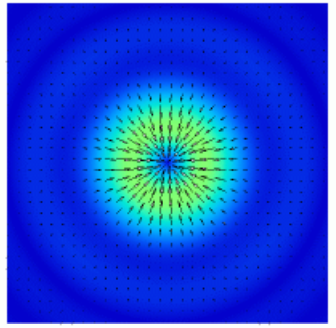


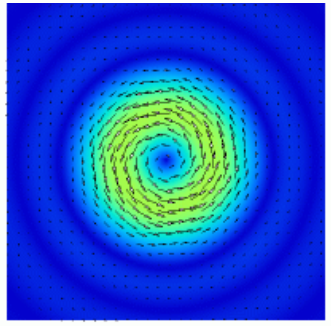


Radial and azimuth polarization



Laguerre Gaussian

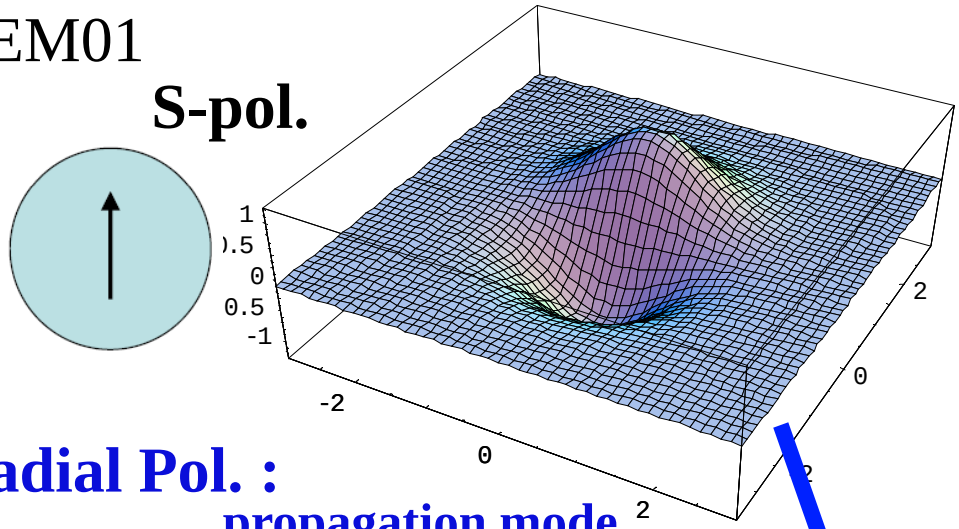




Radial Polarization laser beam

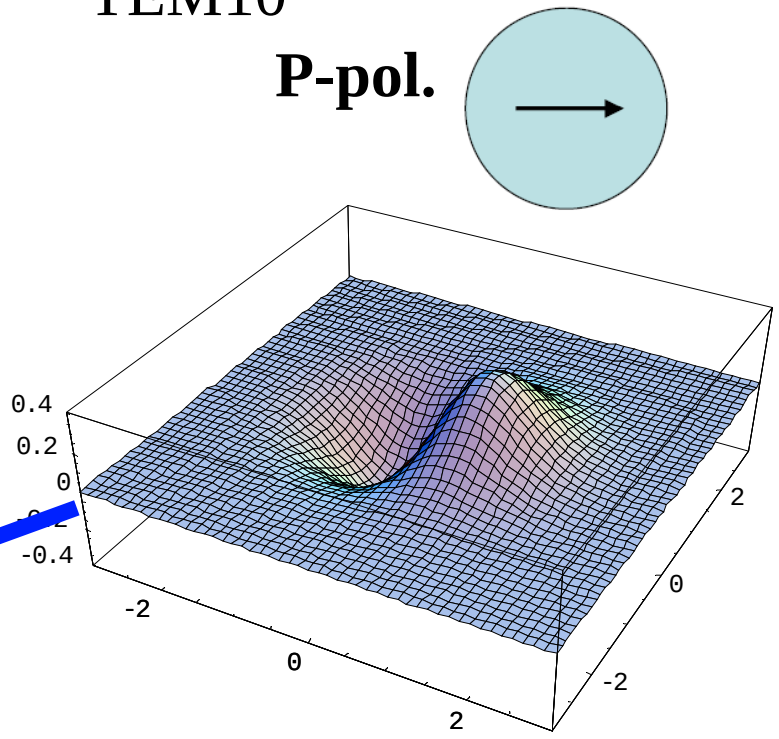
TEM01

S-pol.



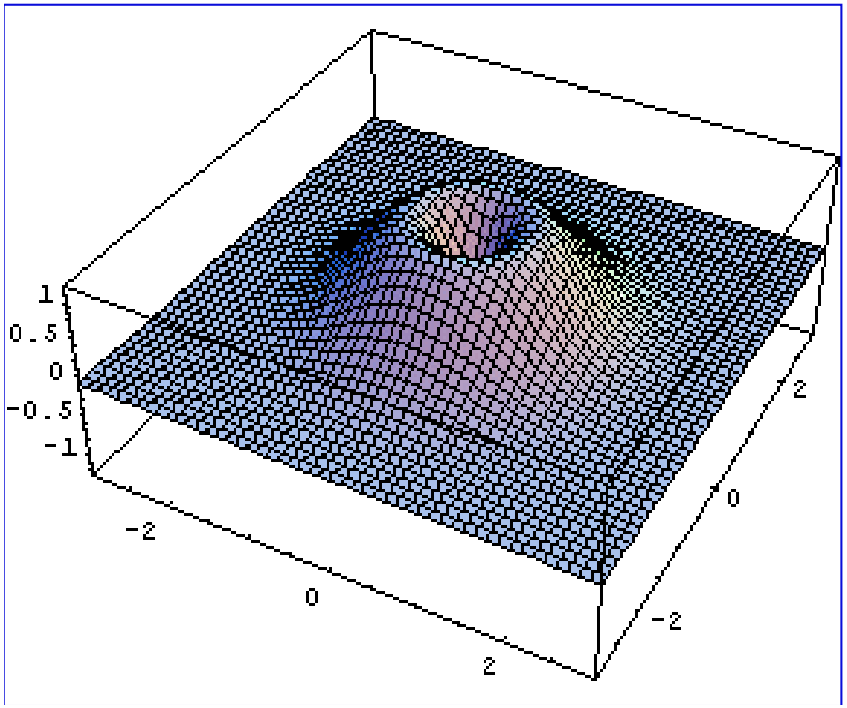
TEM10

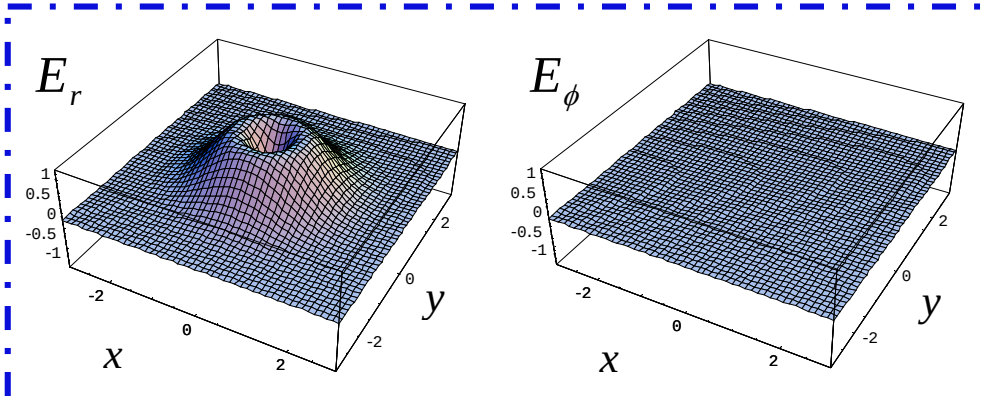
P-pol.



Radial Pol. :

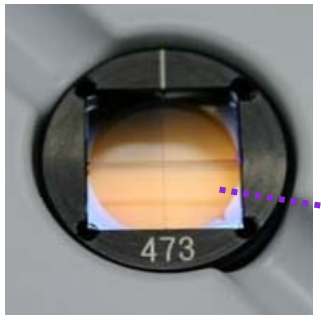
propagation mode

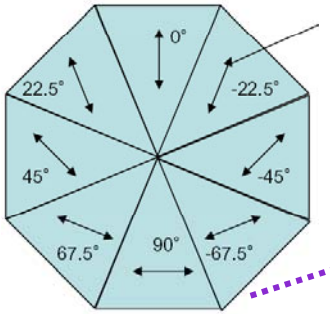


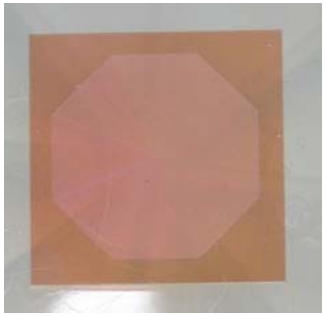


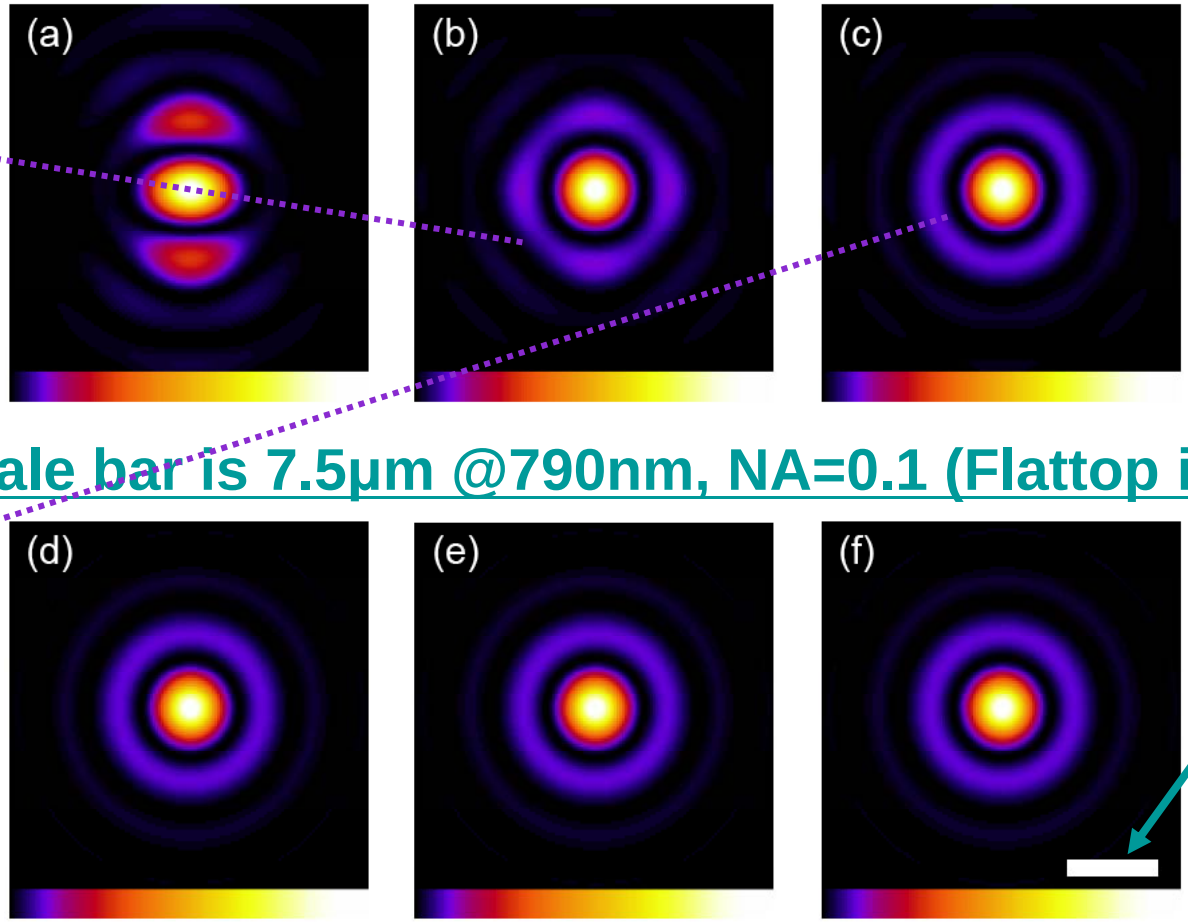
Z-polarization field on the cathode:

Divided number(2~32) dependence







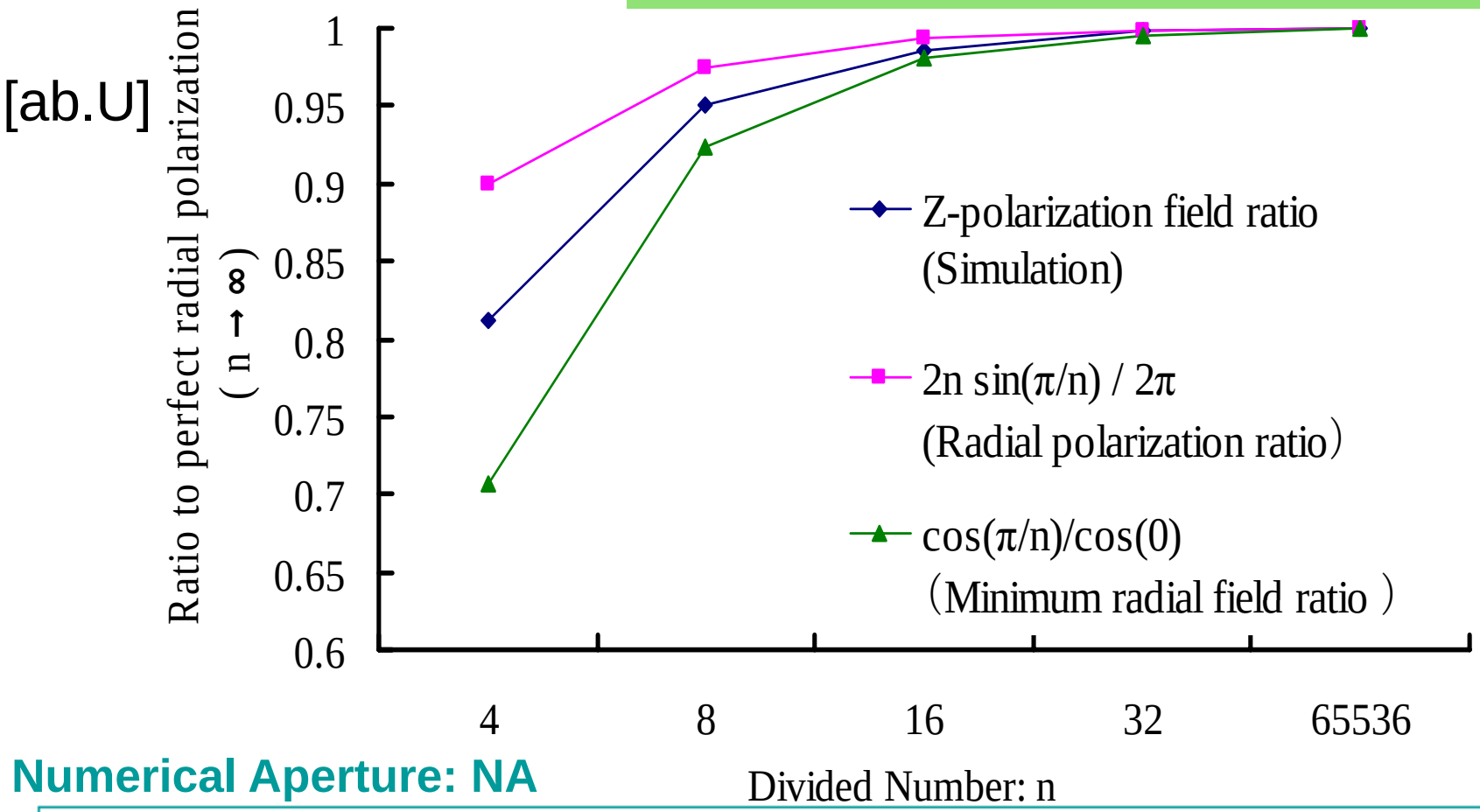


Scale bar is 7.5μm @790nm, NA=0.1 (Flattop incidence)

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

Z-polarization ratio with divided waveplate

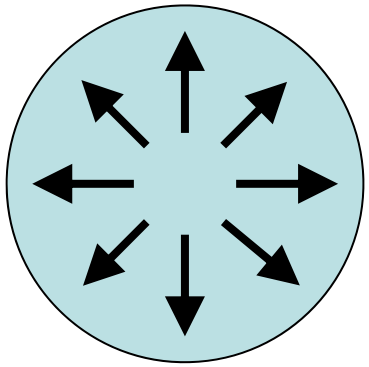
More than n=8, ideal radial polarization

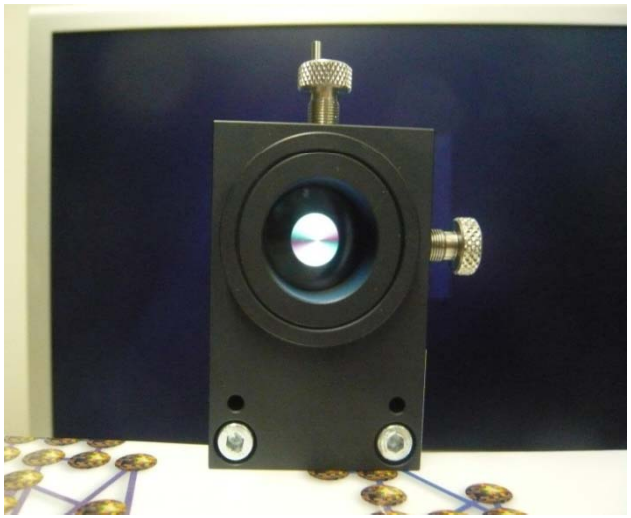


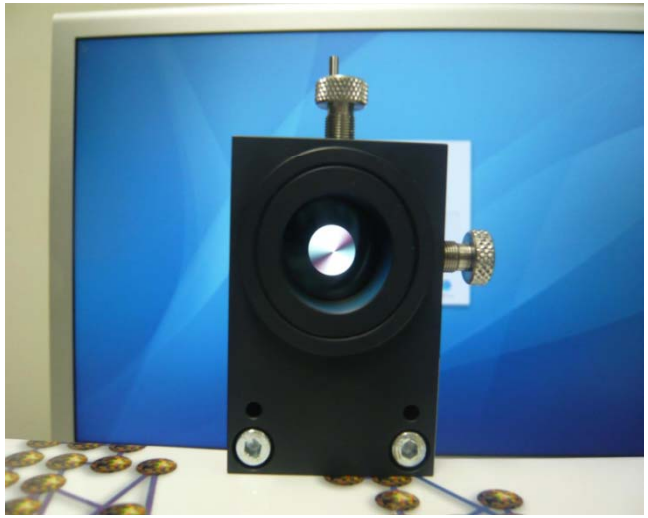
Numerical Aperture: NA

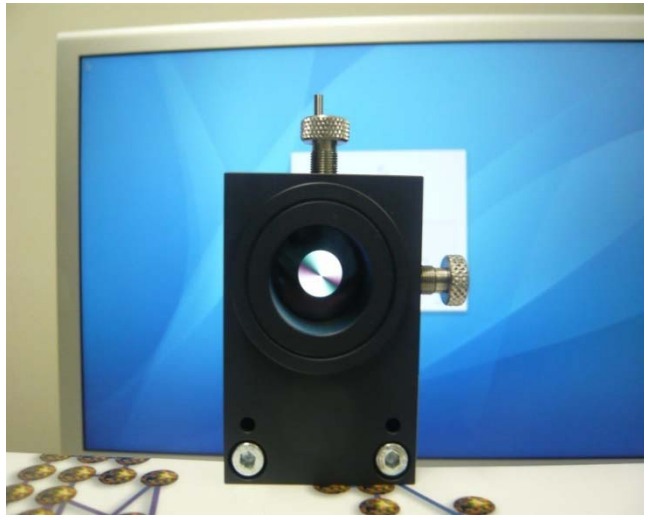
- The strength of Z-polarization field $\propto 1/(\text{WaveInrgth}:\lambda)^2$
- The strength of Z-polarization field $\propto (\text{NA})^{-2}$
  $\propto 1/(\text{Focus length})^2$

Demonstration of Radial polarization with rotation of polarizer

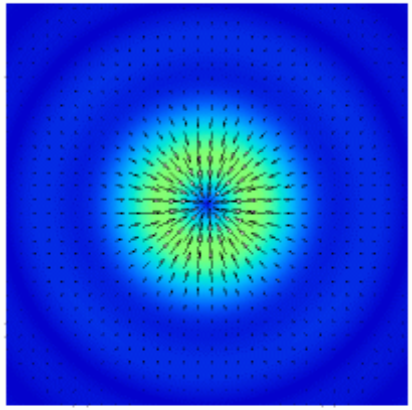






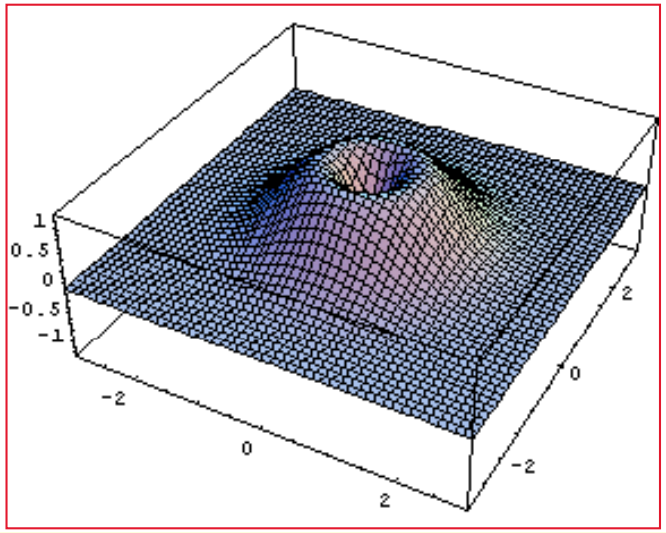


Z-polarized laser on the cathode & field emission with Schotkky effect (It's not proved yet!)

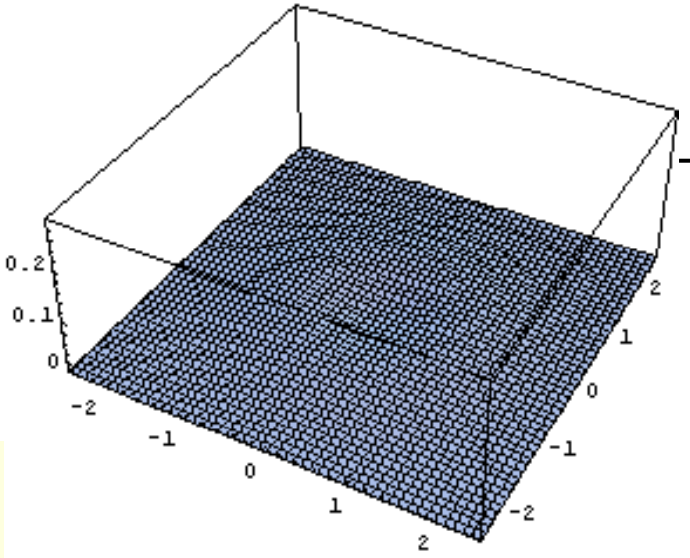


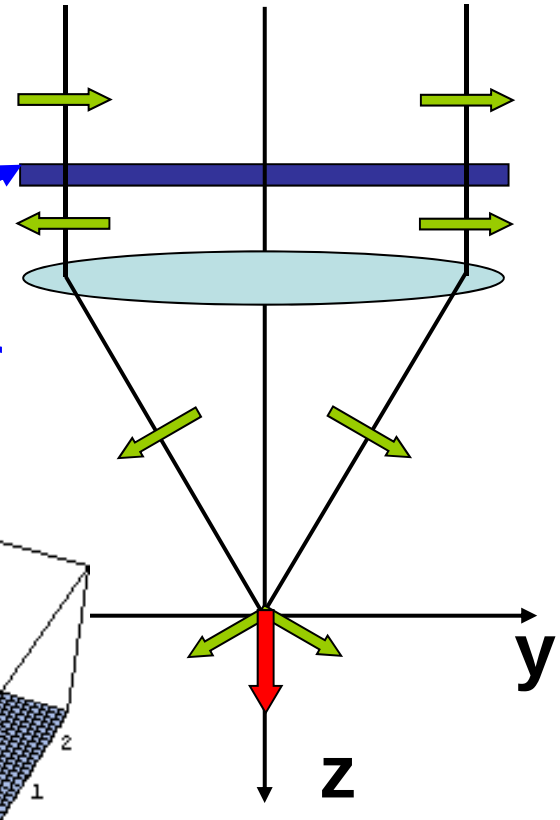
At the focus point, laser electrical field is reinforced in its propagating direction

Radial polarization :



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



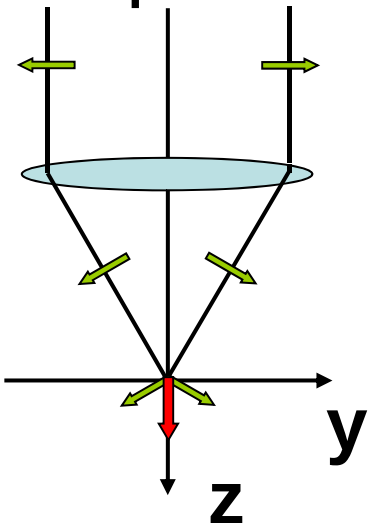


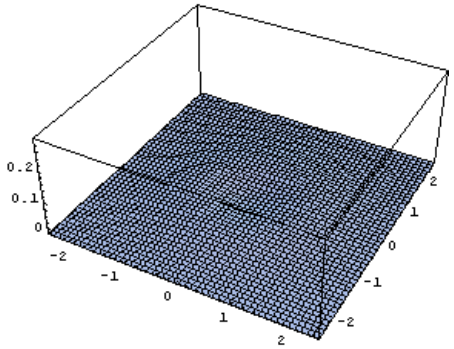
Work function of various metal cathode

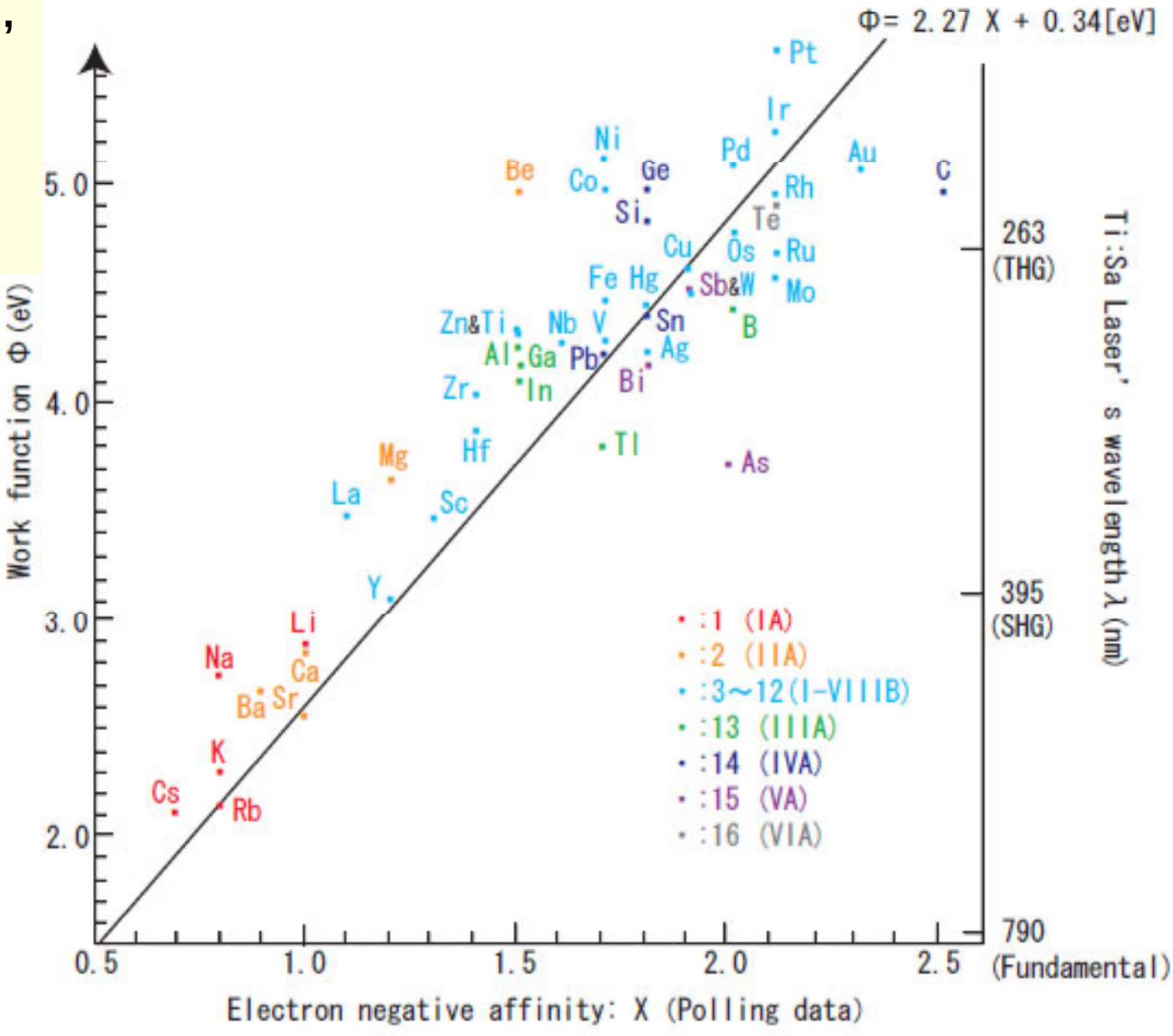
With 1~2GV/m field, Work function reduces ~2eV.

Drive Laser wave-length can be IR.

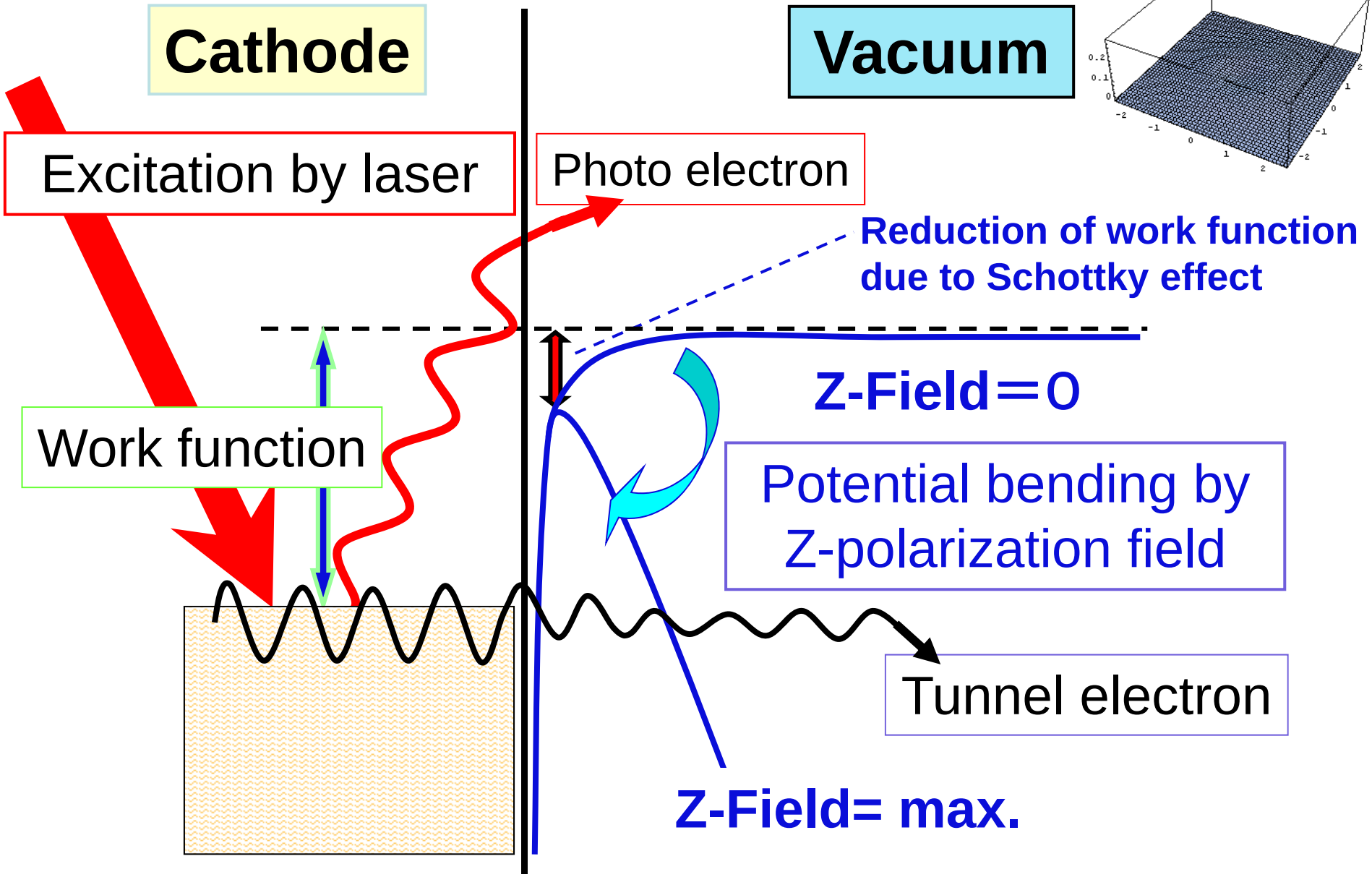
Radial polarization







Z-field on the cathode surface reduces work function



No Pulse shaping optics!!: Luiten scheme

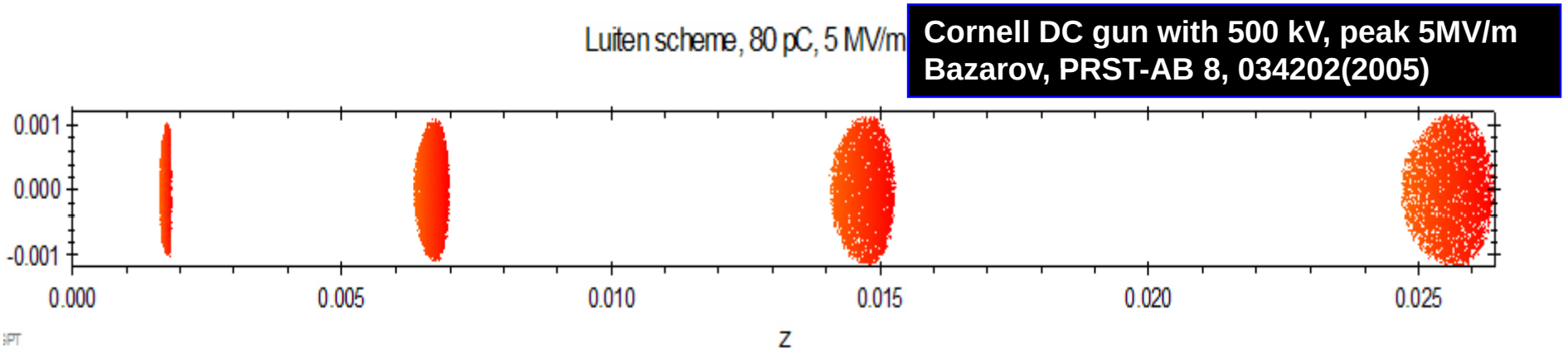
<u>If it works, we can generate ultra-low emittance.</u>

Idea: Use "pancake" laser pulse, allow beam to self-evolve to ideal ellipse
Proposed by Serafiniin 1997; again by Luitenin 2004.

We can start from femtosecond pulse at the cathode.

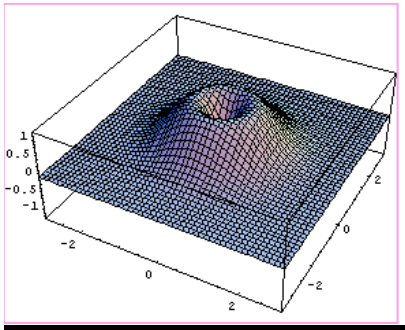
Luiten, "How to realize uniform 3-dimensional ellipsoidal electron bunches", Phys. Rev. Letters 93, 094802 (2004)

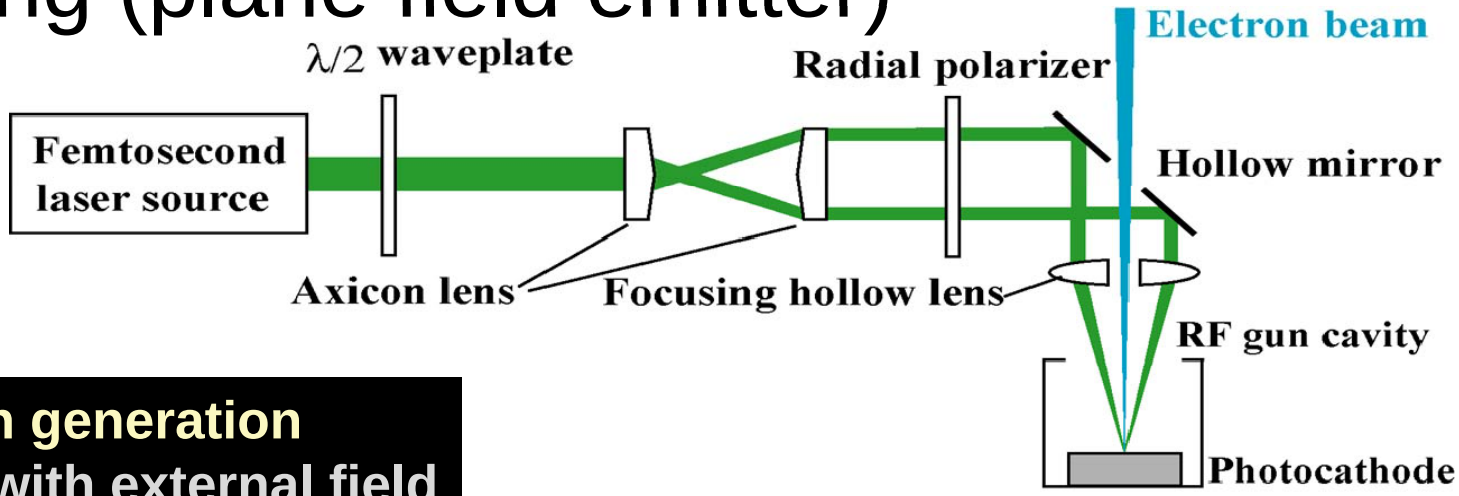
Laser: 100 fs with parabolic transverse distribution with 1 mm radius



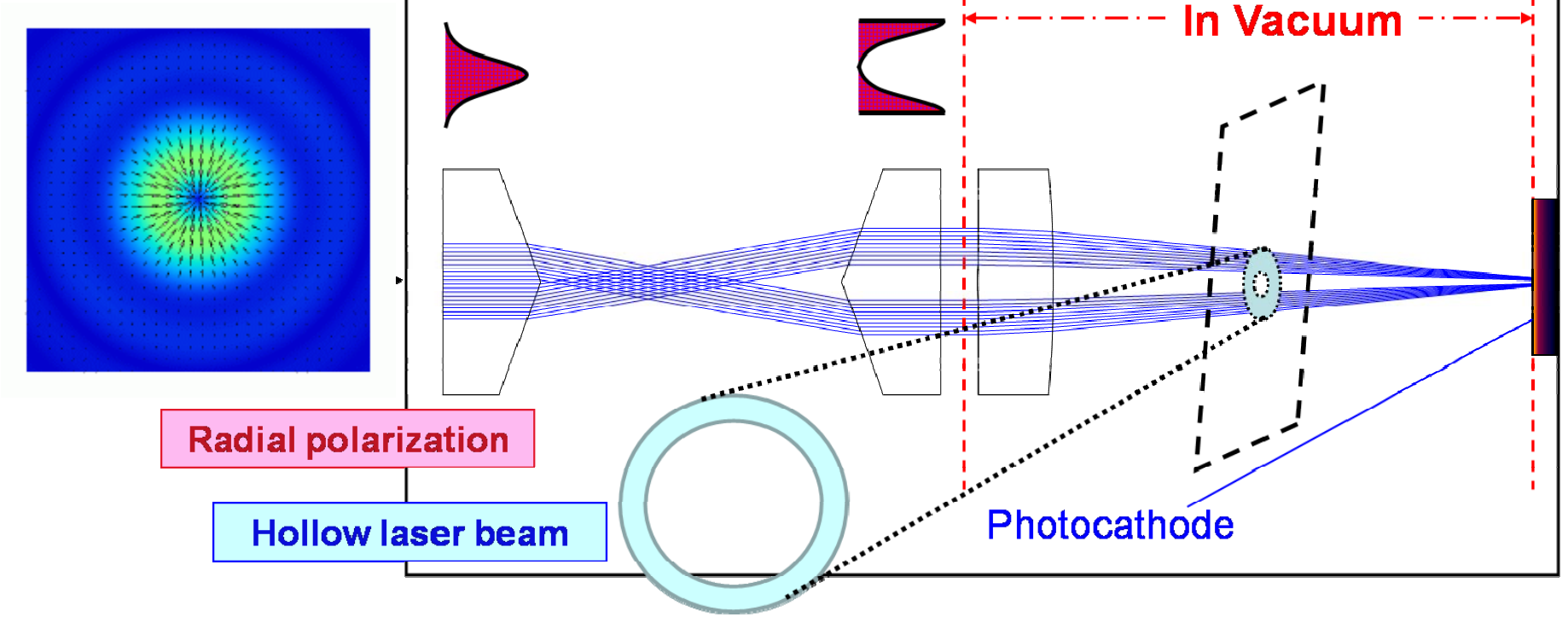
Cornell DC gun with 500 kV, peak 5MV/m
Bazarov, PRST-AB 8, 034202(2005)

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

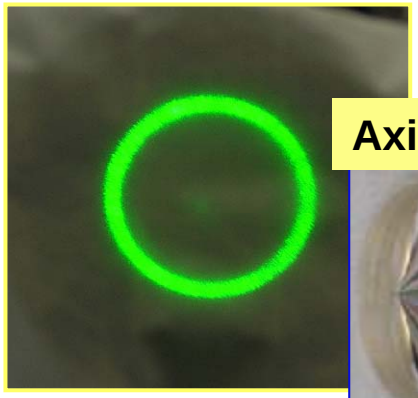




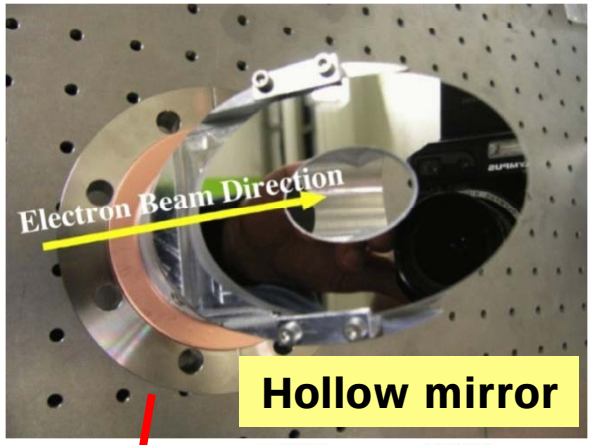
Z-pol. : electron generation
E-gun: extract with external field

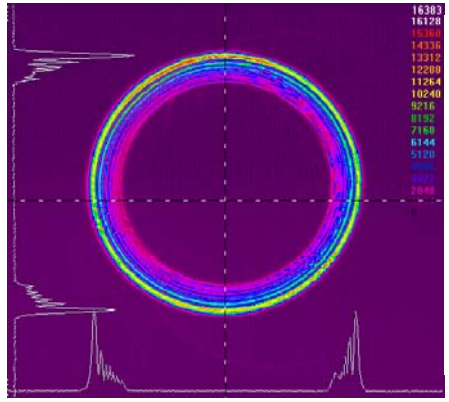


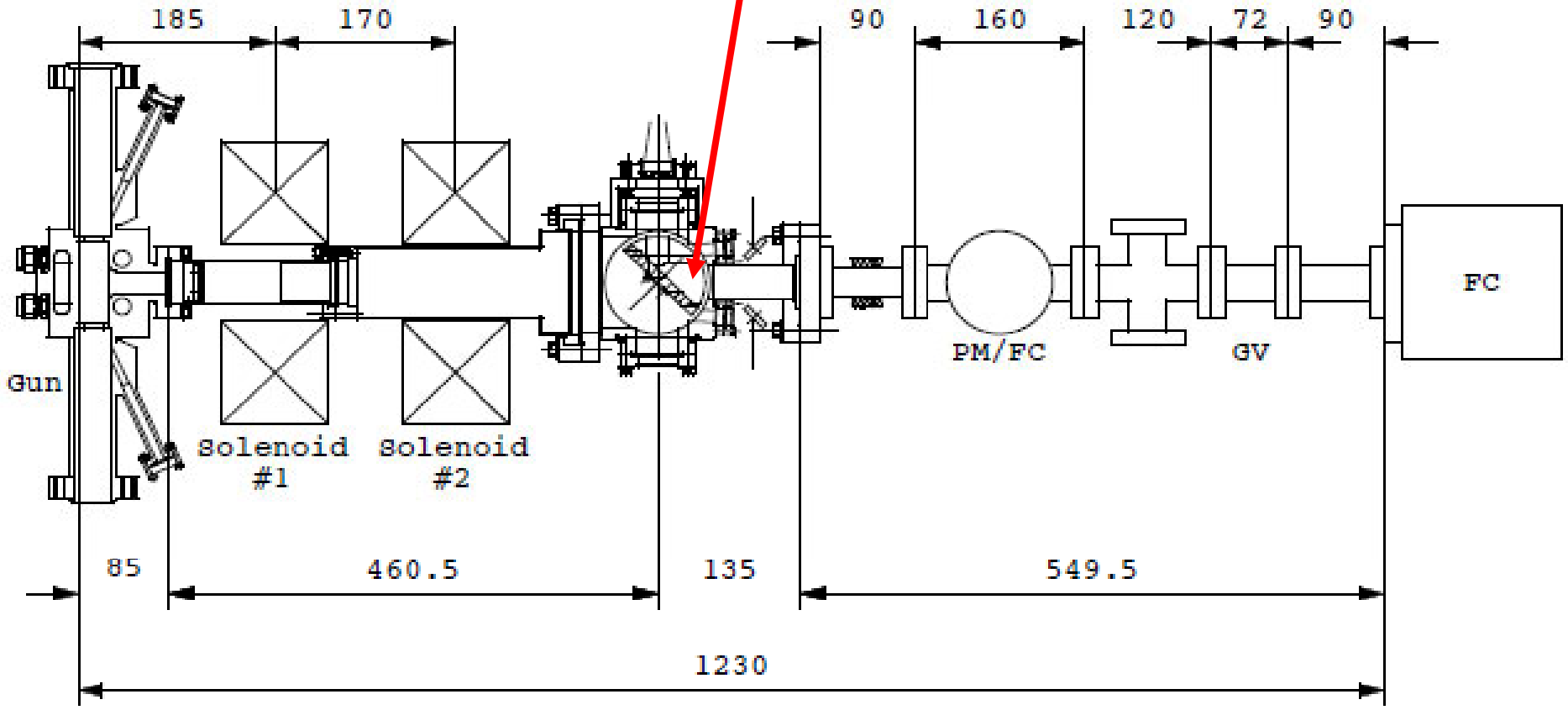
The hollow laser beam incidence

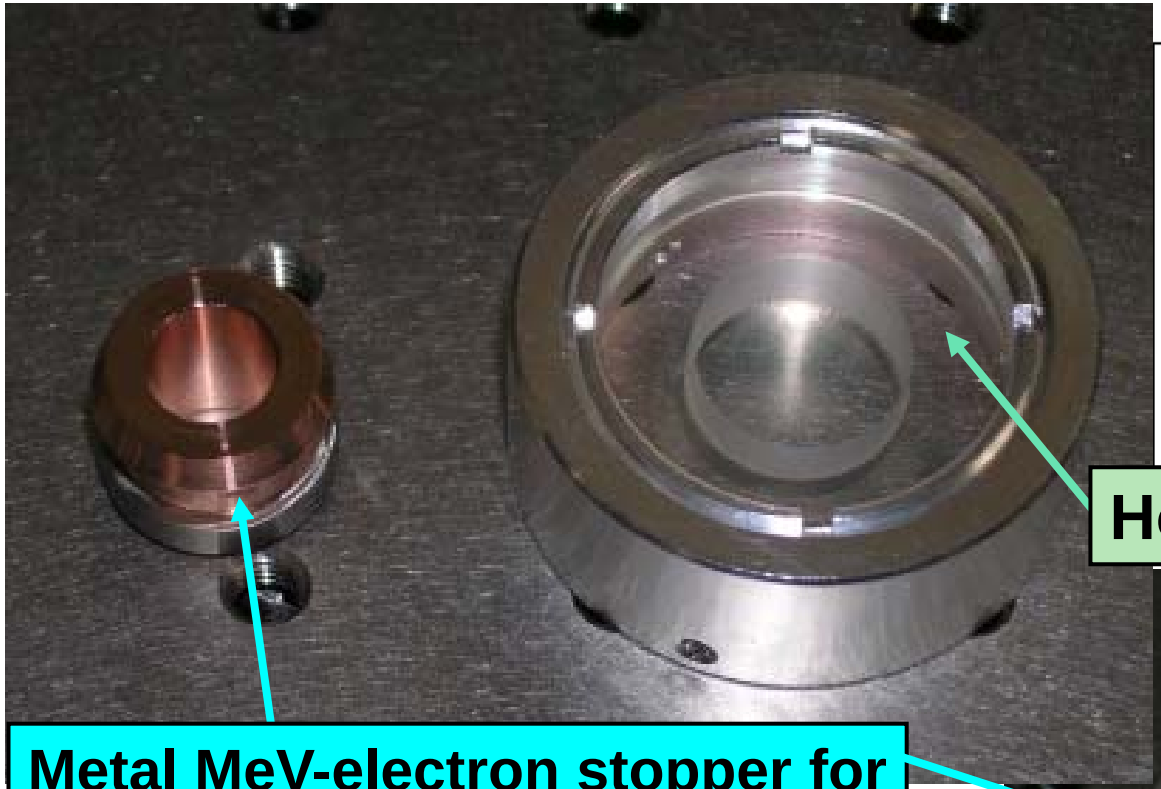


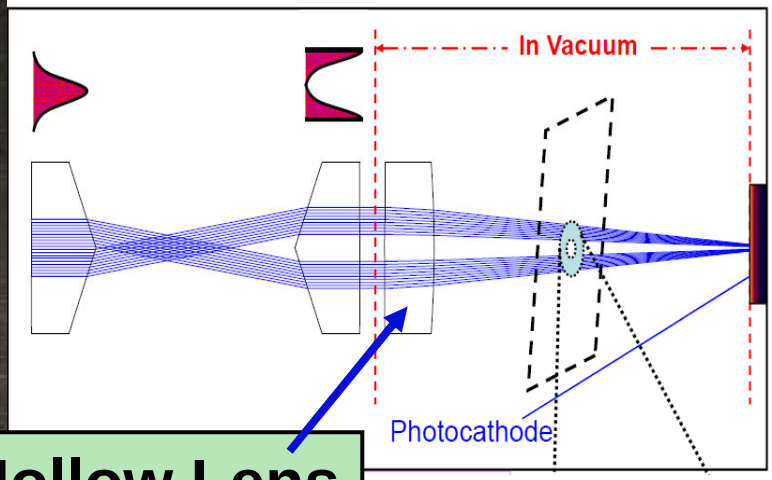
Axicon lens pair





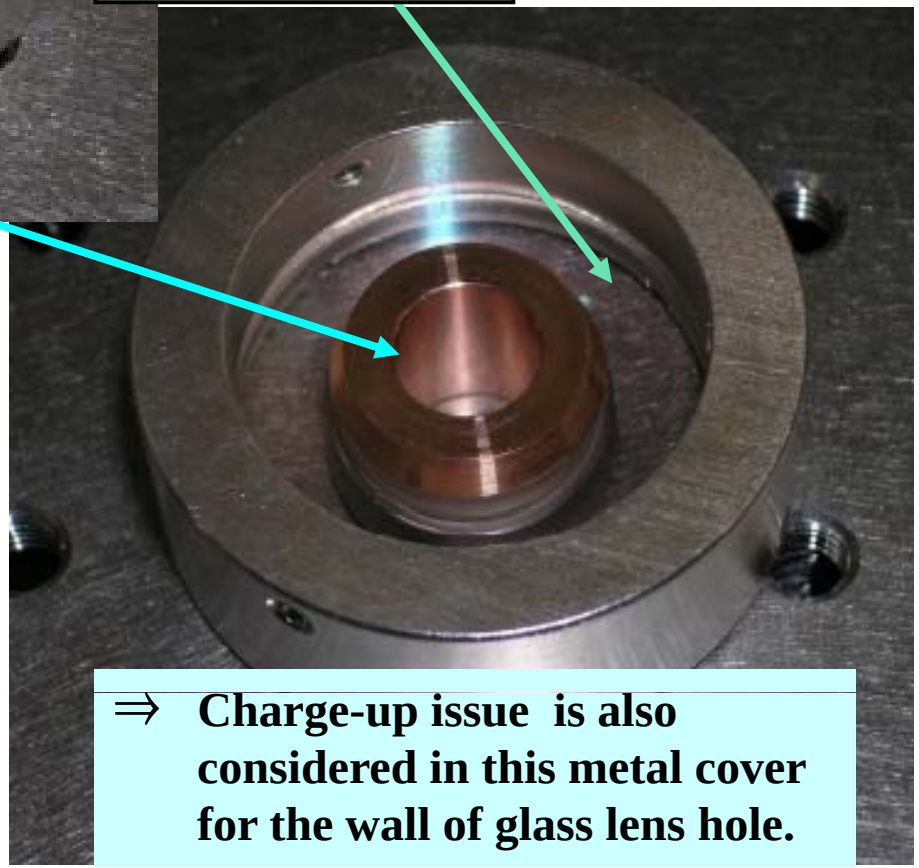






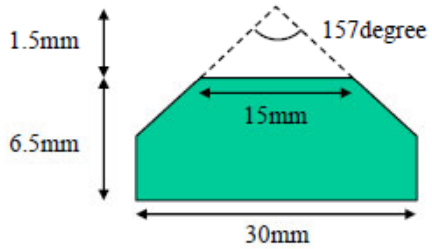
Hollow Lens

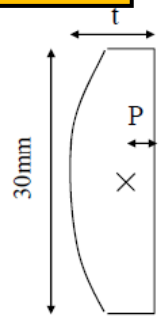
Metal MeV-electron stopper for Lens protection



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

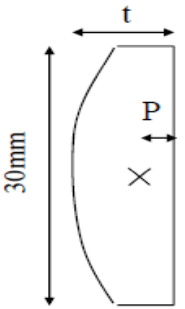
2 type of focusing lens:
Axicon lens & convex lens





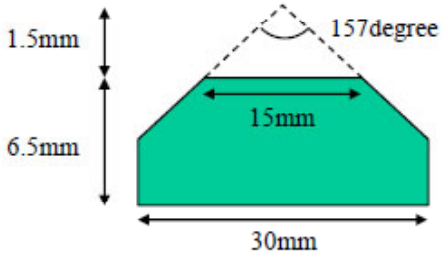
Type1: Convex focusing lens: ~< 10~100μm spot size

for very low bunch charge generation

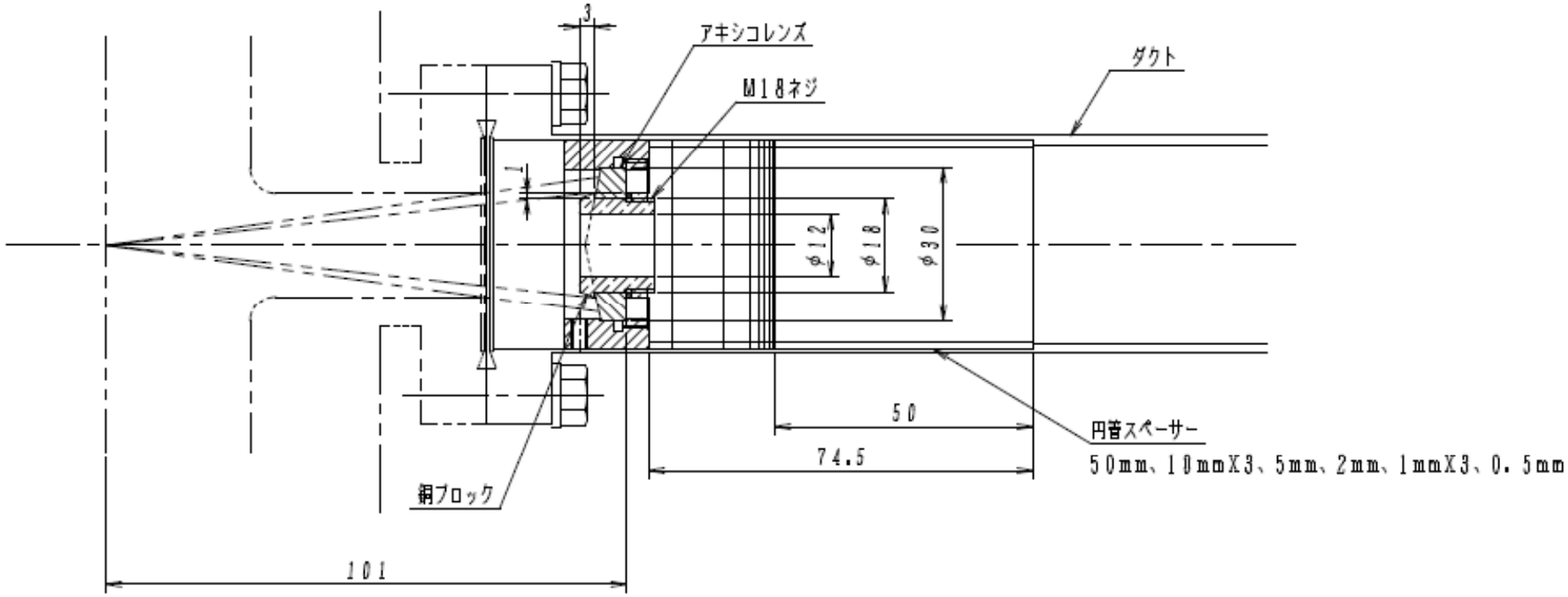


Type2: Axicon focusing lens: ~< mm spot size

for higher bunch charge generation

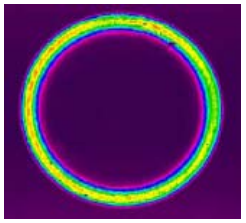


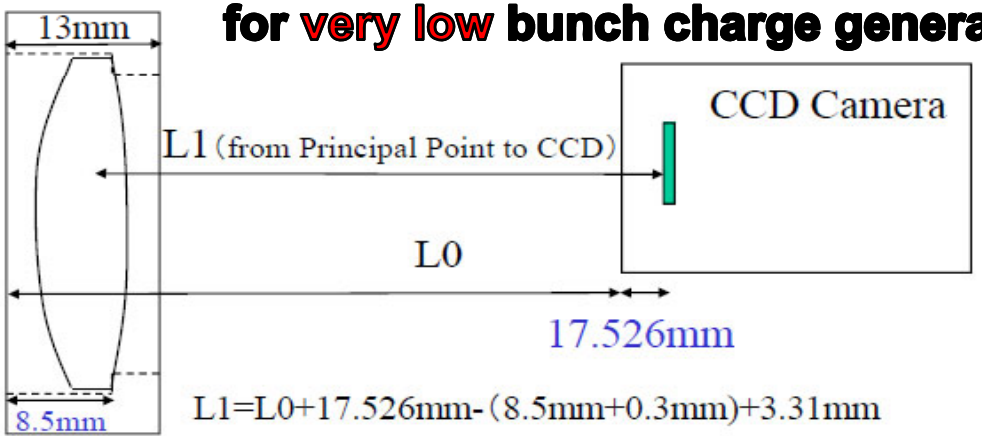
5mm-copper cover to stop 3MeV electron for lens protection

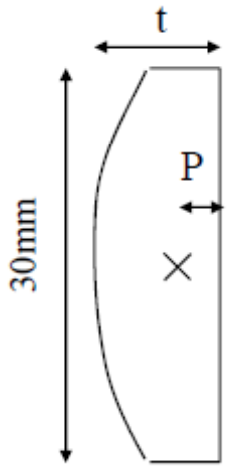


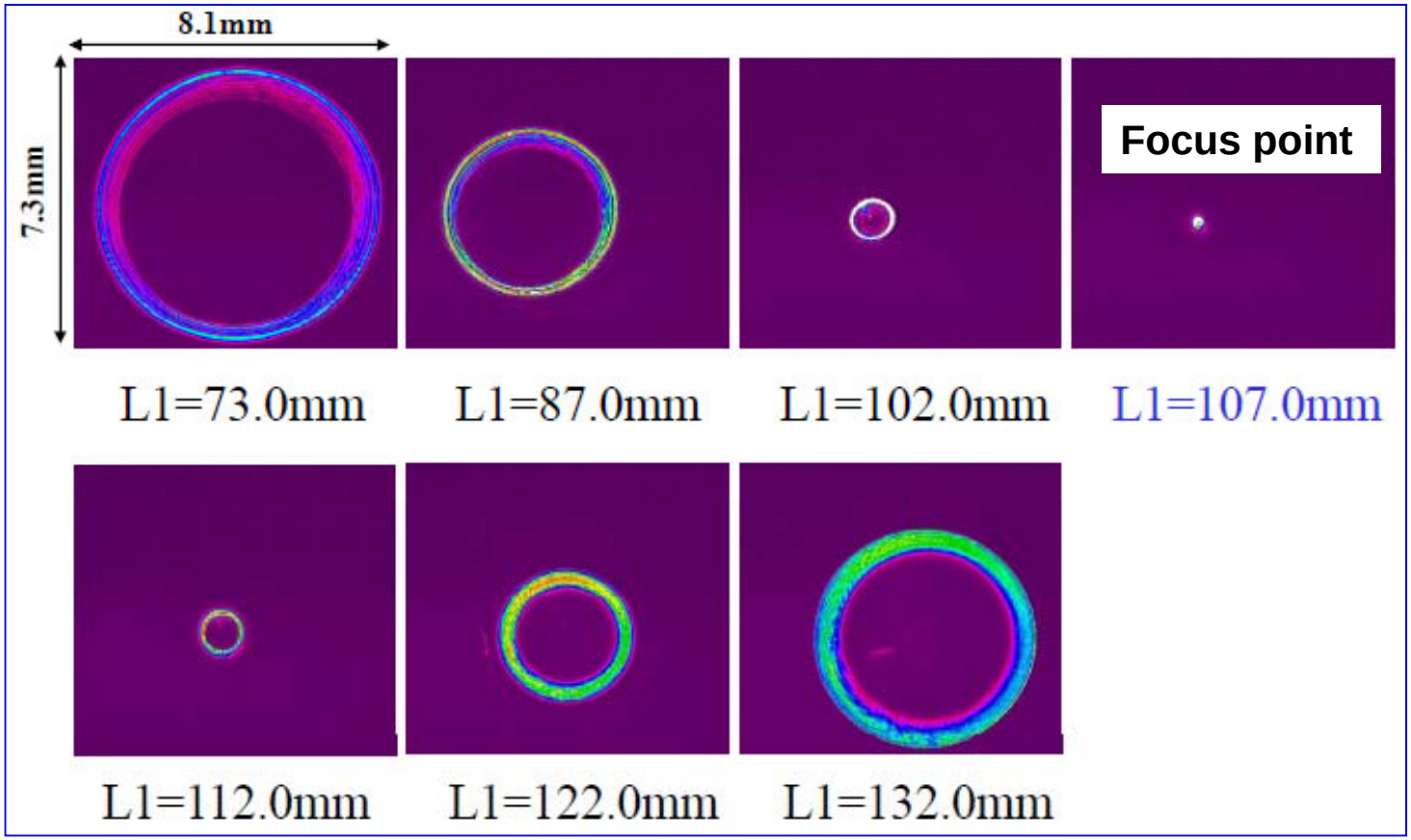
Type1: Convex focusing lens: ~< 10~100μm spot size

for very low bunch charge generation



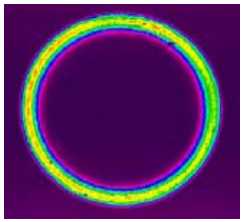


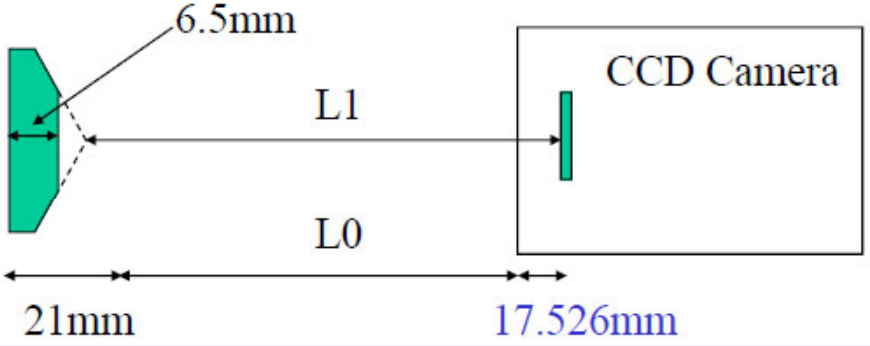


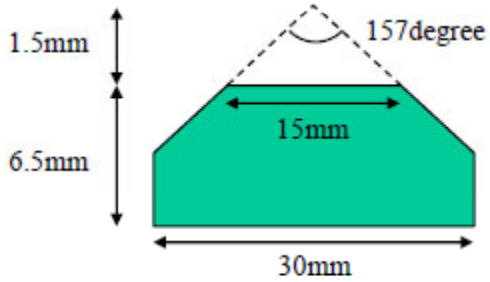


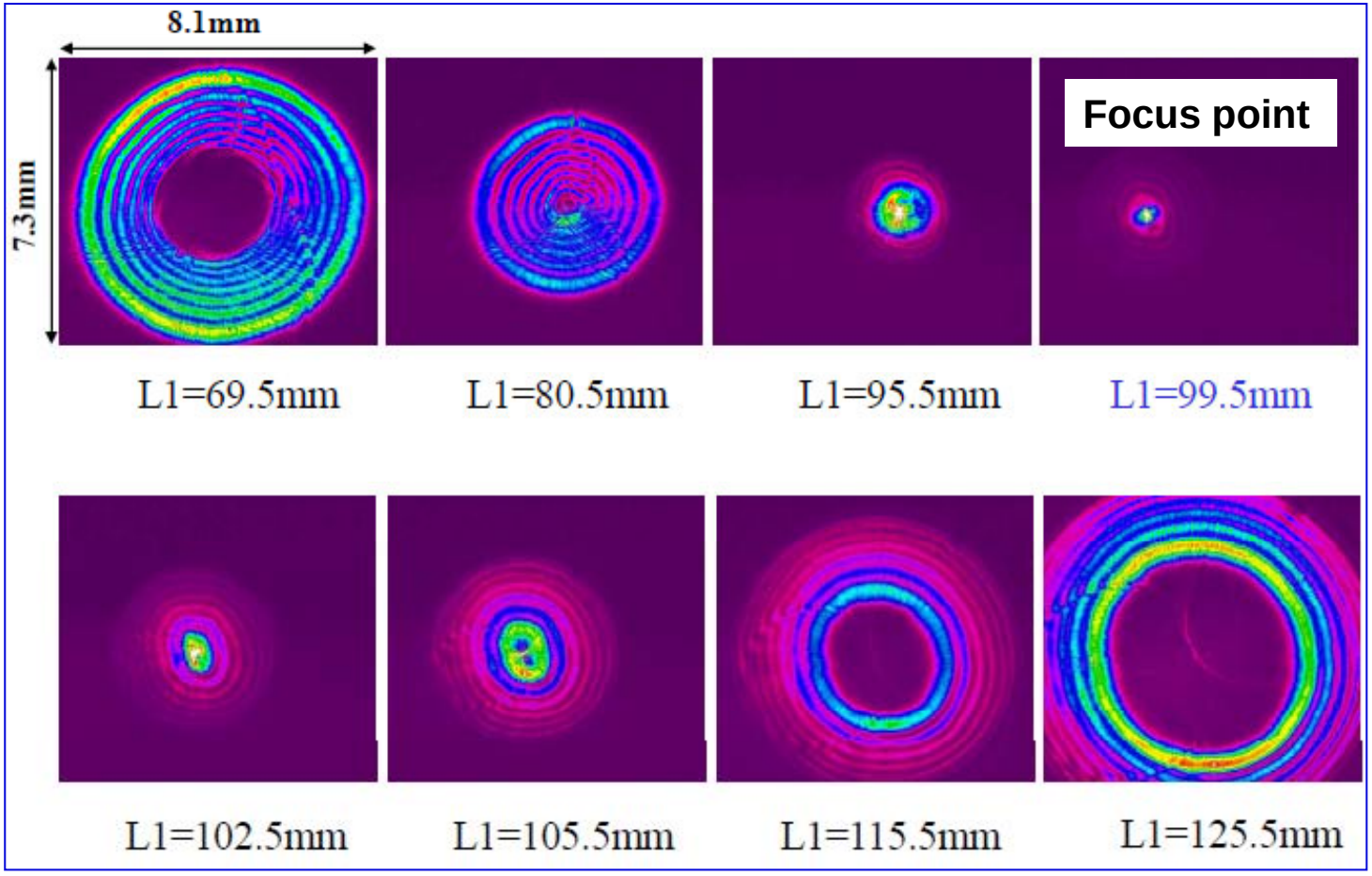
Type2: Axicon focusing lens: ~< mm spot size

for higher bunch charge generation

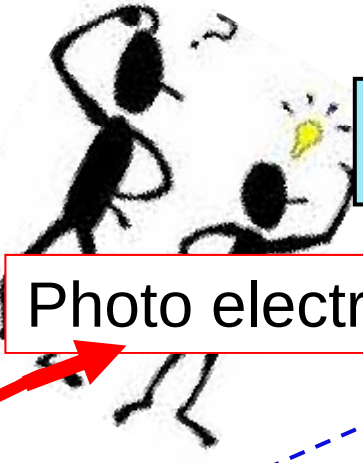


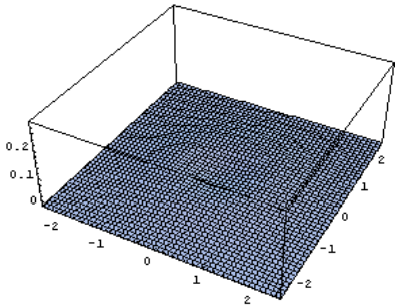






Is the response of metal cathode femtosecond ?





Metal

Vacuum

Excitation by laser

Photo electron

Reduction of work function
due to Schottky effect

Z-Field＝0

Work function

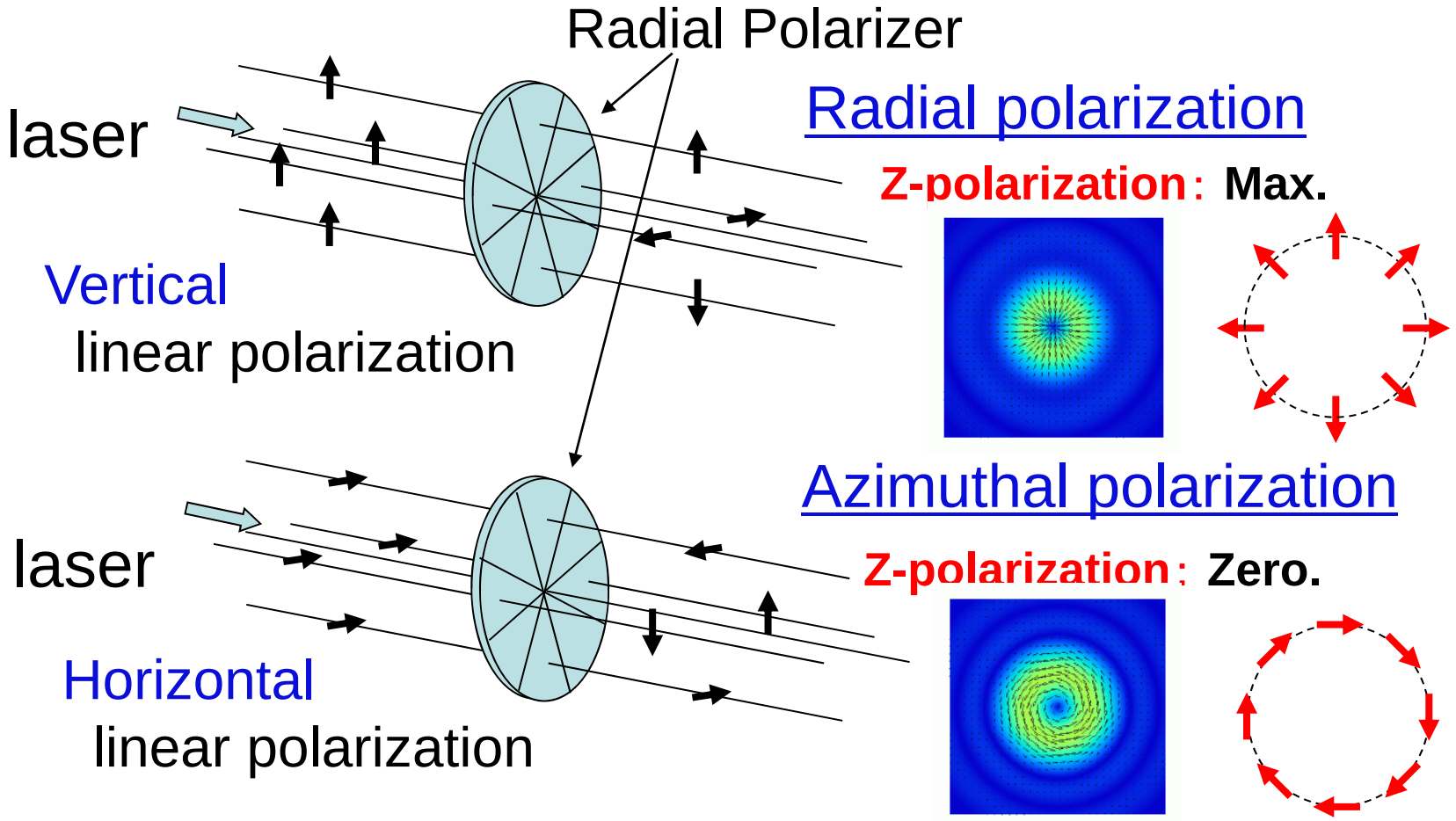
Potential bending by
Z-polarization field

Tunnel electron

Z-Field= max.

Feasibility test for Z-polarization effect

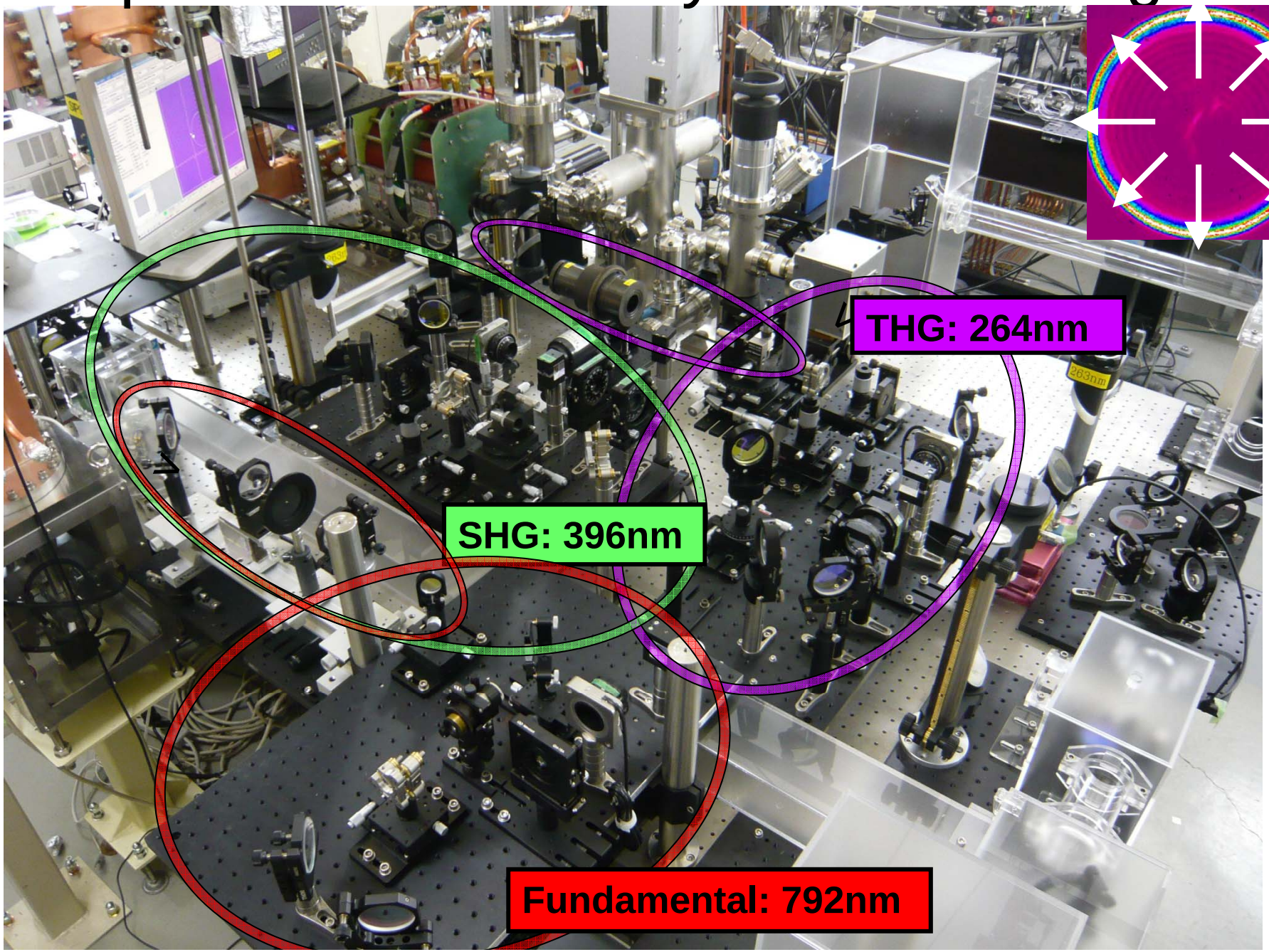
(Comparison between radial & azimuthal polarization)



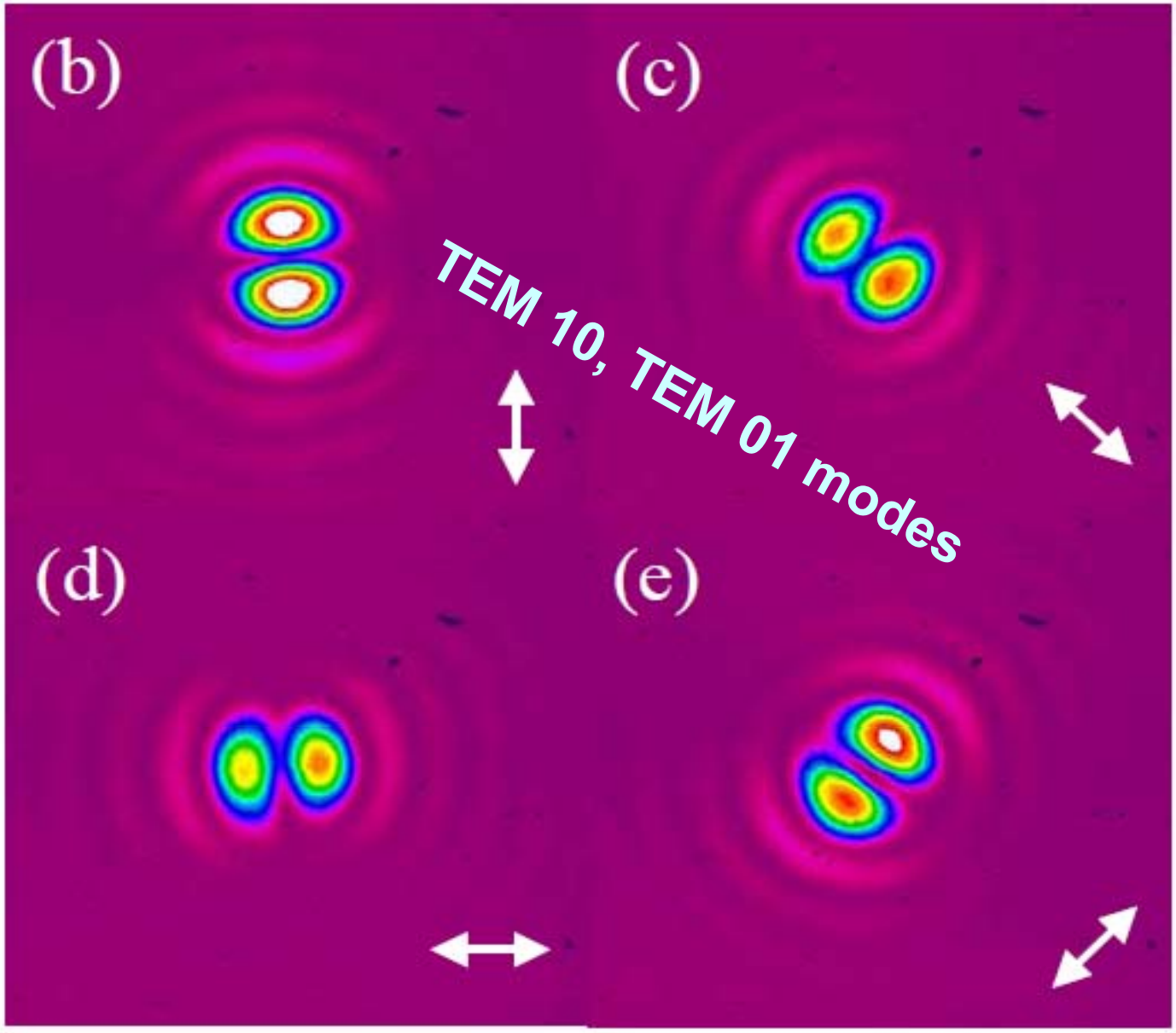
(1) We can switch radial to azimuthal with rotating half waveplate!

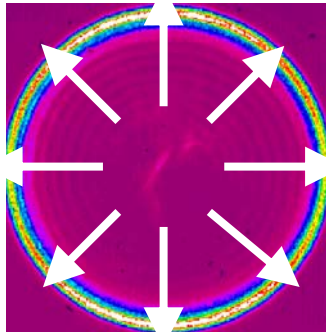
(2) Comparison between radial and azimuth polarization can tell Z-polarization effect on the cathode (spot size & photon density).

Z-polarization Gun System at SPring-8



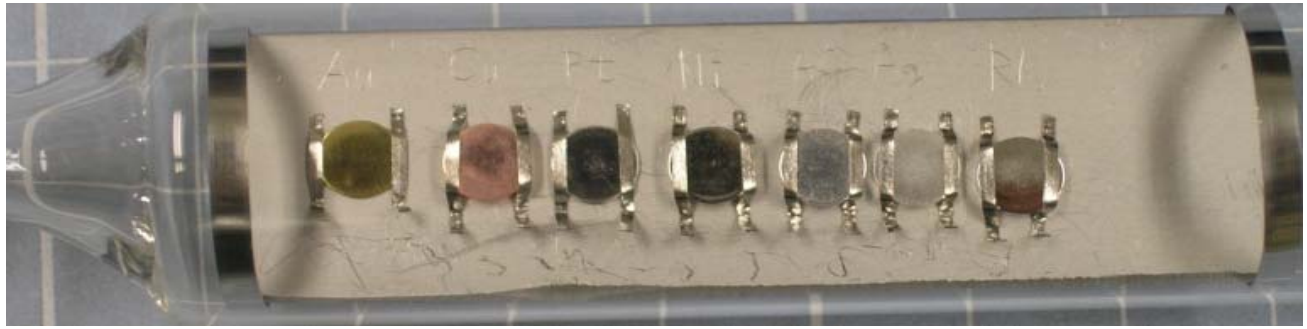
Radial polarization laser test with a polarizer at SPring-8

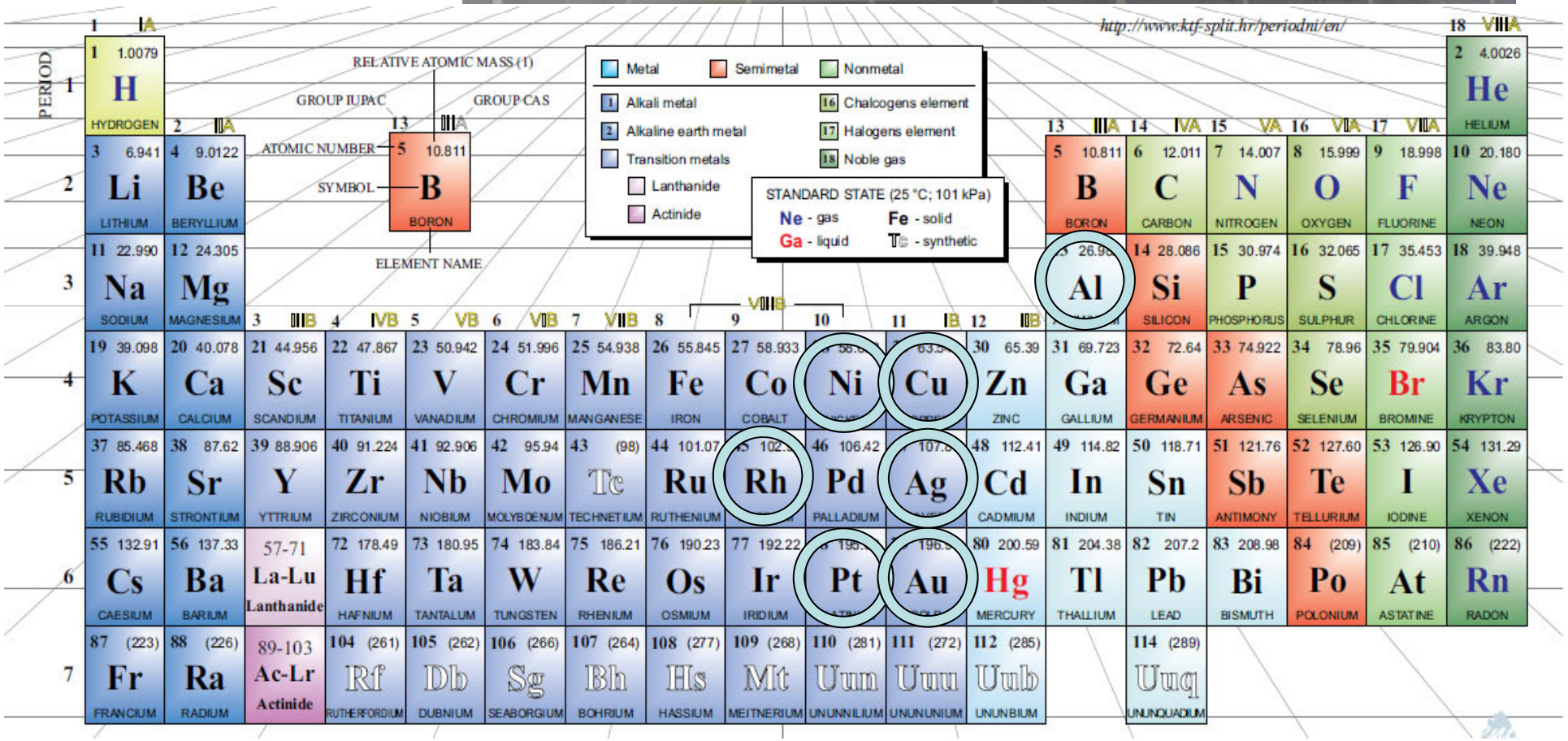




Cathode candidates for UV Z-polarization

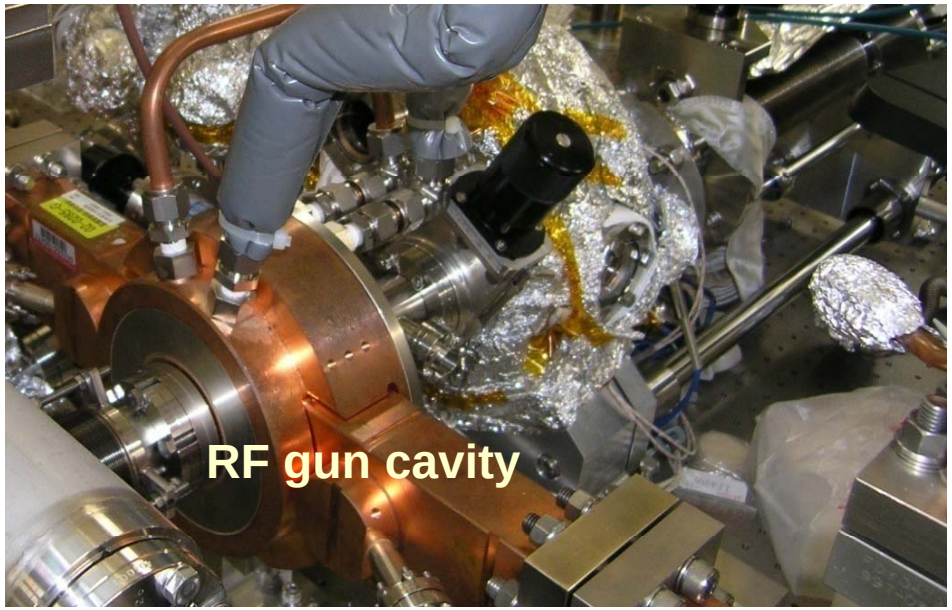
Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni



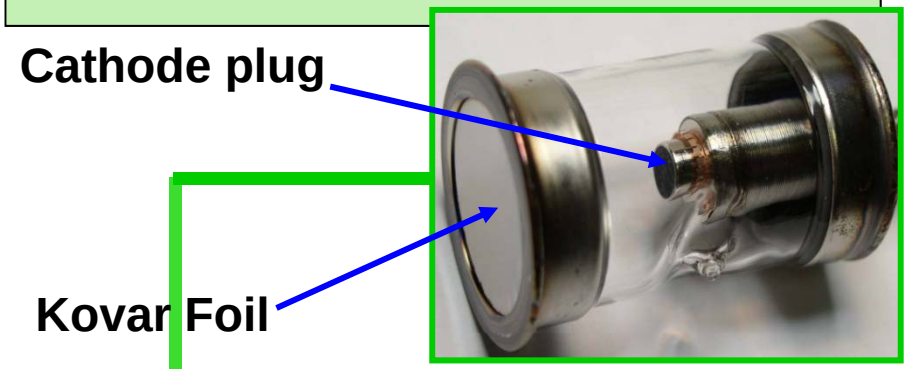


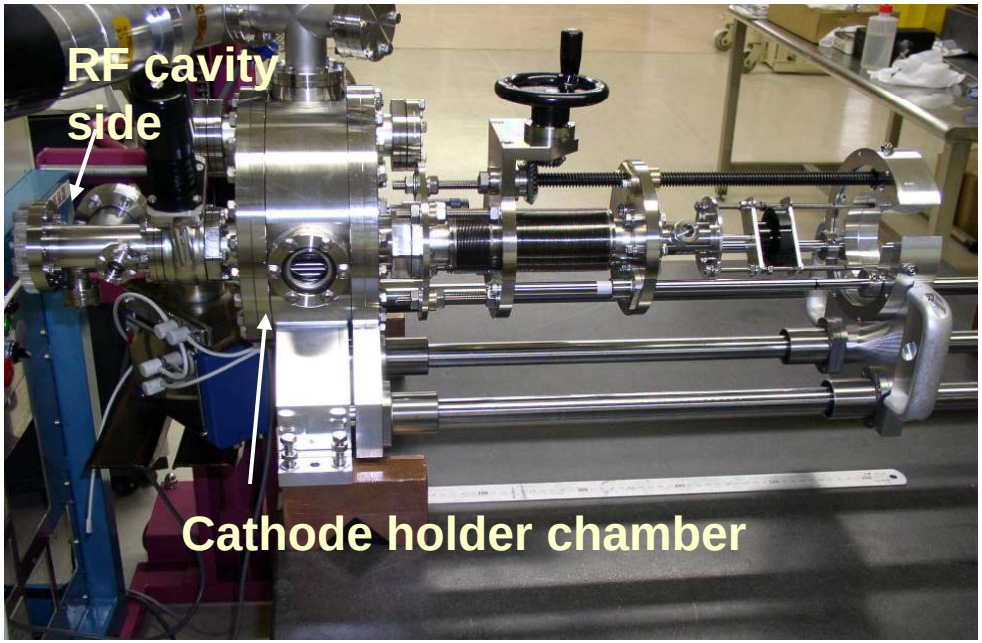
Experiment setup for different cathode test

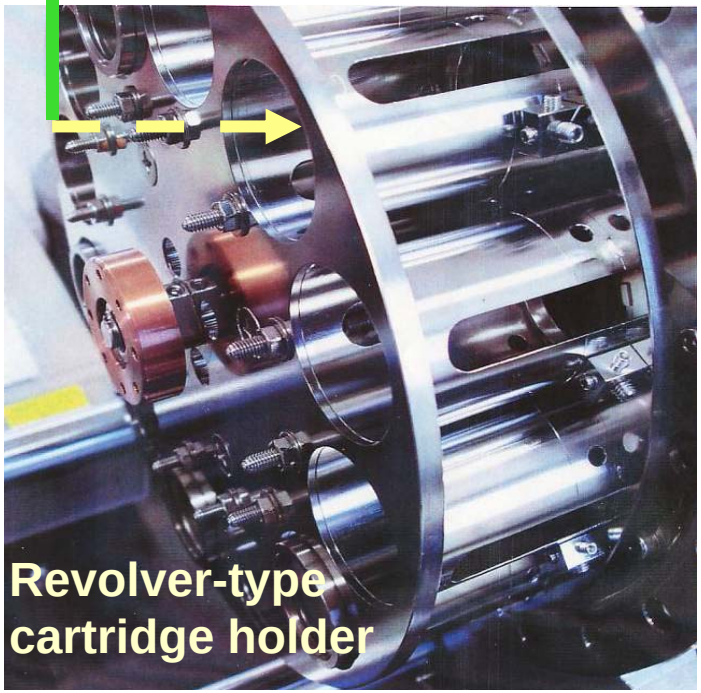
Cathode: Au, Ag, Cu, Pt, Rh, Al, Ni



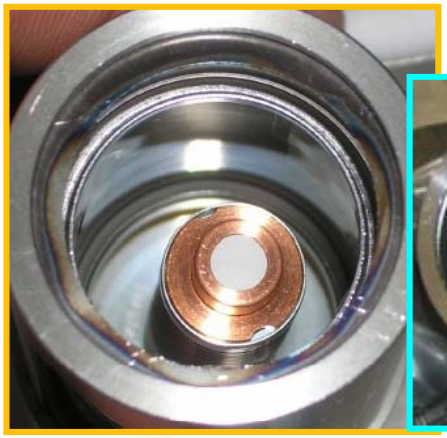
Cartridge type cathode holder accommodates up to 12 cartridges



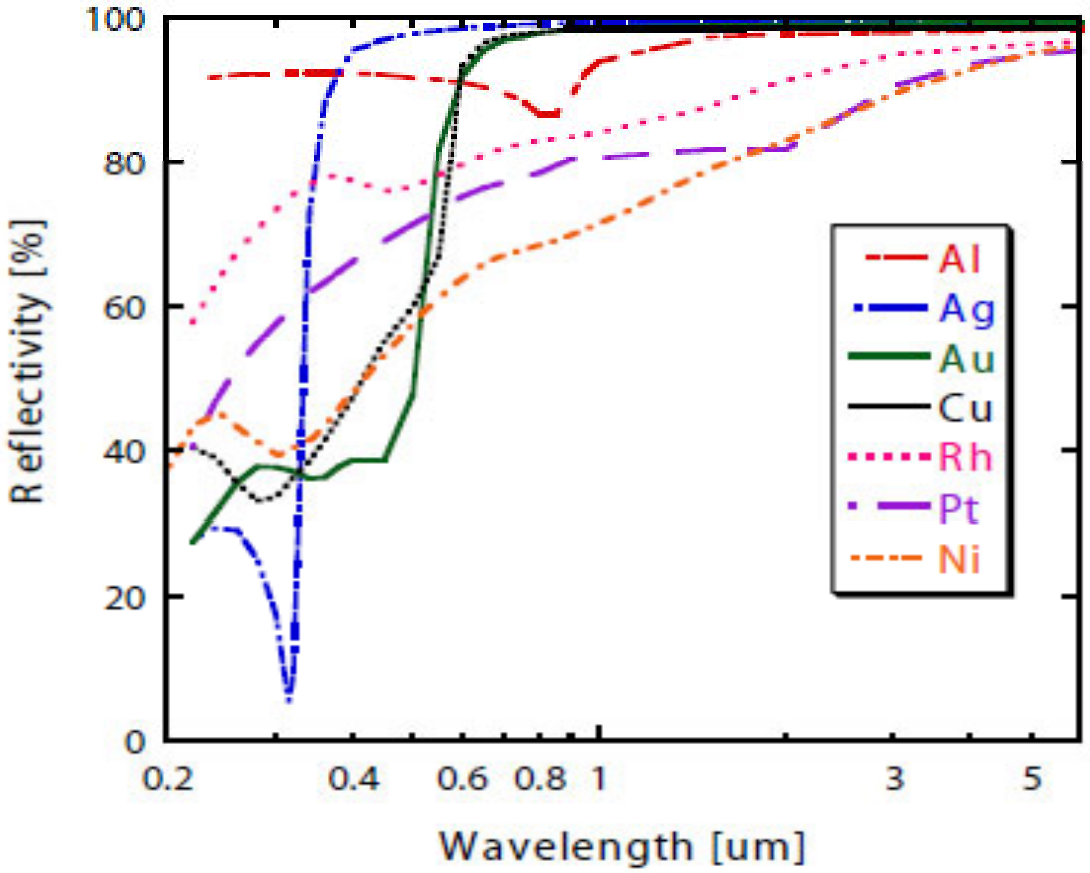




Metal cathode candidates in cartridge tubes



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



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

Uncertainty Principle:

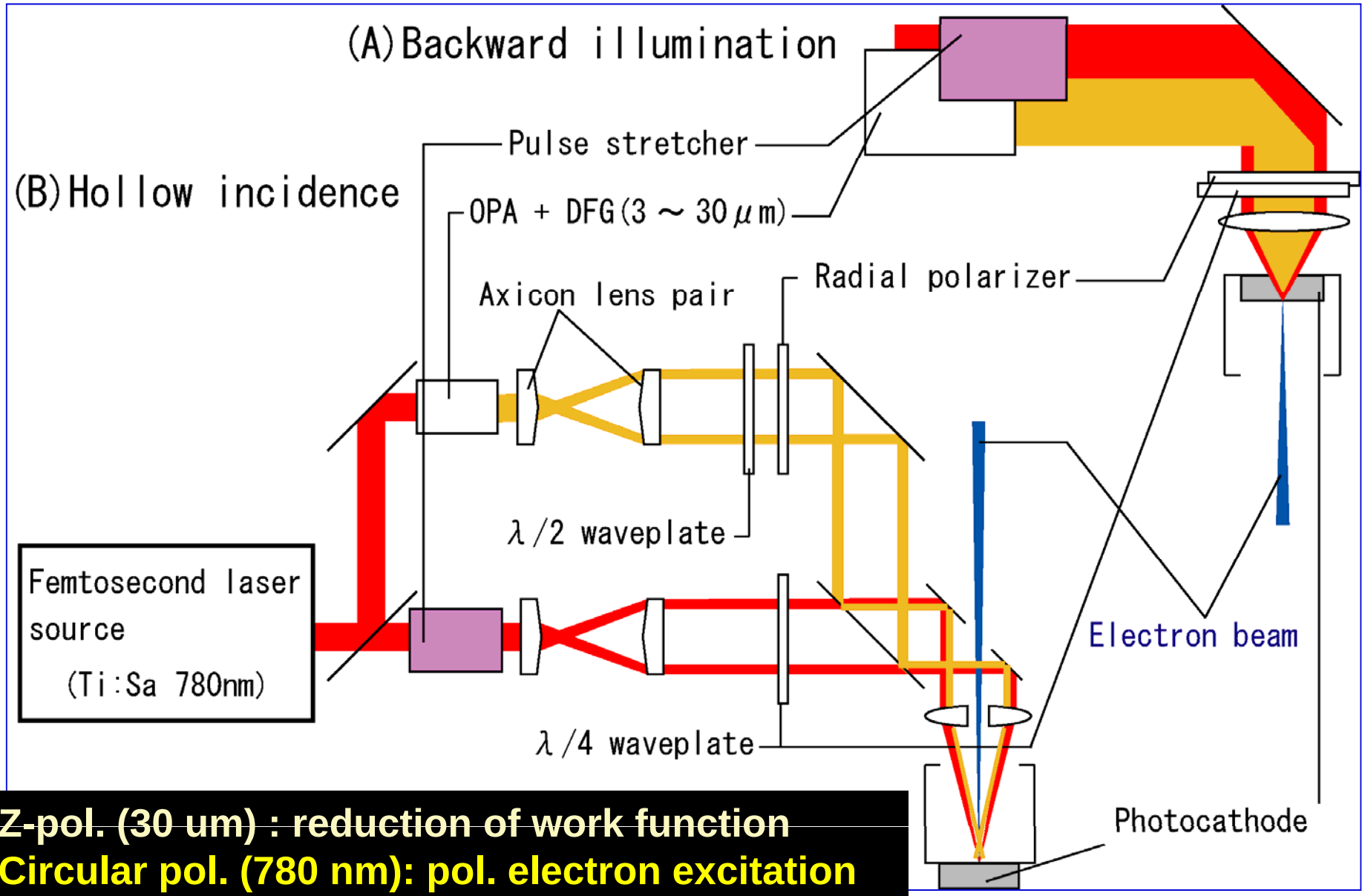
$h/2\pi$ ~ [fs] [eV]

(Dirac's constant)

Skin depth:

Metal ~ $\lambda/20$

Polarized electron RF gun (laser–induced field gating)

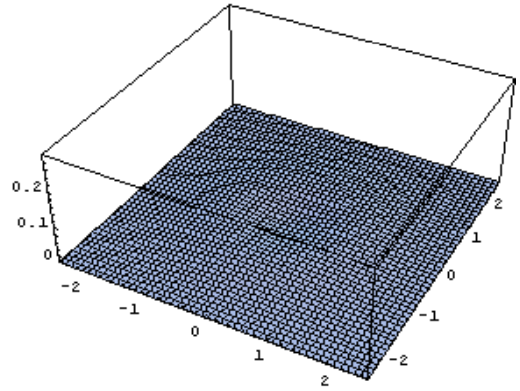


~~Z-pol. (30 um) : reduction of work function~~
Circular pol. (780 nm): pol. electron excitation
E-gun: extract with external field

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**

Preparing Optics

Feasibility study

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**