

# High Energy Electron Radiography for HEDP/ICF Diagnostics

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for

High Energy Density Electron  
Imaging Collaboration  
(ANL/IMP/THU)

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# Outline

- I. Background;
- II. Structure of Electron Radiography;
- III. Details of Electron Radiography:
  1. Passage of fast electrons through matter ;
  2. RF photocathode gun based electron Linac;
  3. Point to point imaging based on quadrupole magnet;
  4. 4-D imaging.
  5. Initial results and future plan.
- IV. Summary.

# I. Background

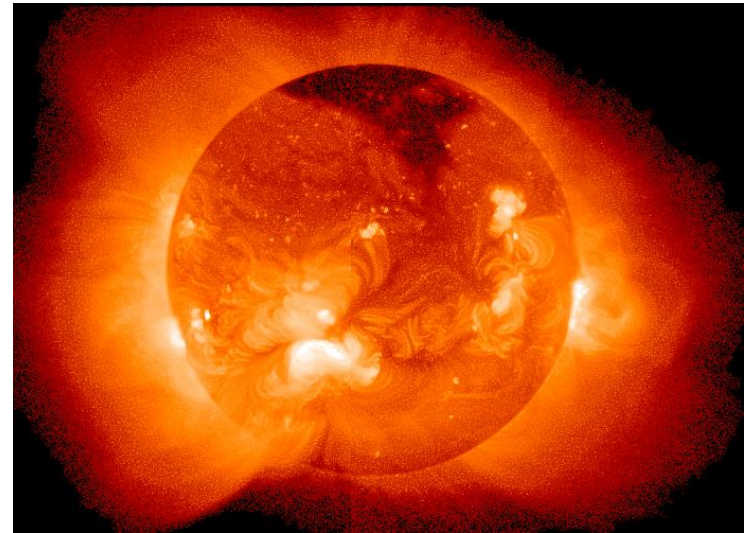
## Motivation

The **fossil fuel** era is almost over. If we continue to burn fossil fuels such as oil or natural gas for energy, they will last only another few hundred years.

**Taming fusion** will provide us with a virtually inexhaustible source of clean, accessible energy. **Inertial Confinement Fusion (ICF)** seems to be a viable alternative way.

**National Ignition Facility (NIF)** achieved fuel gain exceeding unity in an inertially confined fusion implosion, however, still far from expect designed.

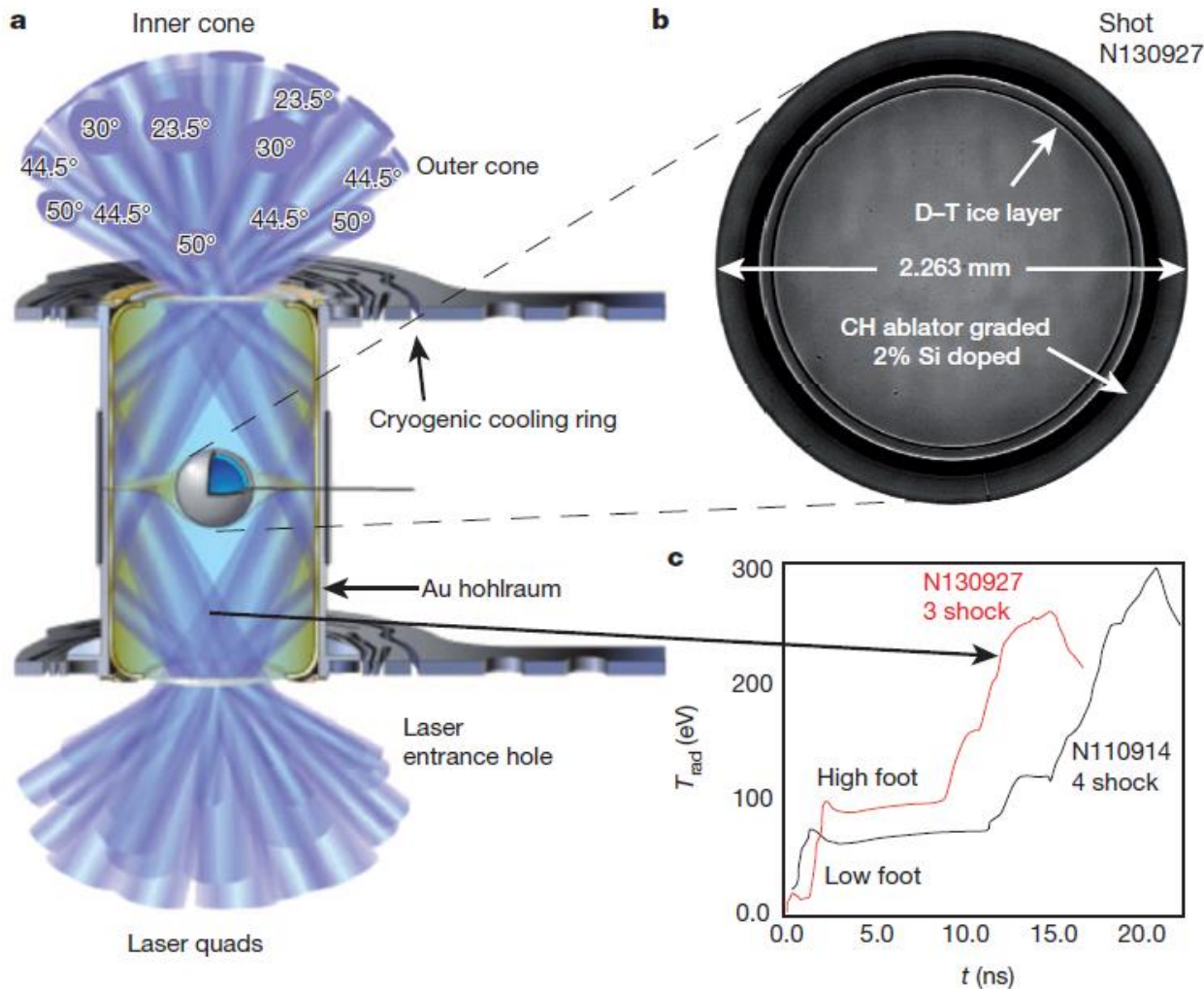
Fuel pellet is being **squeezed asymmetrically**, which **lowers** the pressure at its center. The asymmetry also causes the isotopes to mix unevenly, **lowering** the temperature in the pellet.



The Sun is a main-sequence star, and thus generates its energy by nuclear fusion.

# Imaging diagnosis requirement for ICF/High Energy Density

## Physics (HEDP) :



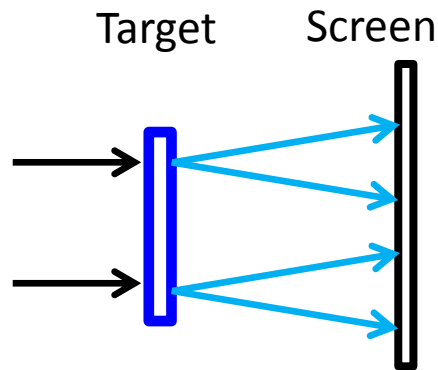
Provide ultimate real time feedback on the target information, thus the drive beam can be adjusted to compensate for any non-uniform target compression.

Before ignition the properties of fuel matter under extreme states of temperature and pressure. The pressure exceeds **1 Mbar** (100 GPa), thus the hydrodynamic response of the sample is a high expansion velocity in the range of km/s ( $\mu\text{m}/\text{ns}$ ). Therefore diagnostics which are capable of high **time resolution** ( $< \text{ns}$ ) and **space resolution** (10  $\mu\text{m}$ ) are needed.

[Ref. O. A. Hurricane, D. A. Callahan, D. T. Casey, et al., Nature 506, 343-348 (20 February 2014) doi:10.1038/nature 13008.]

# Common Imaging Method

## Scattering Projection Imaging

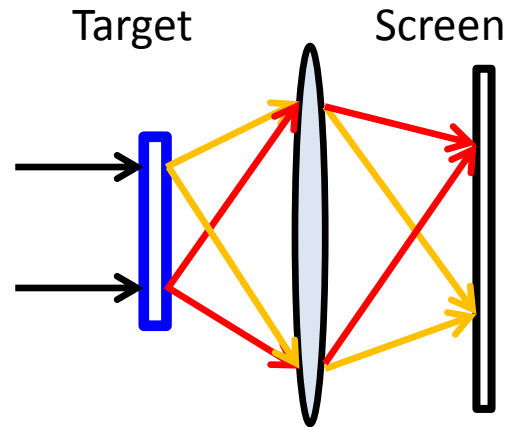


- ✓ Suitable for thin target
- ✓ Sensitive to marginal range
- ✓ Restriction spatial resolution

Example: X-ray Flash Imaging;  
electron/particles shadowgraphs

- It is challenging to focus and transport **X-rays** with lenses or mirrors and to achieve the necessary contrast if high and low Z target materials are simultaneously involved. Moreover, it is technically arduous to tune the X-ray wavelength to the specific needs of the experiment.
- **Shadowgraphs** using laser produced proton, electron, or even neutron beams constitute significant progress, but these techniques are restricted to geometrical imaging due to the large momentum spread of the laser generated particle beam.

# Electromagnetic Lens Imaging

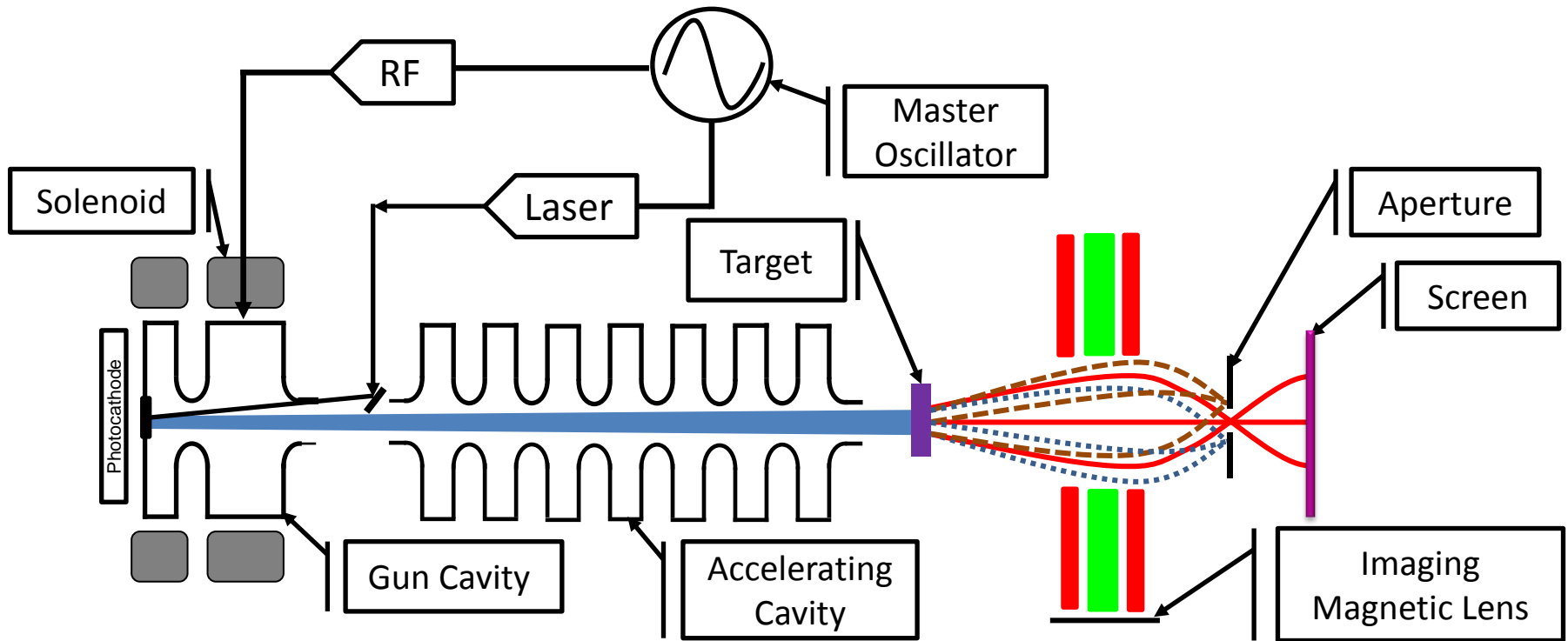


- High spatial resolution
- High time resolution
- Large field of view

Example: TEM; proton/electron lens imaging

- ✓ High energy proton radiography developed at Los Alamos National Laboratory(LANL) has shown excellent results with respect to space and time resolution in high energy density matter diagnostics;
- ✓ Electron radiography has been also considered and a resolution of 100  $\mu\text{m}$  had been demonstrated for a 30 MeV beam by LANL;
- ✓ Although it is arguable whether use of a proton beam is superior to an electron beam in penetrating the target, a high energy proton accelerator is costly. Also, a picosecond bunch length proton beam is not yet available in the lab.

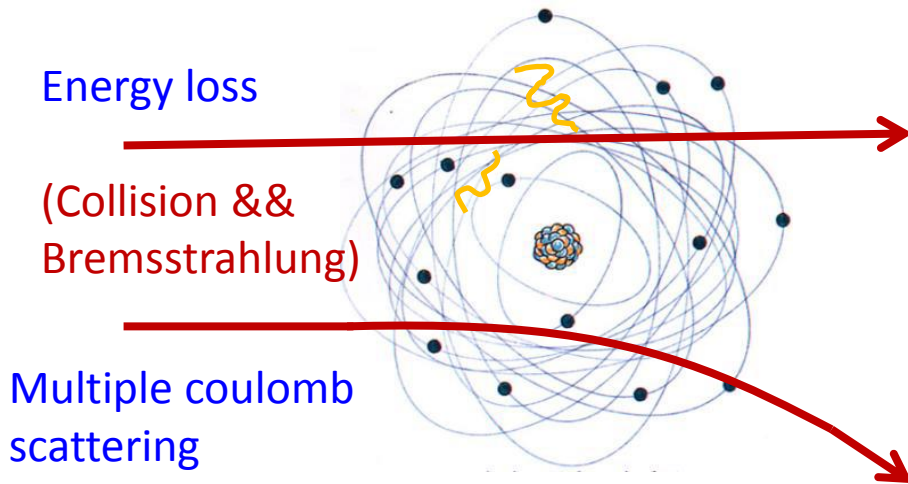
## II. Structure of the Electron Radiography



A fast electron beam from the photoinjector traverses the HEDLP target where the electrons are scattered by the nuclei. The angular distribution depends on the density and thickness of the target. The scattered electrons then travel through the point-to-point imaging lattice with a suitable magnification. A small aperture is used to collimate the scattered electron beam for off axis particles and bremsstrahlung photons, and the target image will be detected by a luminescent screen located after the imaging lattice.

# III. Details of the Electron Radiography

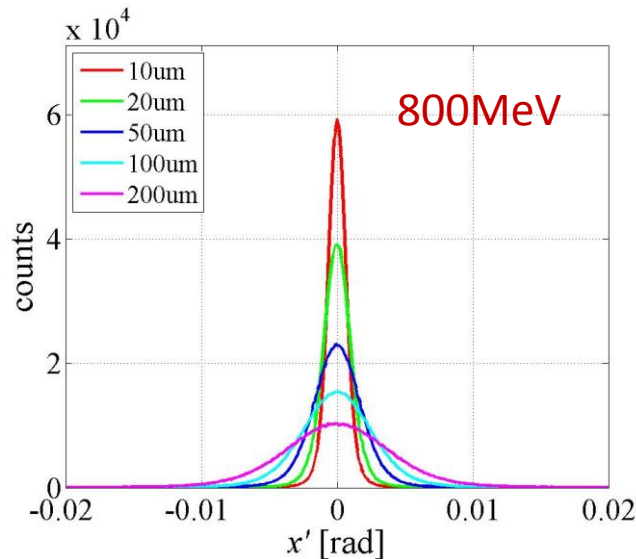
## 1. Passage of fast electrons through matter



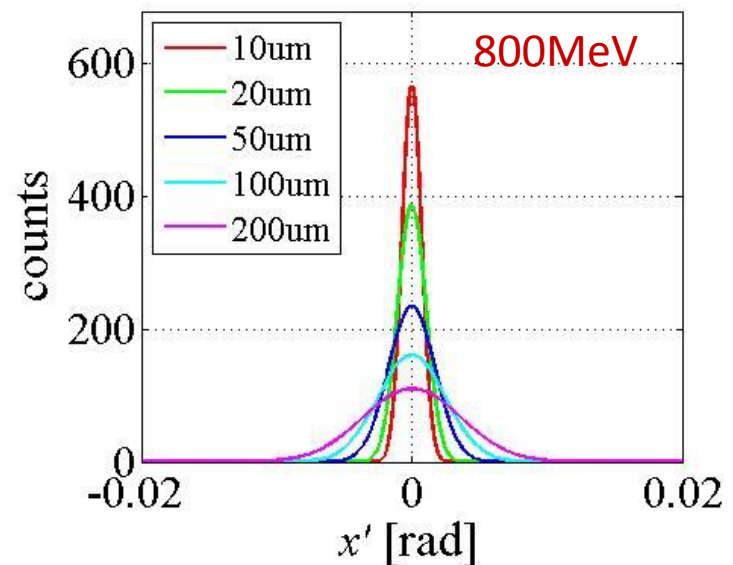
Scattering angle distribution:

$$\frac{N(t, \phi)}{N_0} = \frac{1}{\phi_0(t)\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\phi}{\phi_0(t)}\right)^2}$$
$$\phi_0(t) = \frac{13.6\text{MeV}}{\beta c p} \sqrt{t} (1 + 0.038 \ln(t))$$

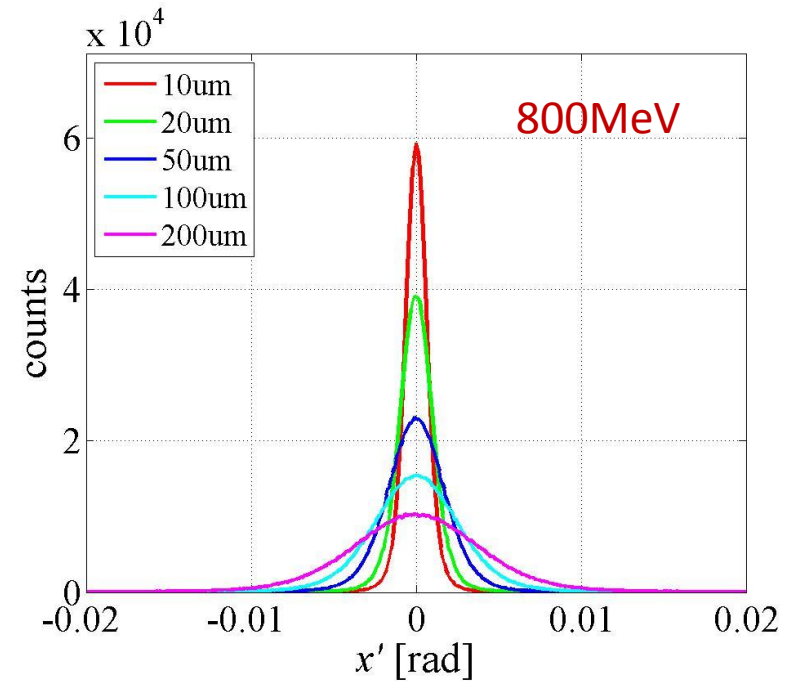
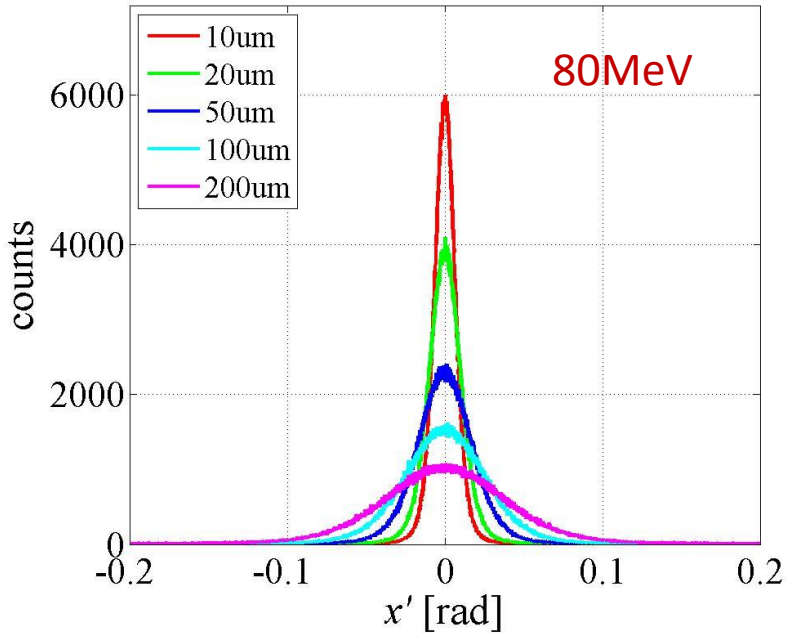
EGS simulation



Theory calculation

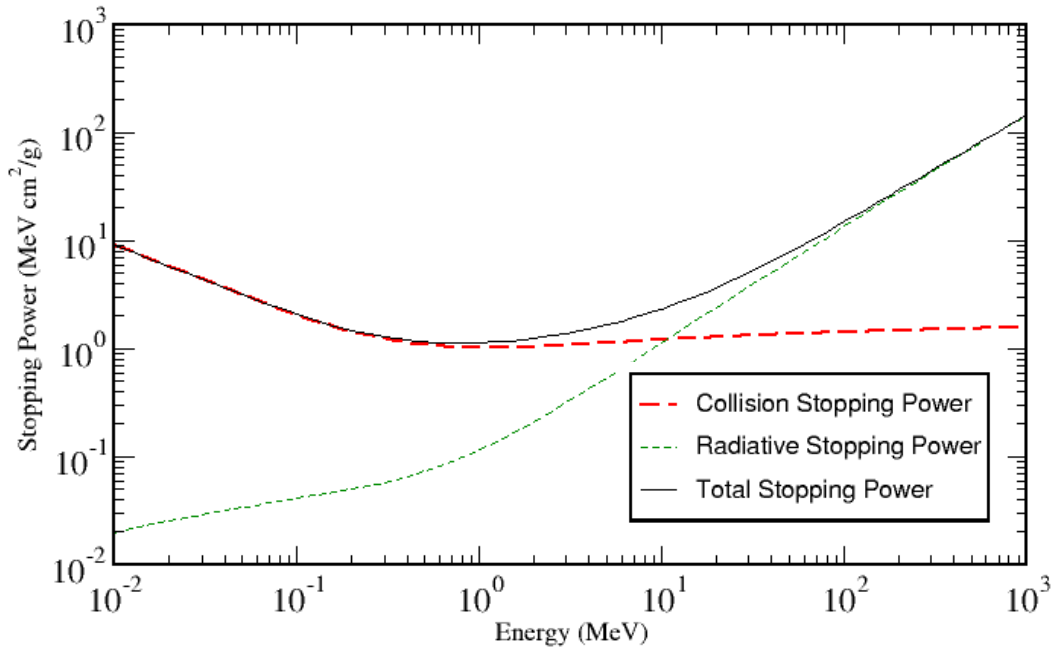




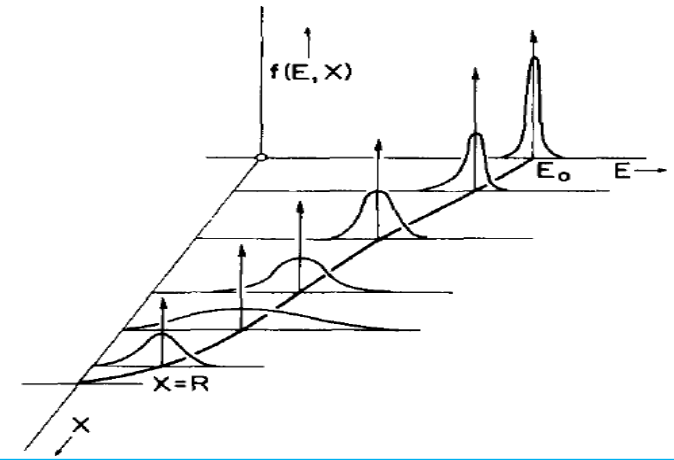


- ✓ Angle distribution is a Gaussian distribution relative to the Target thickness at same energy;
- ✓ There was significant linear correlation between Gaussian distribution FWHM and the electron energy in the same thickness.

## Energy Loss combine Collision Stopping Power with Radiation Stopping Power:



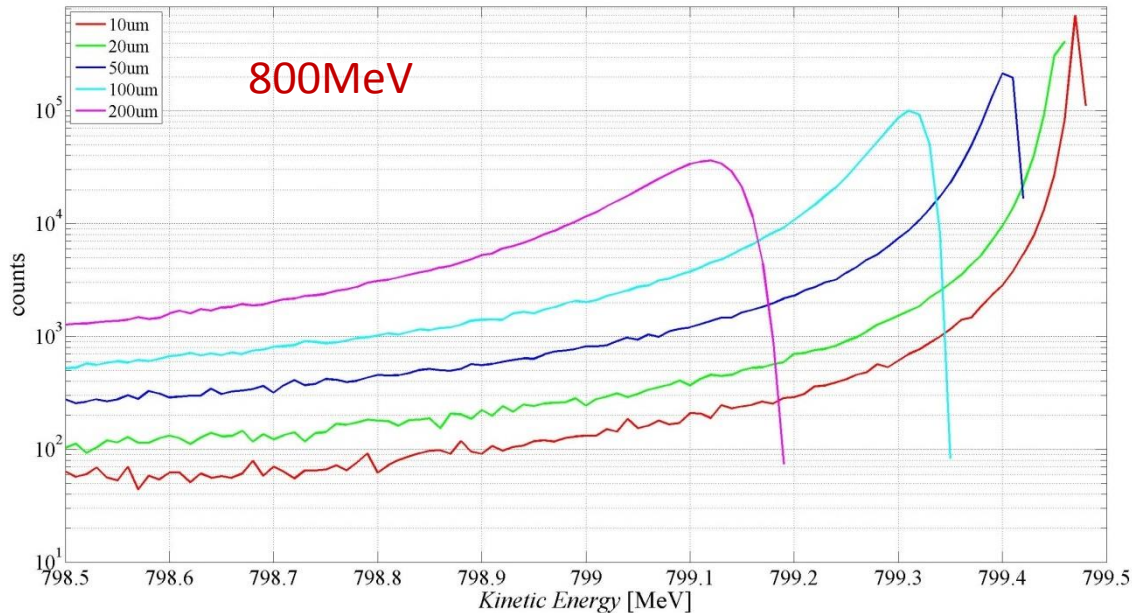
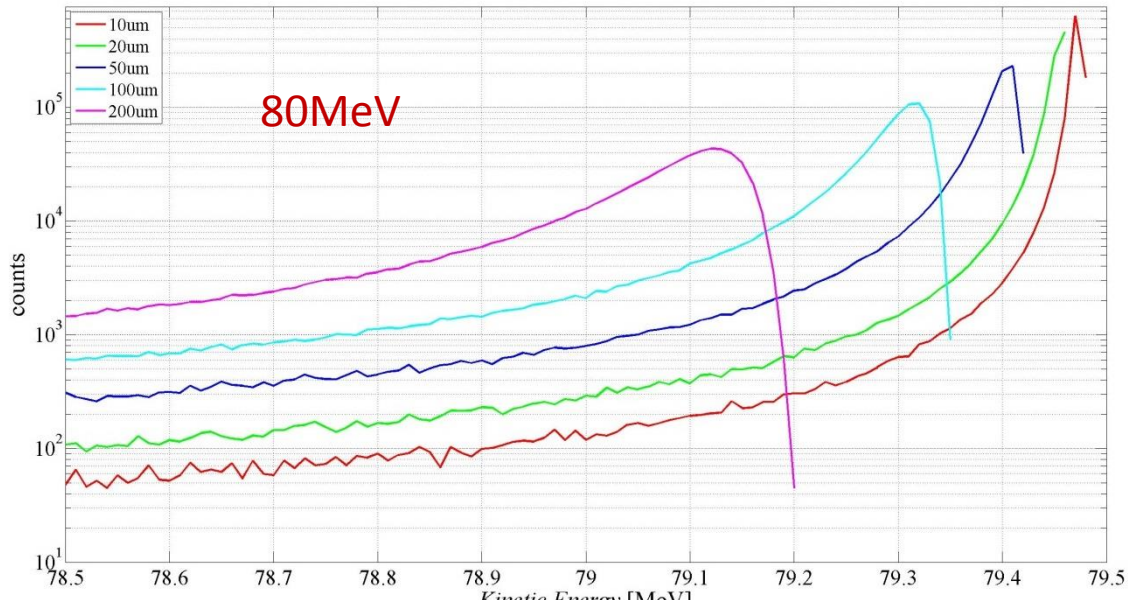
### Energy straggling after Collision:



Radiation Stopping Power described as Bremsstrahlung, the energy spectrum is a continuous spectrum, which was deeply researched by Y.T.Tsai can be formulation:.

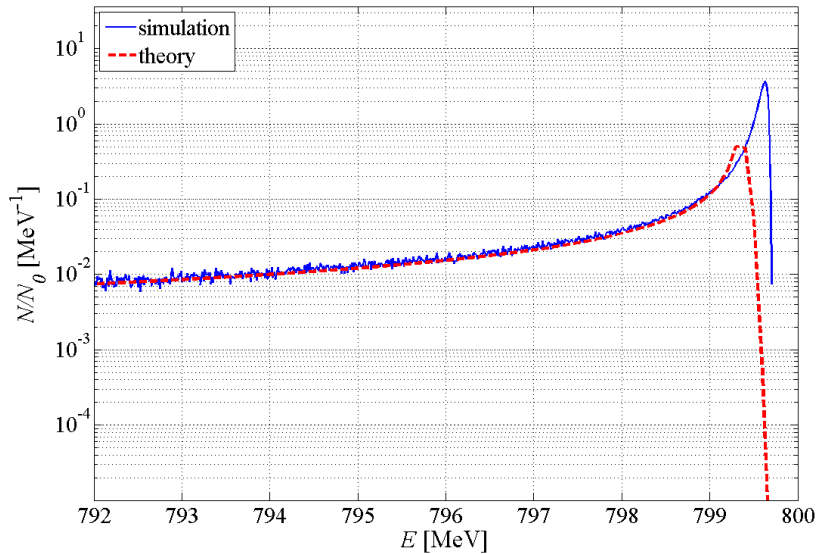
$$\frac{N(t, E)}{N_0} = \frac{1}{E_0} \frac{\left[ \ln \left( \frac{E_0}{E} \right) \right]^{\frac{4}{3}t - 1}}{\Gamma \left( \frac{4}{3}t \right)}$$

## Kinetic Energy spectrum distribution by EGS simulation:

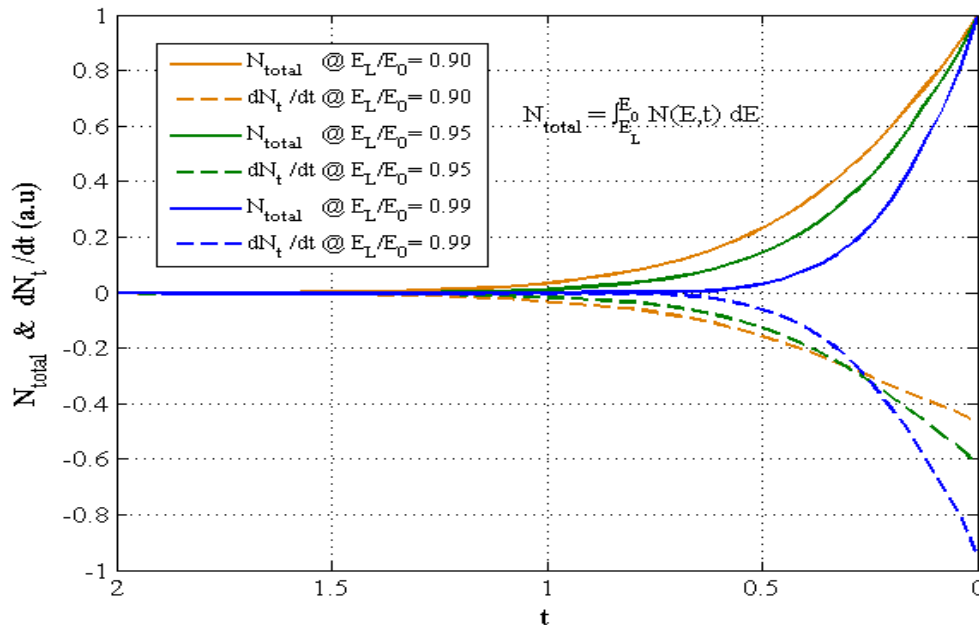
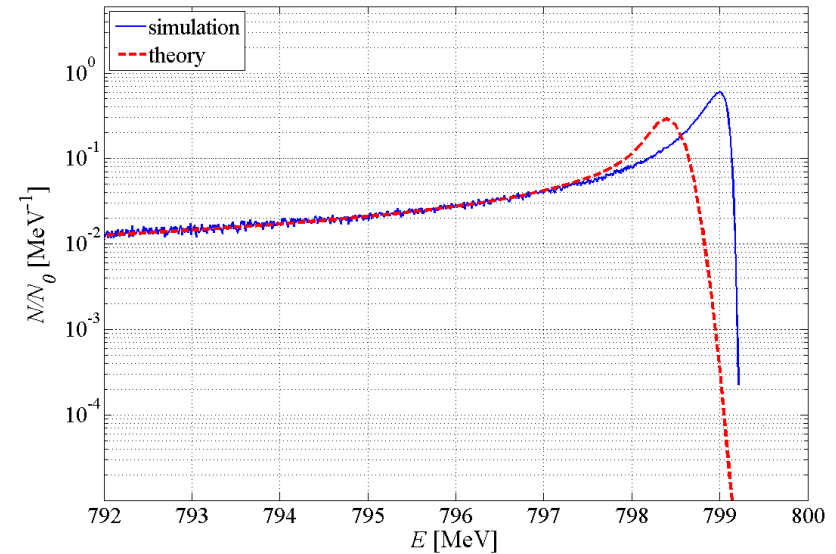


Energy loss straggling is not very sensitive to the electron energy, just depends on the Target thickness when electron pass through a thin Target.

800MeV electron, 200um Tungsten

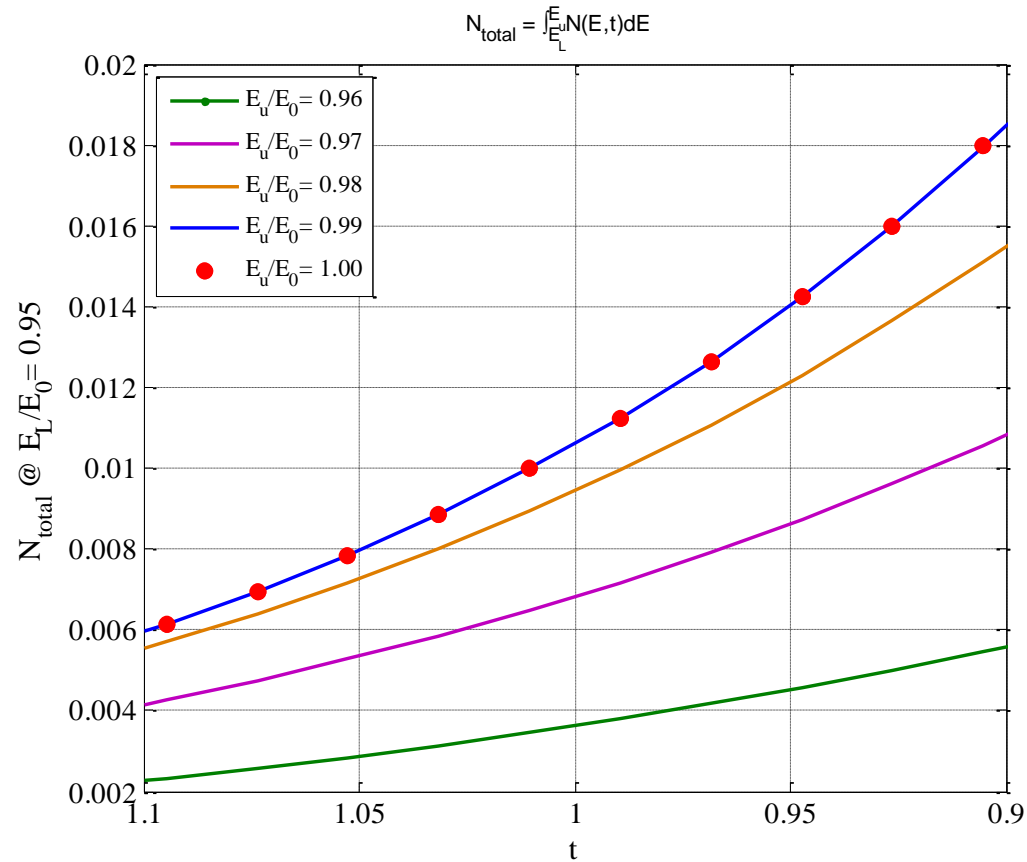


800MeV electron, 500um Tungsten

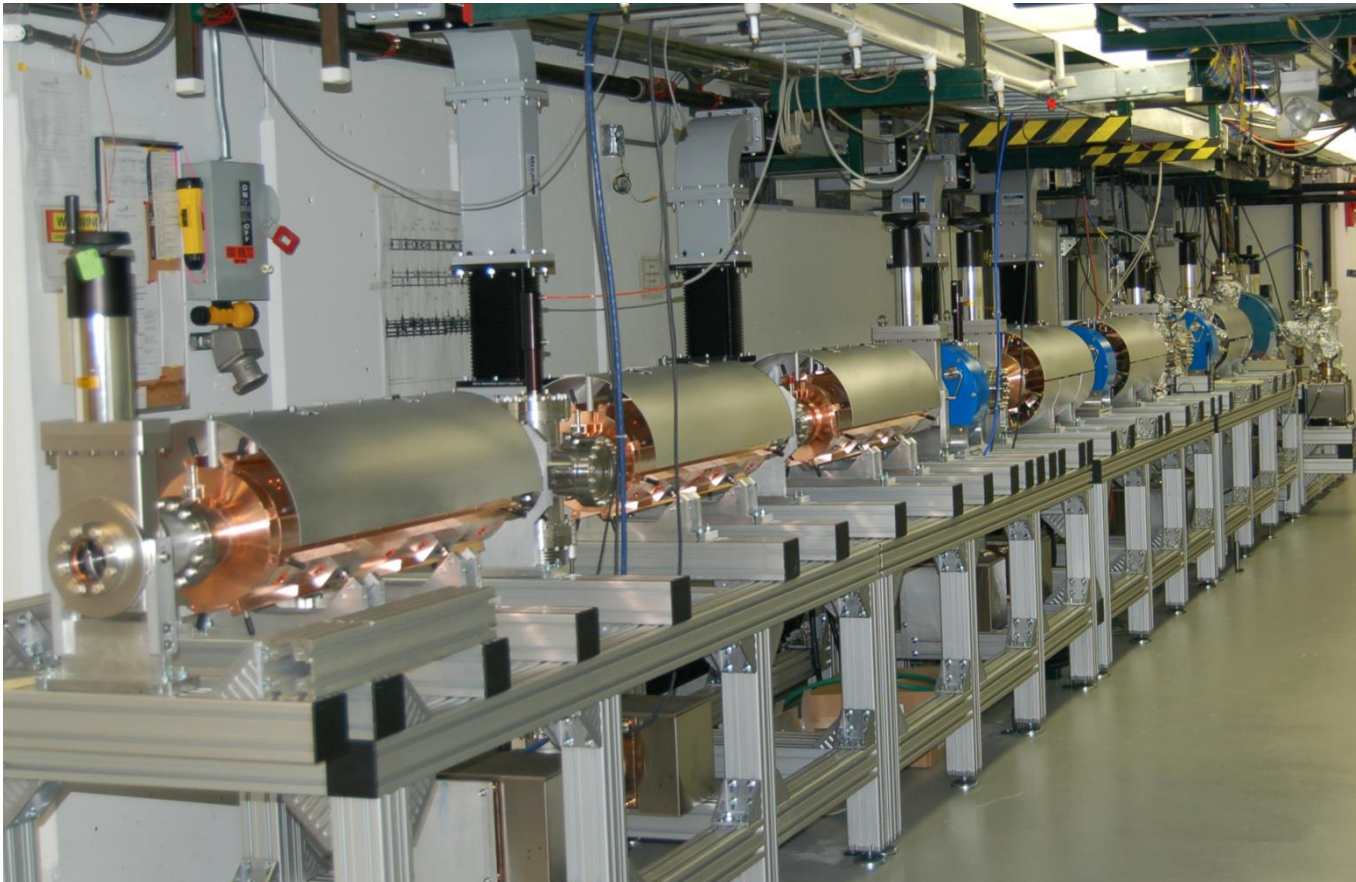


- Theory calculation seems coincide with EGS simulations;
- Amount of electrons in assigned energy spectrum range and the rate of the amount change with thickness seems sensitive to the thin Target thickness;

# Integrated Particle Distribution from 95% - ?

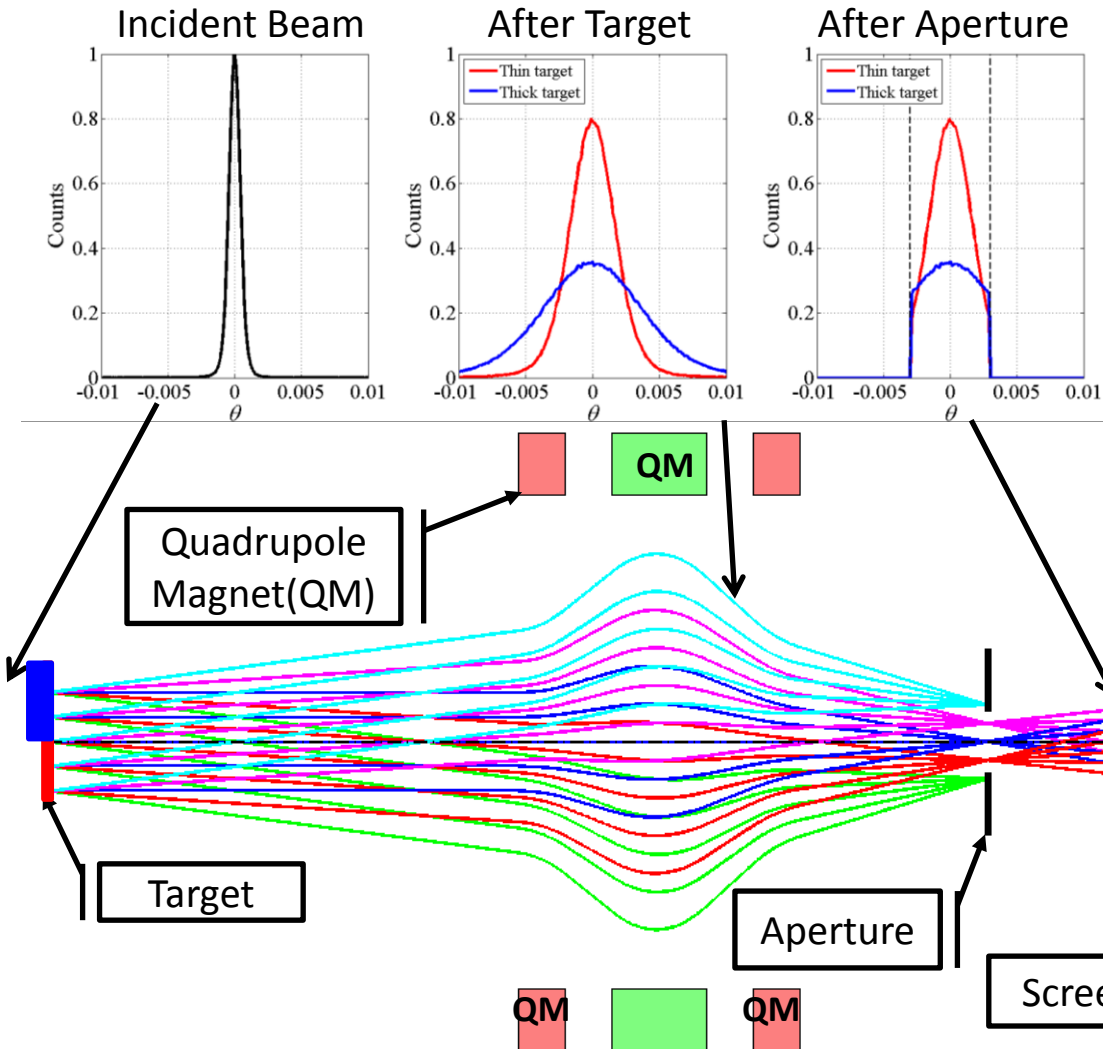


## 2. RF photocathode gun based electron Linac



- ❑ Beams ranging from a few pC to 100 nC/bunch and energy in the range of a few MeV to 1000 MeV can be generated, operating at RF frequencies in the 1~12 GHz range.
- ❑ Normalized emittances from RF guns are typically 1 mm-mrad/nC with about 1 % energy spread, so that the beam can be easily focused down to micro-spot sizes for high spatial resolution studies.

### 3. Point to point imaging based on quadrupole magnets



First order beam optical matrix:

$$\begin{pmatrix} x_{image} \\ x'_{image} \end{pmatrix} = \begin{pmatrix} M_x & 0 \\ * & * \end{pmatrix} \begin{pmatrix} x_{object} \\ x'_{object} \end{pmatrix}$$

Second order beam optical function:

$$x_i = M_x x_o + T_{116} x_o \delta + T_{126} x'_o \delta$$

Matching :  $x'_o = -\frac{T_{116}}{T_{126}} x_o$

Chromatic blur resolution:

$$\Delta x = \frac{T_{126} \phi \delta}{M_x}$$

$\phi$ : Aperture collimate angle

Counts of electrons reflect density of the Target

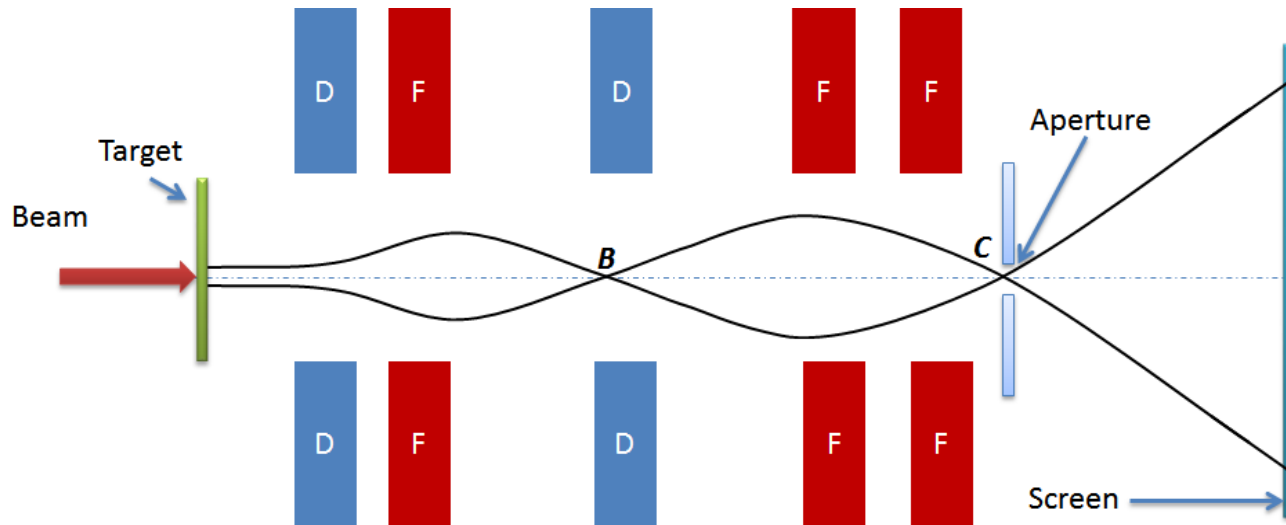
Overall system optimizations are performed using the criteria:

- a) Sufficient transmission of the electron beam through the target with a small energy spread at the imaging plane;
- b) appropriate beam energy to obtain a high contrast ratio for different densities.

The system resolution may be limited by a number of factors, like imaging detector thicknesses and chromatic aberrations. However, these factors are always inversely proportional to the incident electron beam motion; thus by increasing the electron beam energy, a very high resolution can be achieved.



# A imaging simulation



Main parameters of the lattice

- Fast electron penetrate through the Target is simulated in the **EGS4** calculations;
- Electron trajectories from the target exit through the magnetic lens section and to the imaging location is computed by **PARMELA**, A charged particle tracking code.

## Parameters of the Quadrupoles

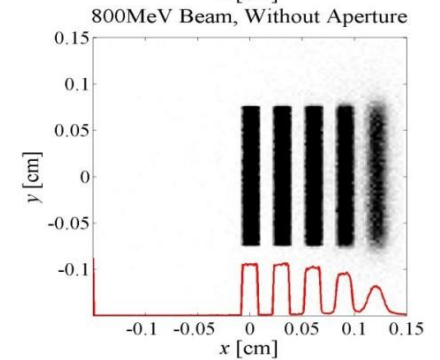
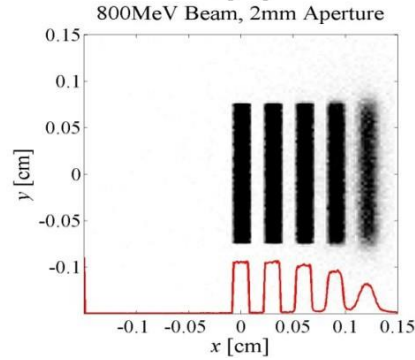
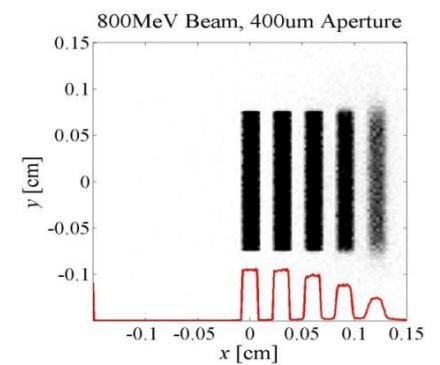
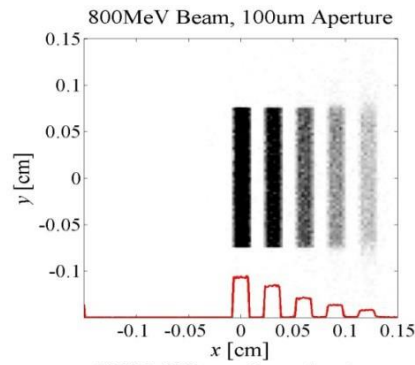
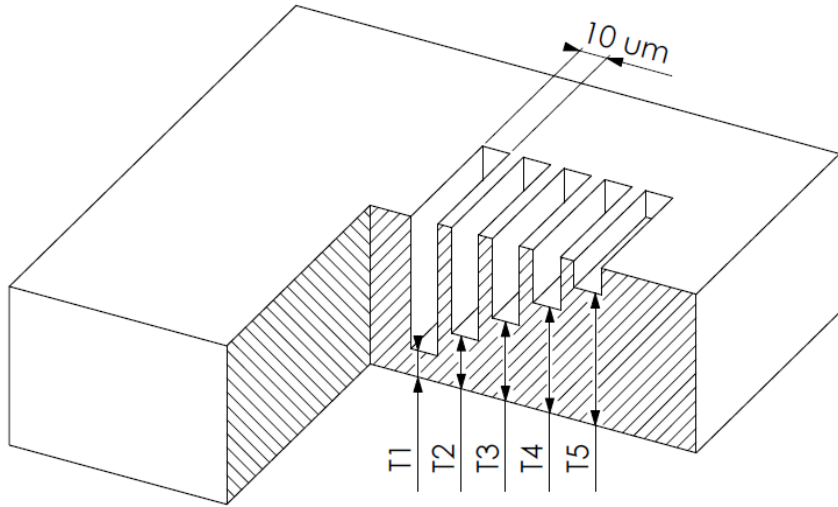
## Parameters of the Drifts

#	Type	Length (cm)	magnetic gradient (kGs/cm)	Radius (cm)	#
Q1	D	12	-10.38	D1	15.0
Q2	F	12	13.5	D2	5.0
Q3	D	12	-8.38	D3	31.0
Q4	F	12	12.8	D4	36.0
Q5	F	12	17.04	D5	6.0
				D6	83.0

## Transfer matrix of the lattice

First order transform matrix	$R_{11}$	15.0
	$R_{12}$	1.09 cm/mrad
	$R_{33}$	-15.0
	$R_{34}$	$-8.78 \times 10^{-4}$ cm/mrad
Second order transform matrix	$T_{116}$	-65.0
	$T_{126}$	-1.7 cm/mrad
	$T_{336}$	-5.5
	$T_{346}$	3.6 cm/mrad

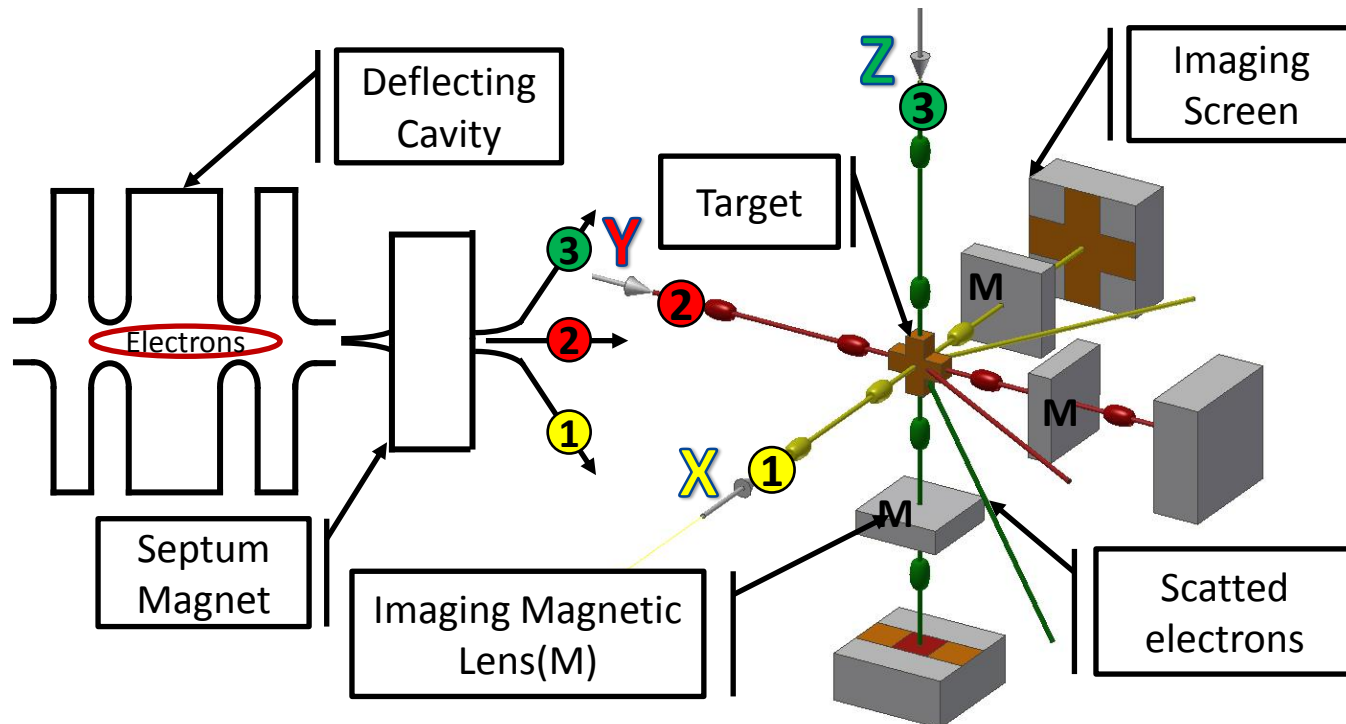
# Simulation Results:



Thickness	100 um Aperture		400 um Aperture		No Aperture	
	T. Ratio [%]	RMS [μm]	T. Ratio [%]	RMS [μm]	T. Ratio [%]	RMS [μm]
T1 10 μm	77.2	0.07	98.1	0.3	99.1	0.3
T2 20 μm	59.5	0.09	96.0	0.3	97.8	0.4
T3 50 μm	36.9	0.3	86.7	0.6	92.9	0.7
T4 100 μm	24.3	0.6	70.5	1	85.0	1.5
T5 200 μm	15.0	1	45.6	3	63.3	5

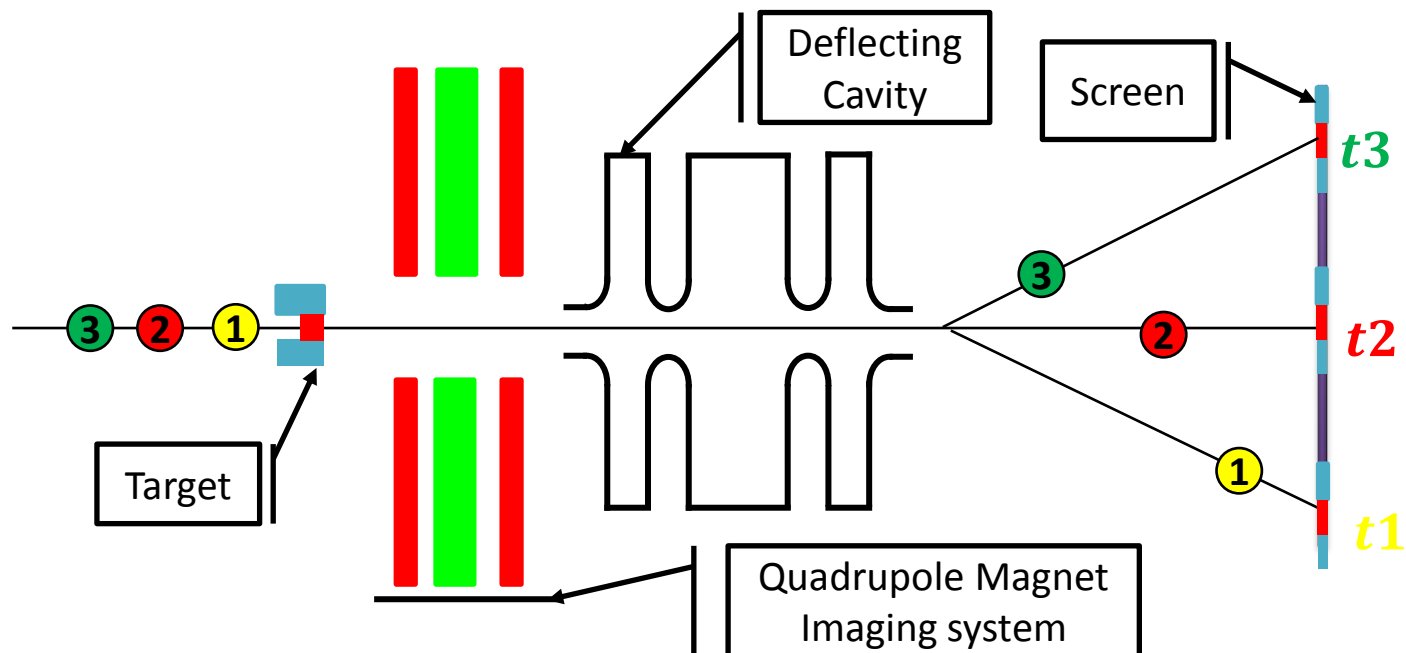
## 4. 4-D imaging

- RF Deflecting Cavity split bunch train into three direction;
- Septum Magnet increase the transverse interval of the bunch rapidly;
- Achromatic matching beam lines transport bunch to the Target in **three orthogonal direction** simultaneously;
- A second and third **bunch group** can be generated at arbitrary time delays and used for a time evolution study of the HEDP target to ps accuracy.



# Imaging information rapid acquiring method:

- ❑ The sequence imaging interval is about ns;
- ❑ The rapid CCD camera repeat frequency is about MHz;
- ❑ Similar with Streak Camera, an RF deflector could be introduced for spatially separating the images of individual time sampling electron bunches to different transverse positions on the screen.



# Electron radiography experiment setup and result based on THU Linac

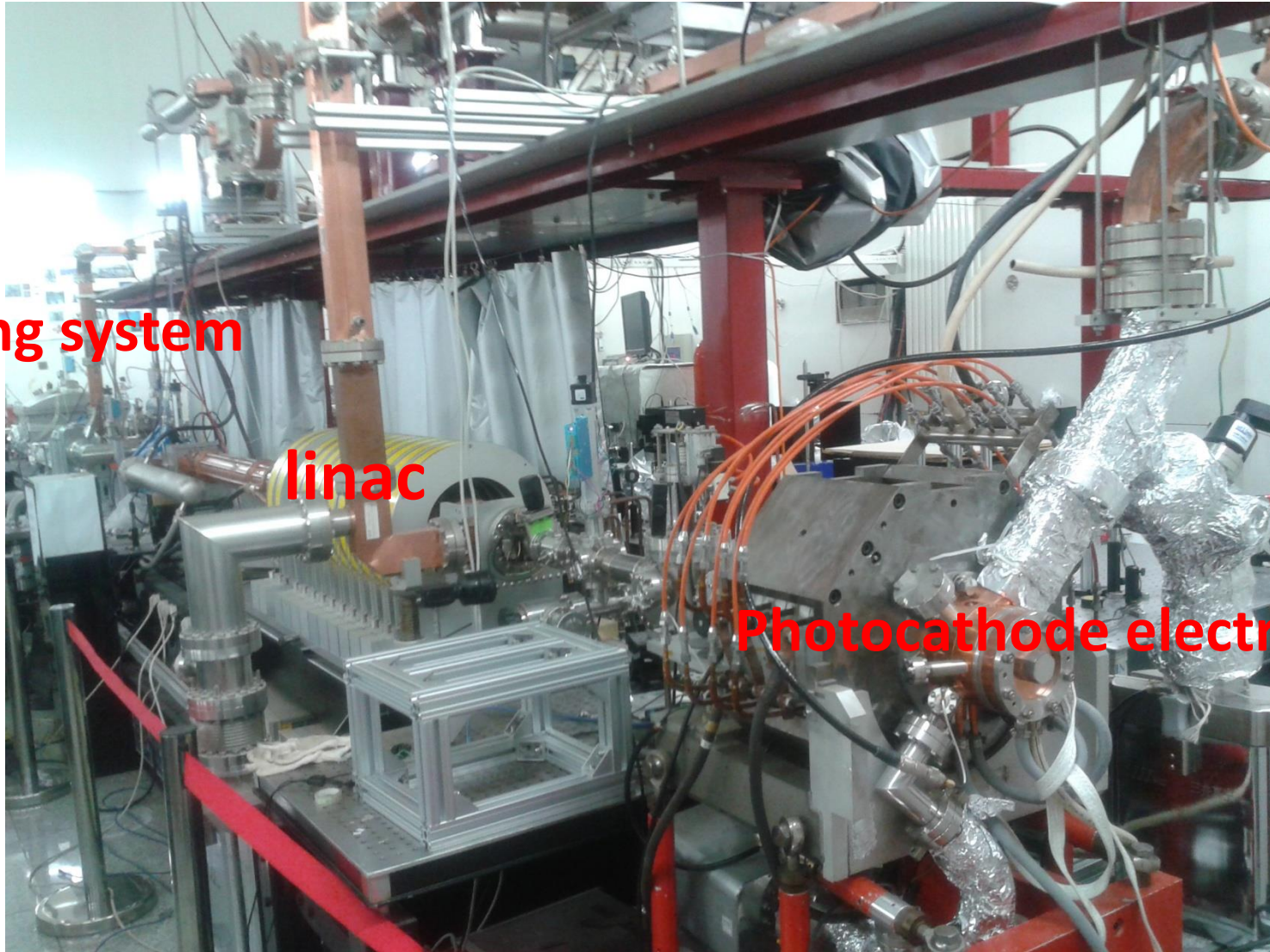
2013-10-16

## a) THU-linac

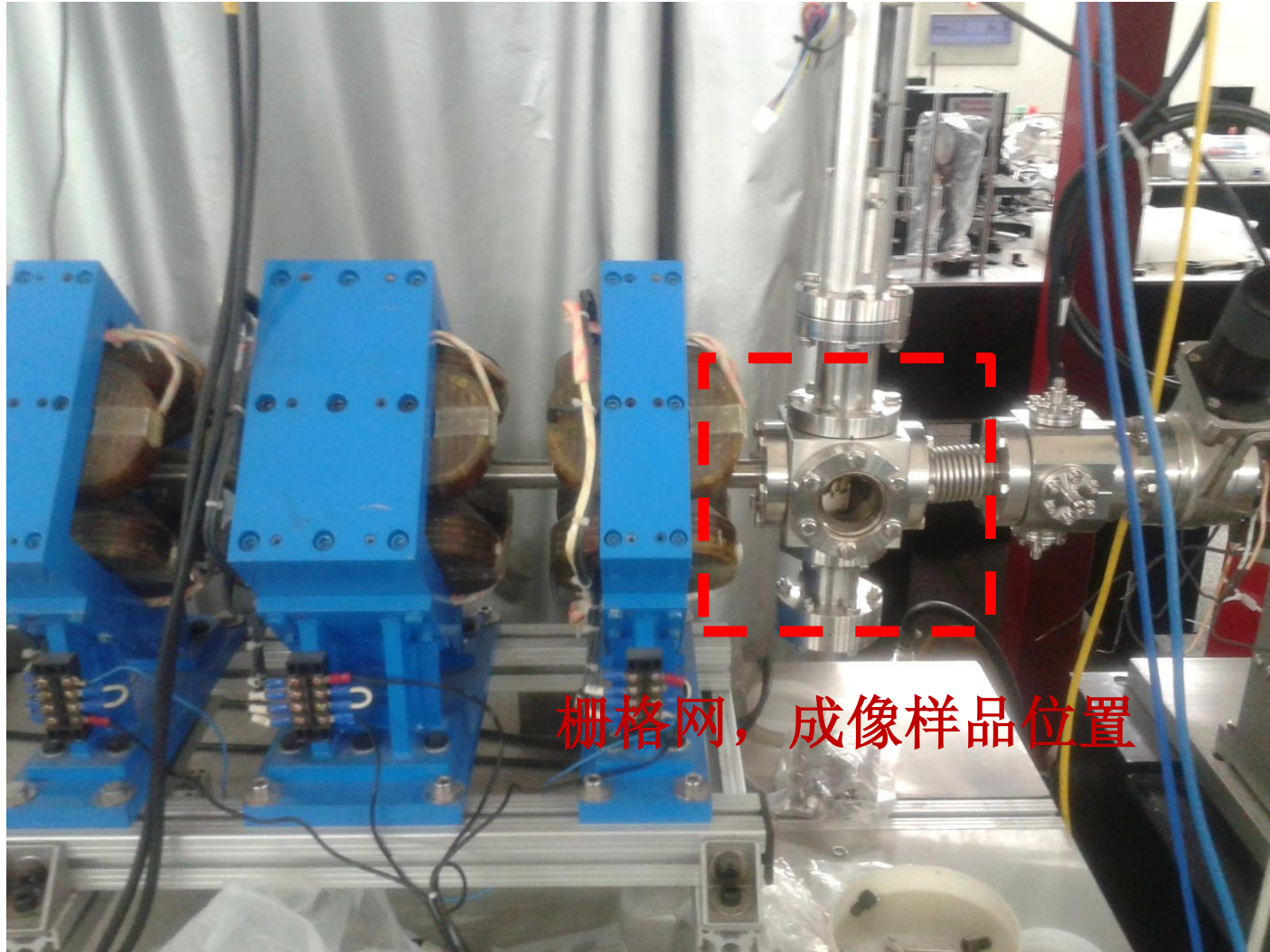
**Imaging system**

**linac**

**Photocathode electron gun**



## b) Sample position

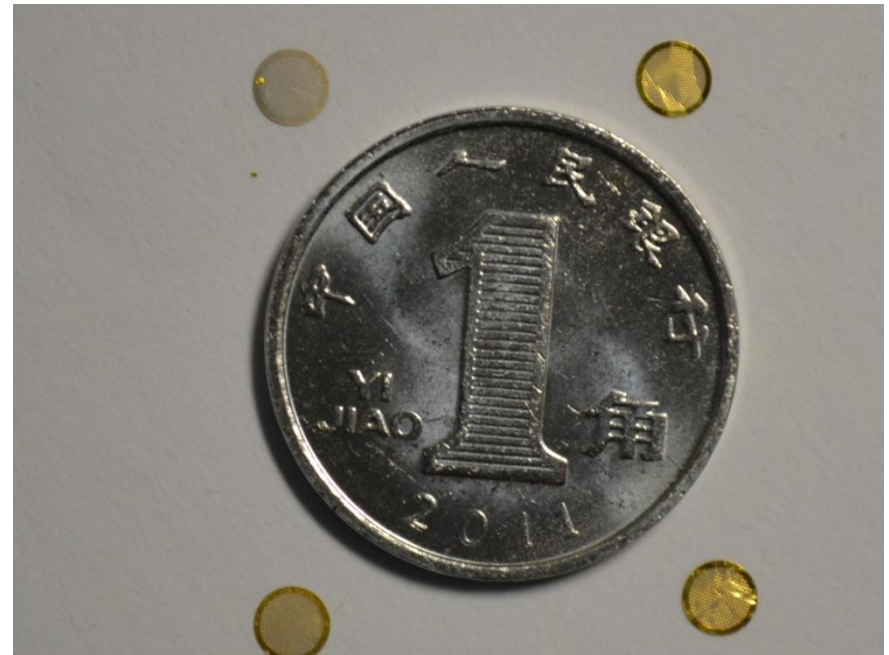
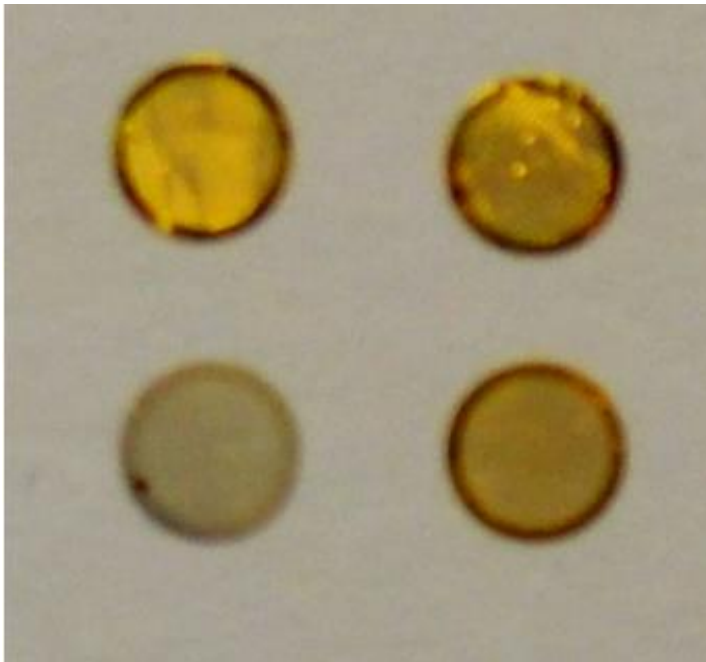


沿着竖直方向放置了五个样品，利用电机调节竖直方向位置，用于成像。

# sample tested

Standard grid for electron lens resolution。

[http://www.gildergrids.co.uk/cat\\_square.shtml](http://www.gildergrids.co.uk/cat_square.shtml)



用肉眼很难分辨50目和200目的不同网格，相对大小如图所示。

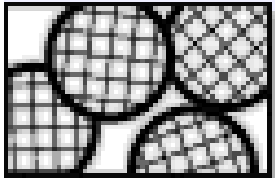


# 四、实验结果

50目铜栅格成像

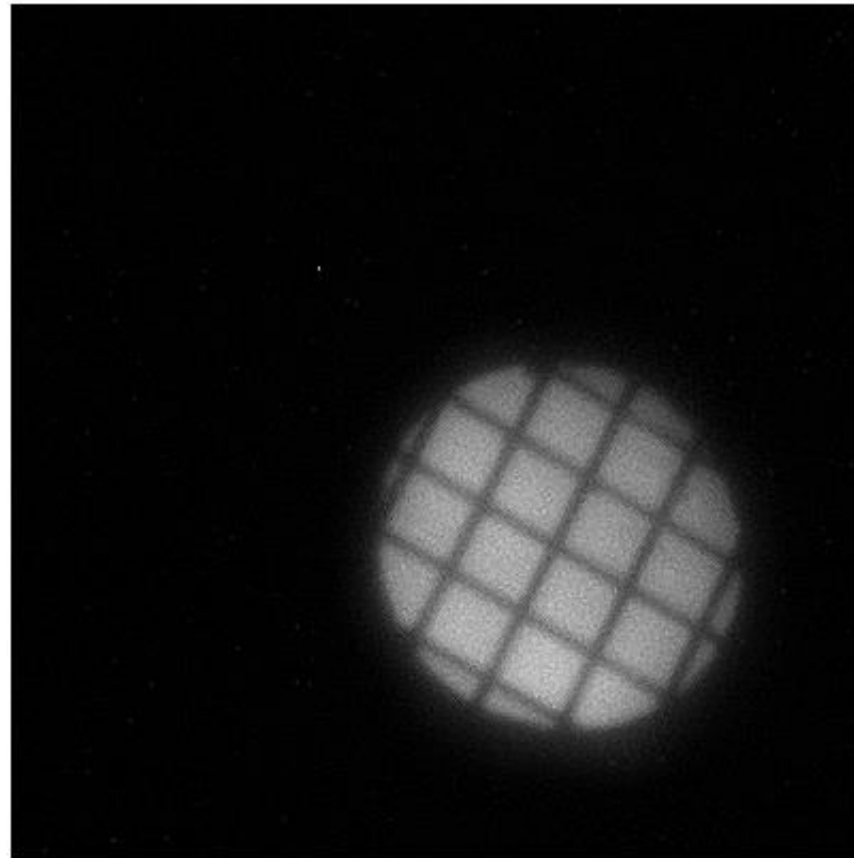
样品形状

Square



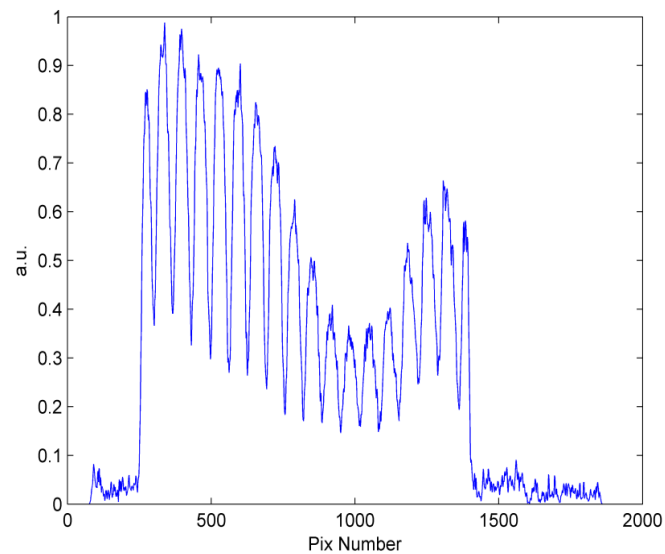
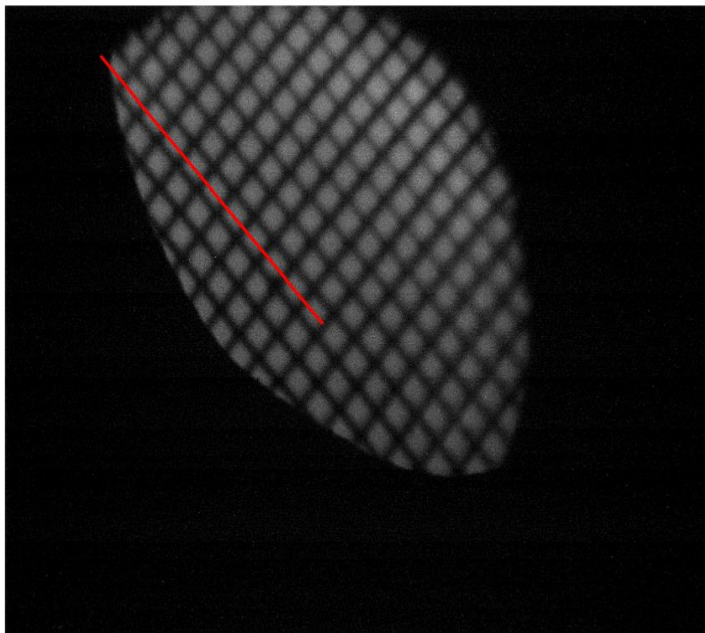
样品来源于:

[http://www.gildergrids.co.uk/cat\\_square.shtml](http://www.gildergrids.co.uk/cat_square.shtml)

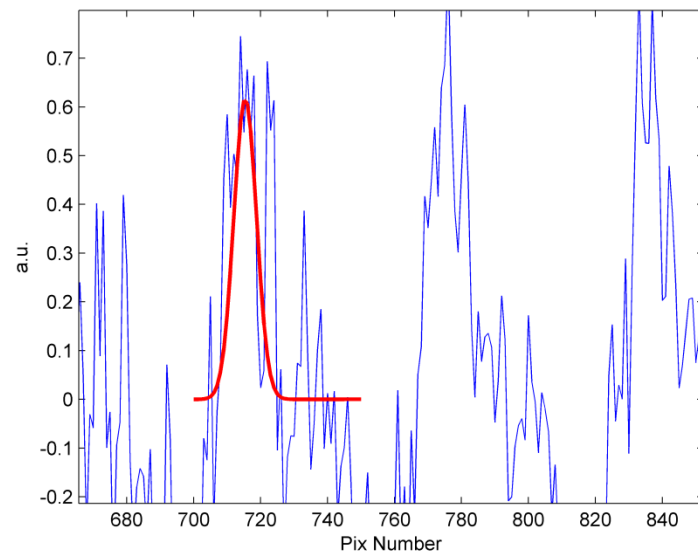


50目孔径为 $420\mu\text{m} \times 420\mu\text{m}$ ，线条宽度为 $80\mu\text{m}$ 。

## 沿红色线条的投影分布



利用高斯拟合，求得RMS空间分辨率  
可以达到10 $\mu$ m.





## IV. Summary

- † Unprecedented resolution can be achieved with very high energy electron beams;
- † 3-D imaging with high precision time resolution can be achieved;
- † Electron radiography is very suitable for HEDP/ICF diagnostics.