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Design and Technique of Apertures for Neutron Penumbral Imaging of Z-Pinch Diagnosis Process

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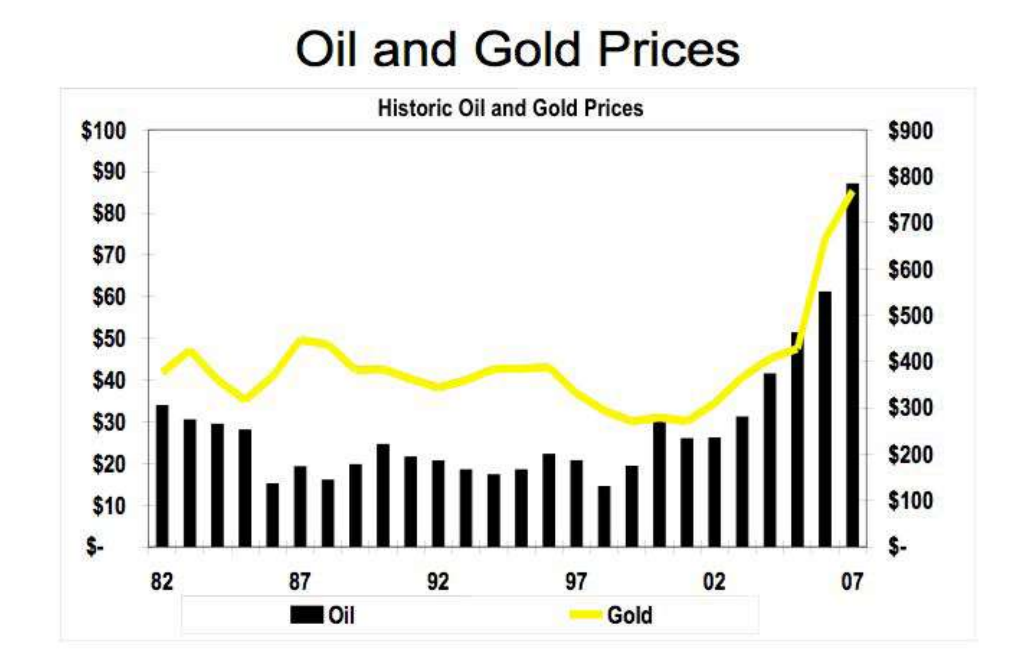
Dubna

2016

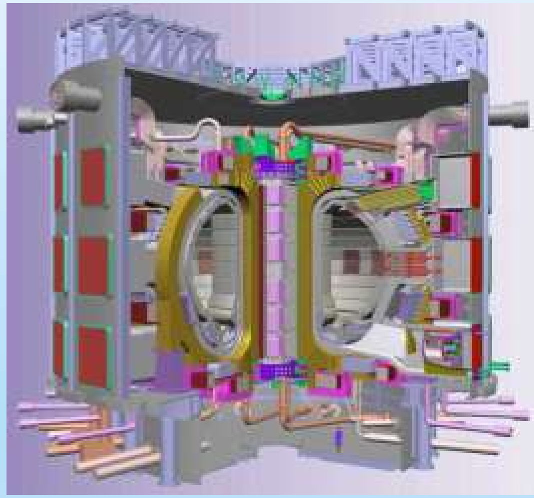
Content

1 Introduction



Source: Bloomberg, State of Alaska, Tax Div.

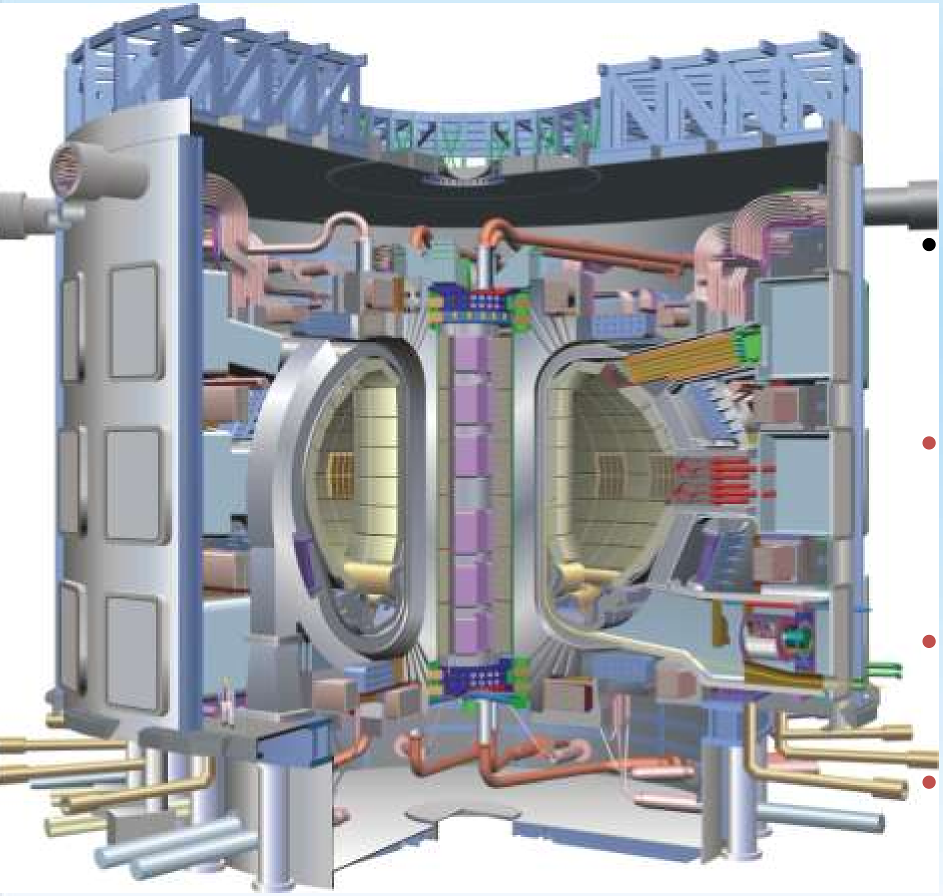
Energy Crisis excites the development of fusion science！



International Thermonuclear Experimental Reactor

National Ignition Facility

ITER

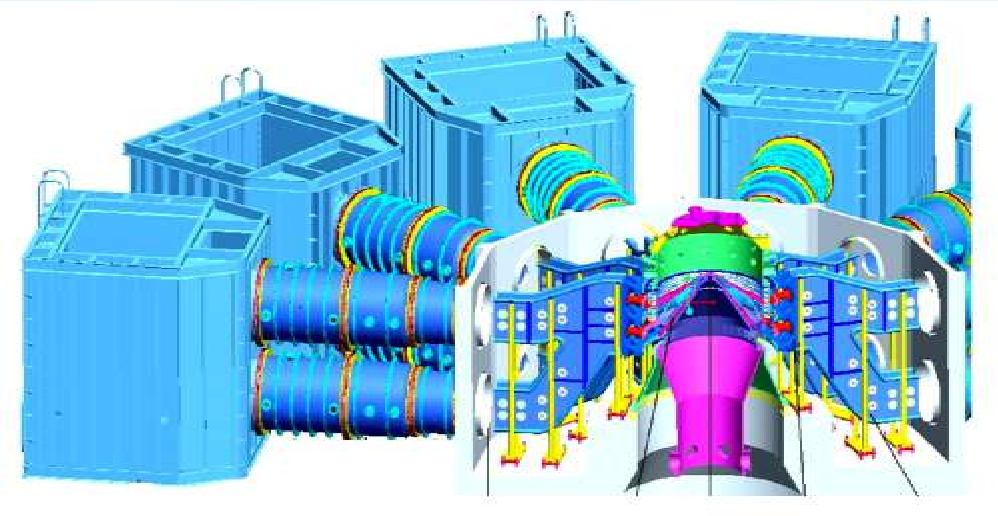


- The ITER machine is a >500 MW (thermal) fusion research reactor of the Tokamak type
- Worldwide collaboration of 7 parties: EU, USA, RF, Japan, China, South Korea, India
- ITER is located at Cadarache, CEA research site, south France
- ITER construction ~$5 bn (EU 50%)
- Presently the largest international scientific collaboration?

EAST （ Experimental Advanced Superconducting Tokamak）

duration of fusion ~1000s

Institute of Plasma Physics Chinese Academy of Sciences



Z-Pinch facility in China

Concepts of fusion-fission hybrid reactors

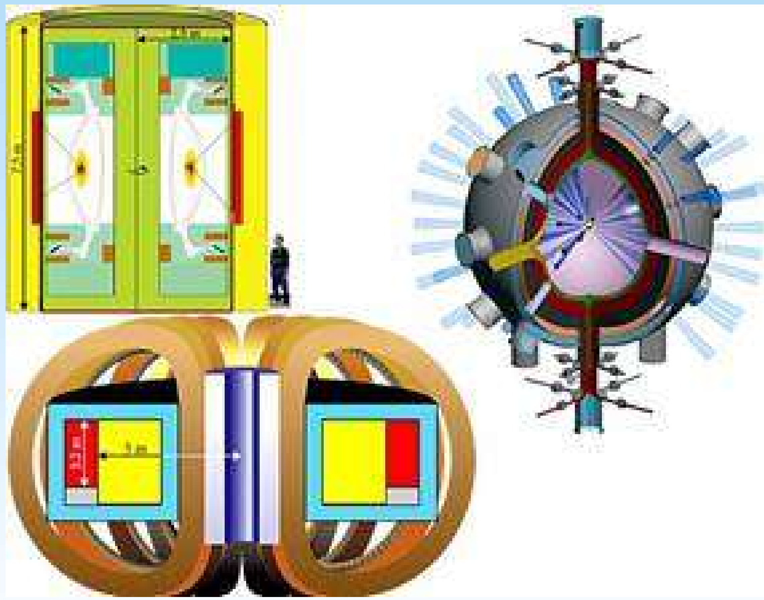


Table 4.22-1 List of Required Plasma Measurements classified by their Operational Role

GROUP 1a Measurements For Machine Protection and Basic Control	GROUP 1b Measurements for Advanced Control	GROUP 2 Additional Measurements for Performance Evaluation and Physics
• Plasma shape and position, separatrix-wall gaps, gap between separatrixes • Plasma current, q(a), q(95%) • Loop voltage • Fusion power • $\beta_N = \beta_{tor}(aB/I)$ • Line-averaged electron density • Impurity and D,T influx (divertor, & main plasma) • Surface temp. (divertor & upper plates) • Surface temperature (first wall) • Runaway electrons • 'Halo' currents • Radiated power (main plasma, X-point & divertor). • Divertor detachment indicator (J_{sat}, n_e, T_e at divertor plate) • Disruption precursors (locked modes, m=2) • H/L mode indicator • Z_{eff} (line-averaged) • n_T/n_D in plasma core • ELMs • Gas pressure (divertor & duct) • Gas composition (divertor & duct) • Dust	• Neutron and α-source profile • Helium density profile (core) • Plasma rotation (toroidal and poloidal) • Current density profile (q-profile) • Electron temperature profile (core) • Electron density profile (core and edge) • Ion temperature profile (core) • Radiation power profile (core, X-point & divertor) • Z_{eff} profile • Helium density (divertor) • Heat deposition profile (divertor) • Ionization front position in divertor • Impurity density profiles • Neutral density between plasma and first wall • ne of divertor plasma • Te of divertor plasma • Alpha particle loss • Low m/n MHD activity • Sawteeth • Net erosion (divertor plate) • Neutron fluence	• Confined α-particles • TAE Modes, fishbones • Te and Ti profile (edge) • ne, Te profiles (X-point) • Ti in divertor • Plasma flow (divertor) • nT/nD/nH (edge) • nT/nD/nH (divertor) • Te fluctuations • ne fluctuations • Radial electric field and field fluctuations • Edge turbulence • MHD activity in plasma core

Neutron measuements!

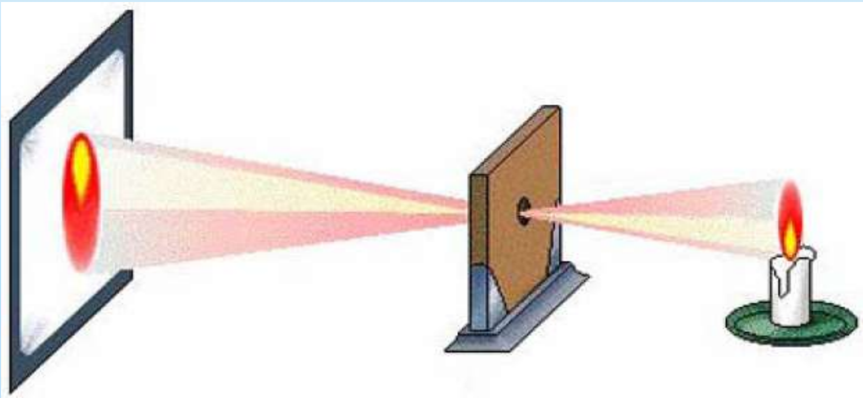
Diagnosis of typical physical quantity for the ICF process

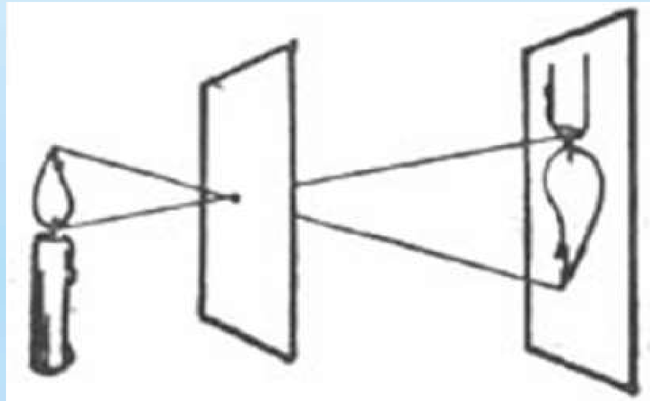
- yield（yield of neutrons and ionizing particles）
- plasma temperature
- thermonuclear burn time
- shape of burn region
- areal density of burn (ρR)

Neutron imaging

- Pinhole imaging
- Penumbral imaging

The phenomenon of pinhole imaging





F(x)A(x)=-mF(x)**

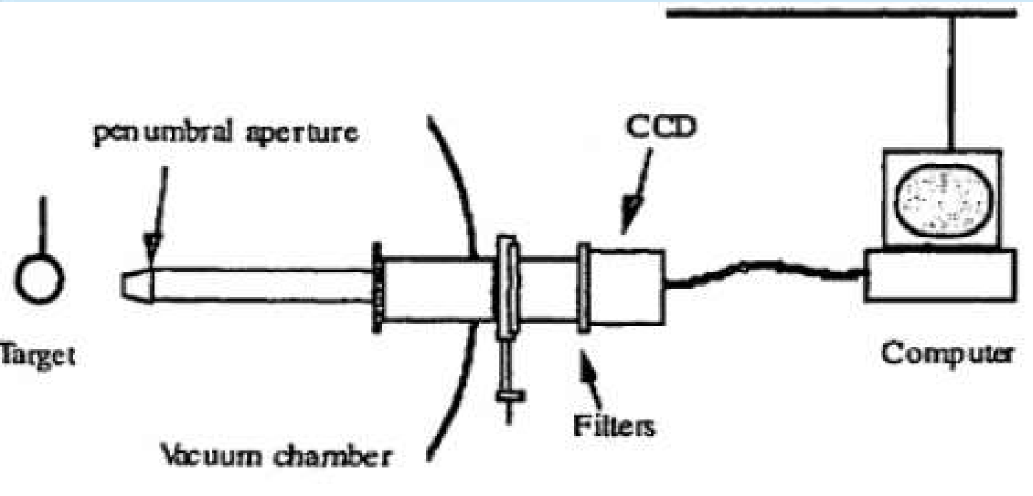
F(x)	the image of the object
**	imaging processing denote convolution
-mF(x)	the inverted real image (magnification is “m”)

Big trouble for neutron pinhole image

- (1)Detection efficiency of neutrons is low
- (2)In effective detecting area neutron imaging requires detecting element to be smaller to get more image elements
- (3) Pinhole Maching too difficult

How to solve the problem?

neutron penumbral imaging devices



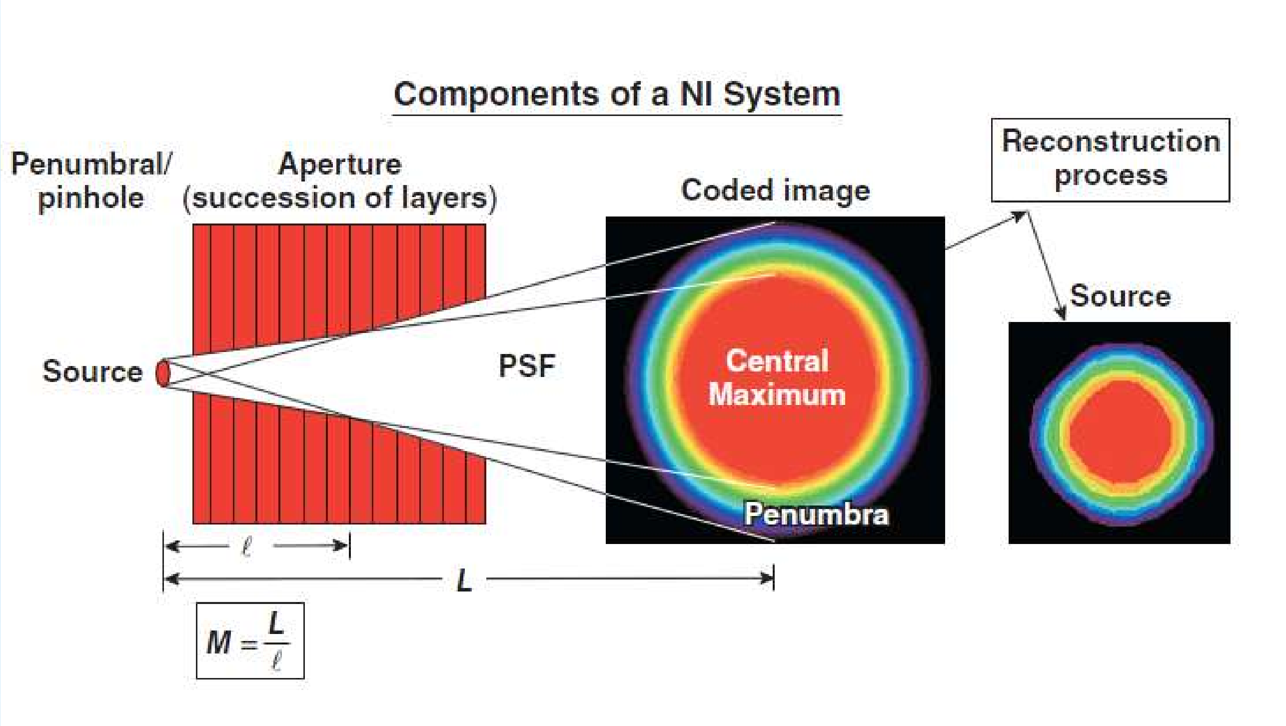
(1) Penumbral imaging is just for weaksource and penetrating radiation.
(to get something or nothing)

(2) It is conceptually similar to pinhole imaging with the essential difference that the aperture is larger than the source

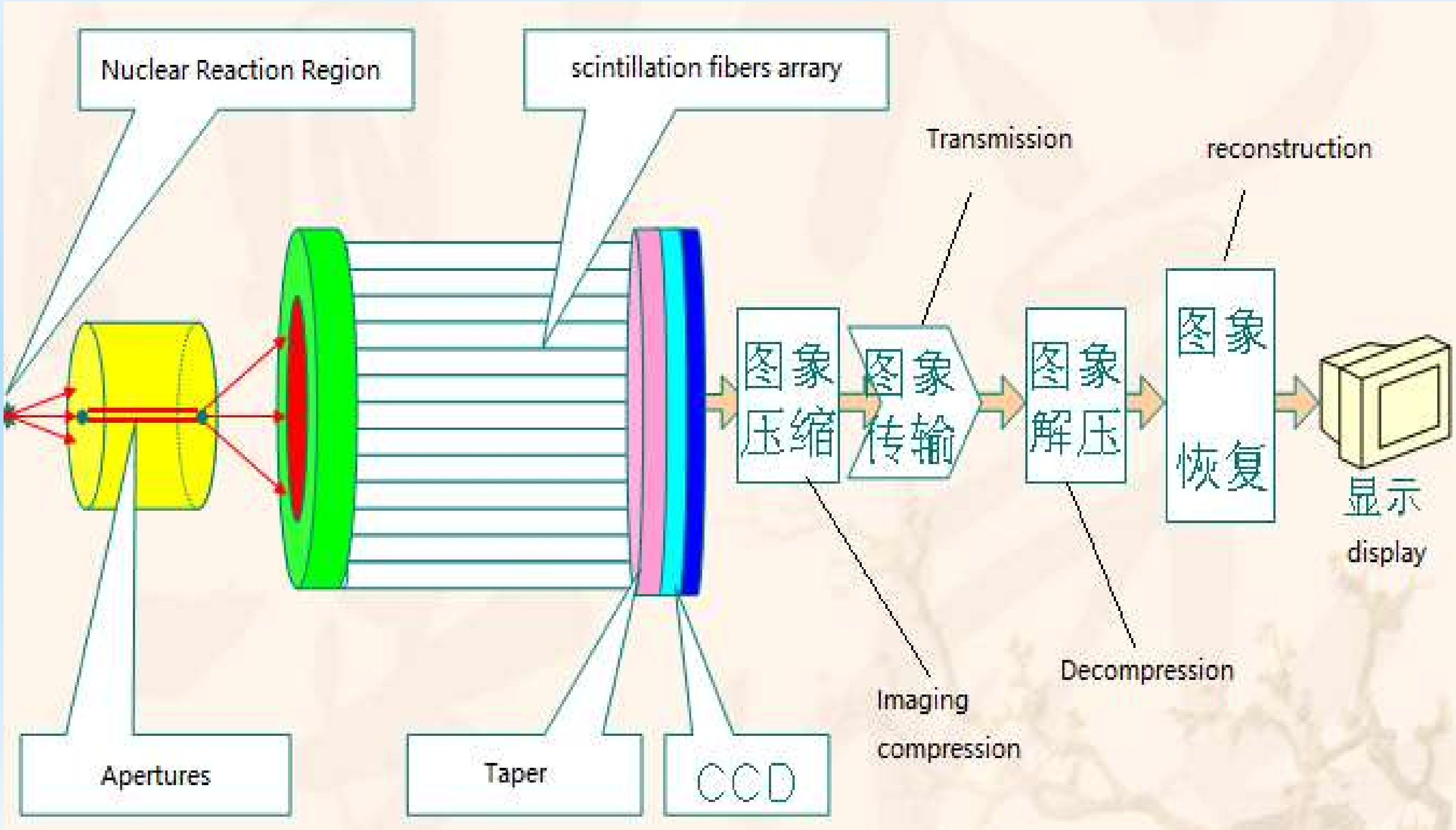
(3) Coded image needs reconstruction

"Design of Thick Apertures for High-Resolution Neutron Penumbral Imaging" IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 37, NO. 2, APRIL 1990

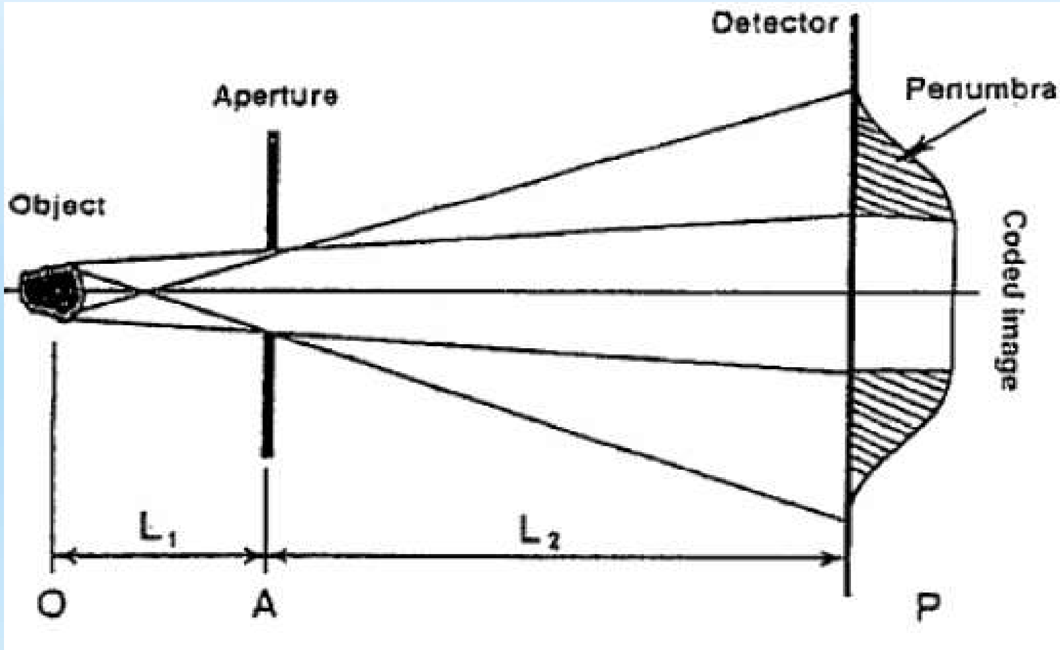
neutron penumbral imaging



D. D. Meyerhofer, T. C. Sangster Laboratory for Laser Energetics University of Rochester
R. A. Lerche Lawrence Livermore National Laboratory
L. Disdier Commissariat a L'Energie Atomique Bruyeres-le-Chatel, France
46th Annual Meeting of the American Physical Society Division of Plasma Physics Savannah, GA 15–19 November 2004


Nuclear Reaction Region
scintillation fibers array
Transmission
reconstruction
图象压缩
图象传输
图象解压
图象恢复
显示
display
Decompression
Imaging compression
Apertures
Taper
CCD

The principle of penumbral imaging



All points of object give contribution to every pixel

$$P(\mathbf{r}) = \int A(\mathbf{r}-\mathbf{r}')\cdot O(\mathbf{r}')\,d\mathbf{r}'$$
$$= A * O$$

where * denotes convolution. Thus given $P(\mathbf{r})$ and $A(\mathbf{r})$, the source function $O(\mathbf{r})$ can be reconstructed by a simple linear deconvolution technique. Usually, the deconvolution (reconstruction) is performed by using a Wiener filter [ ] to reduce noise amplification.

Characteristics of penumbral aperture

☆**Adequate contrast**

several mean free paths thickness

☆**Sufficiently sharp cutoff**

PSF isoplanatic and distortion-free

☆**Acceptable signal-to-noise ratio aperture**

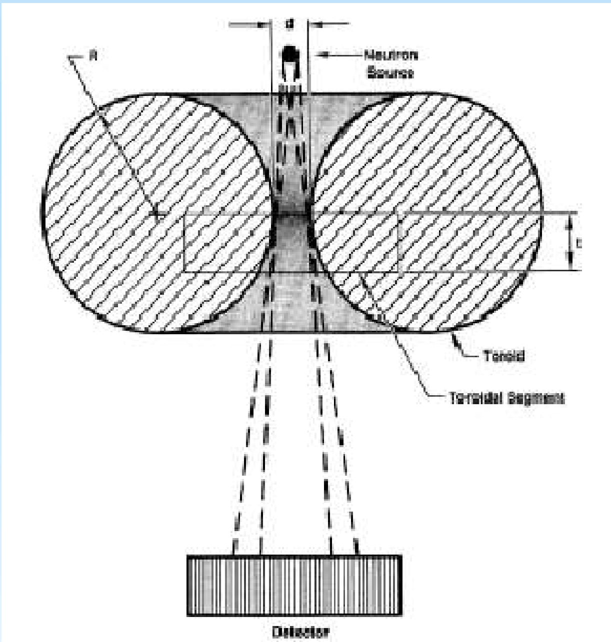
close to the source

☆**Encoded image**

resulting images need numerical construction

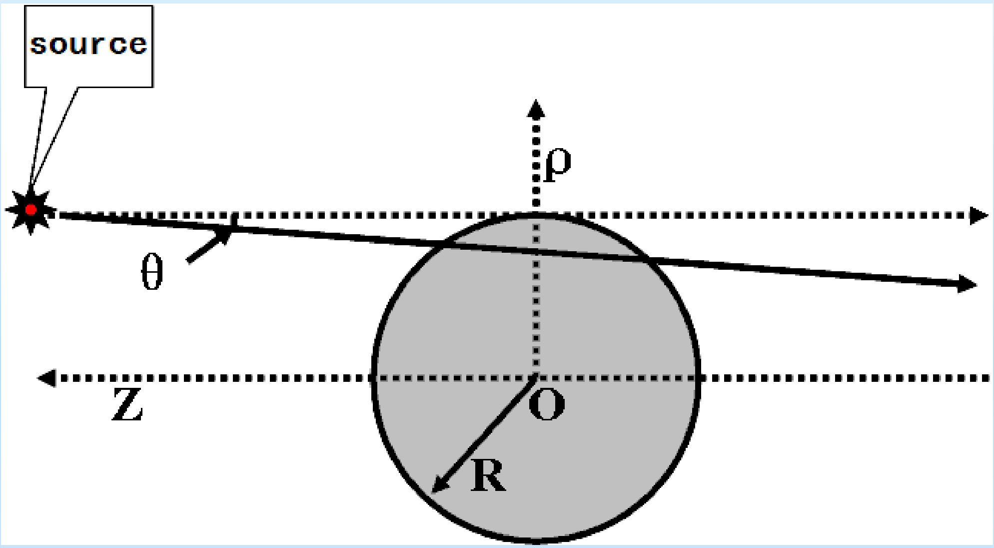
2 Design of penumbral apertures

- We utilize the similar designing suited for laser fusion diagnosis with small source view method that D Ress put forward in 1990.



"Principle of the toroidal segment aperture. To simplify the image reconstruction process, the point-spread function of the aperture must be reasonably isoplanatic. To achieve such a point-spread function with an aperture thick enough to effectively block neutrons requires a three-dimensionally tapered aperture. A particularly satisfactory taper is a toroid where the radius of curvature (minor radius of the toroid) R is much greater than the aperture thickness t. A practical realization of this concept utilizes a segment of the toroid determined by the maximum size of the source and the source-aperture distance. The results presented here were obtained with an aperture 6.1cm long, with a minimum diameter d of 407um and a radius of curvature of 19.5m."

Ress D, Lerche RA, Ellis RJ, et al. Neutron imaging of Laser Fusion Targets[J]. Science，New Series, Aug.19,1988,241(4868):956-958.



$$\Delta z = 2R(1-q)\sqrt{\frac{1}{(1-q)^2} - 1 + \theta^2}$$

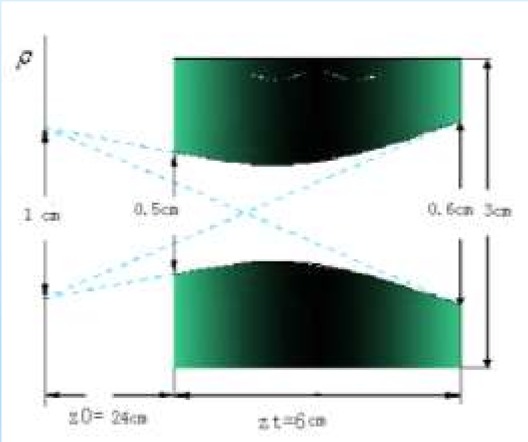
$$R = \frac{z_0}{z} R_0$$

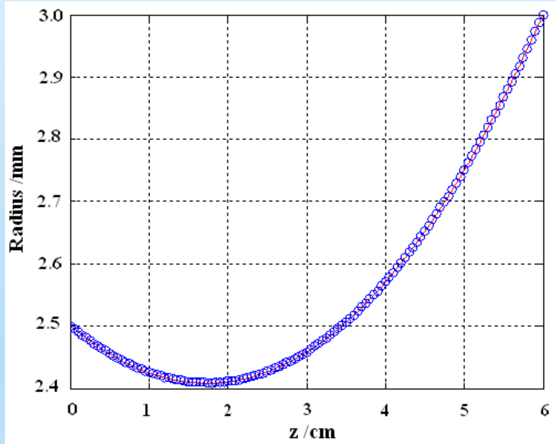
$$\Delta z = 2\sqrt{R z_i \theta}$$

$$\begin{cases} \rho - R = \theta(z - z_i) \\ \rho^2 + z^2 = R^2 \end{cases}$$

$$\frac{d^2\rho}{dz^2} = \frac{z}{z_0 R_0}[1 + (\frac{d\rho}{dz})^2]^{3/2}$$

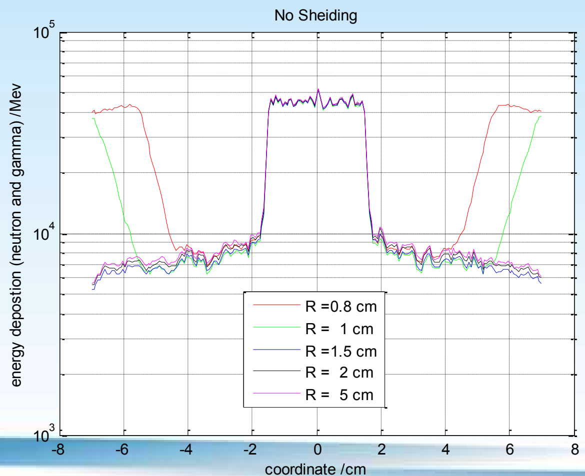
- **Determine the taper function of the penumbral aperture**

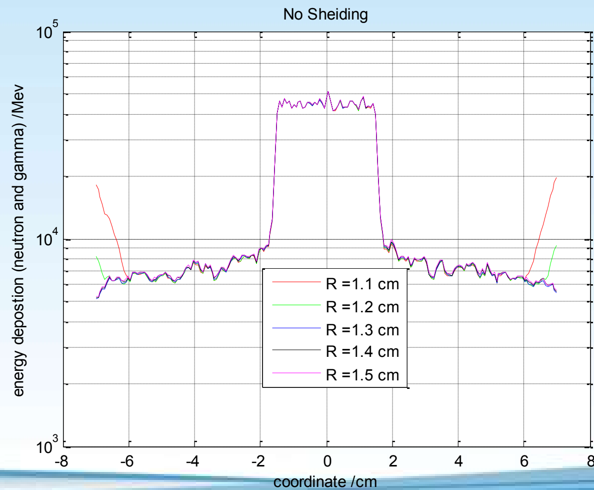




Taper function

- **Determine the outer radius of apertures**

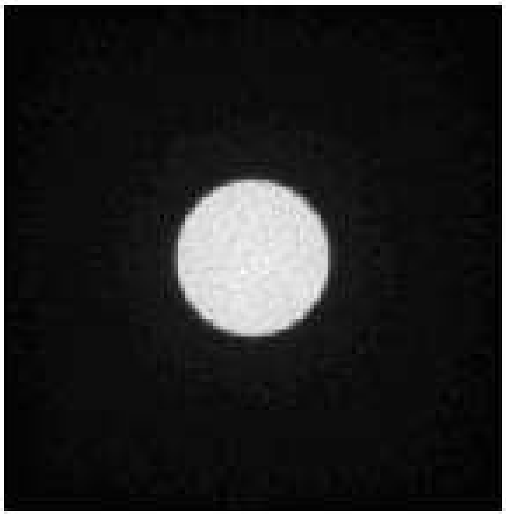


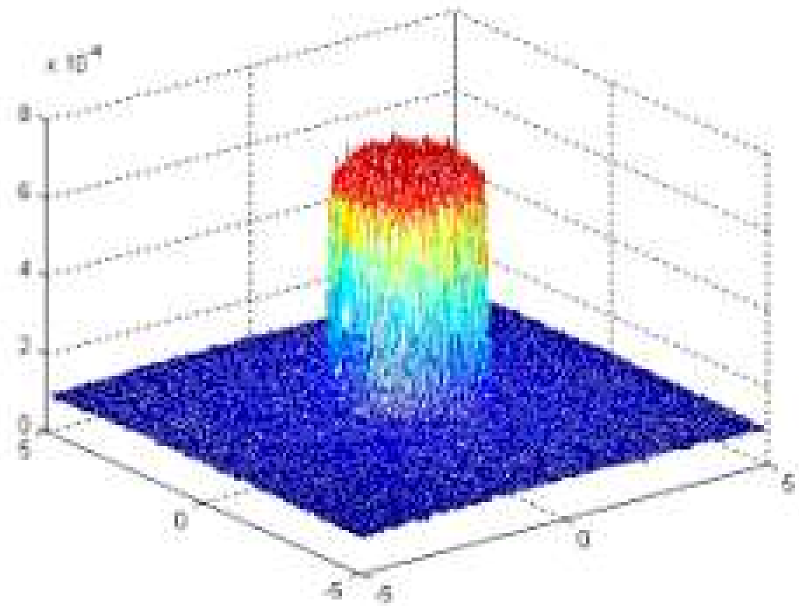


Radius 1.5cm

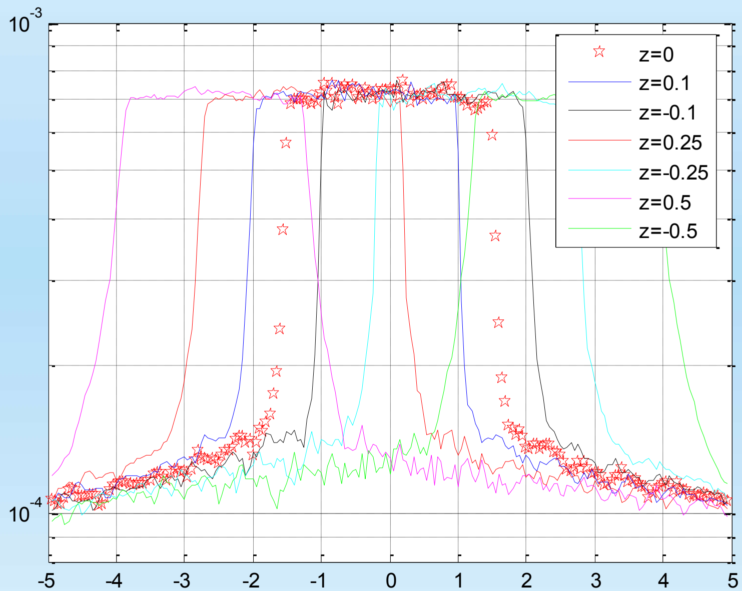
3 Properties of designed apertures

- PSF

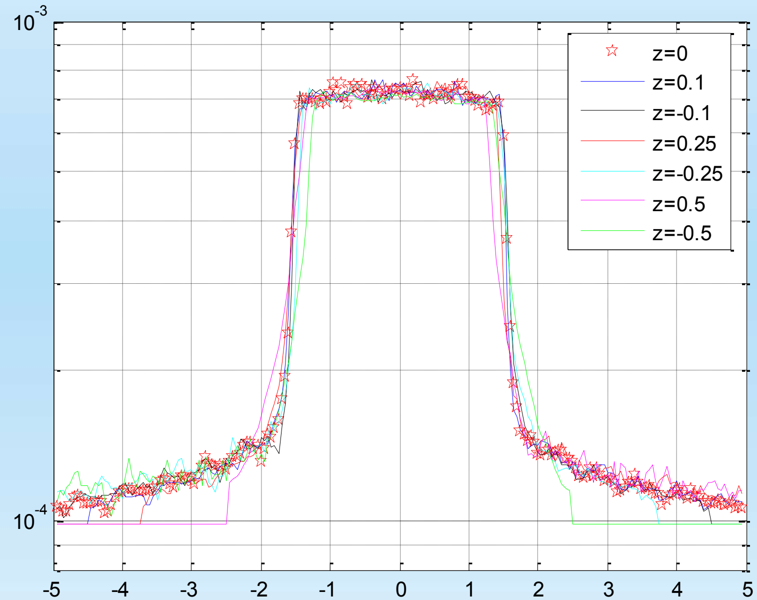




➢ Isoplanaticity

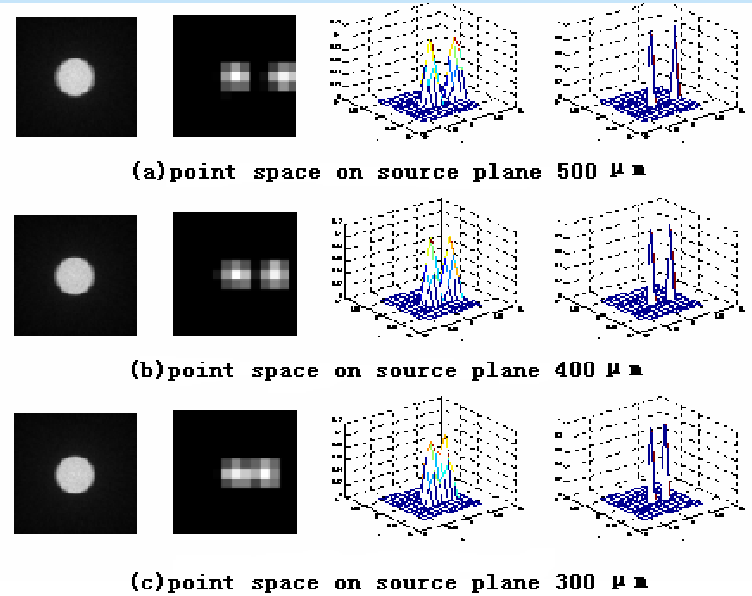


PSF with point source offset axis



PSF after moving to the axis center

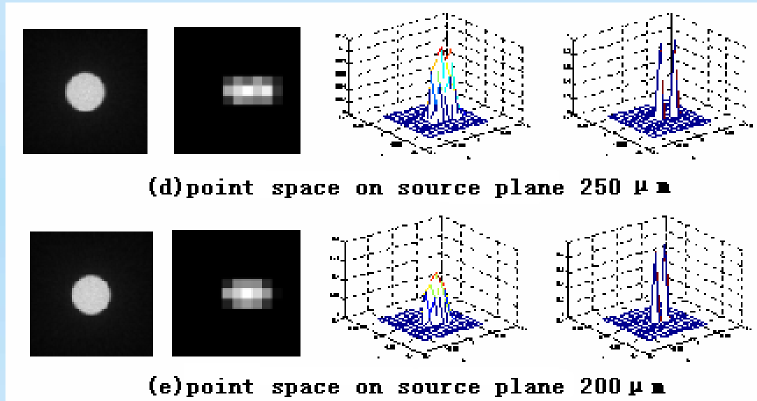
➢ Spatial resolution



(a)point space on source plane 500 μm

(b)point space on source plane 400 μm

(c)point space on source plane 300 μm

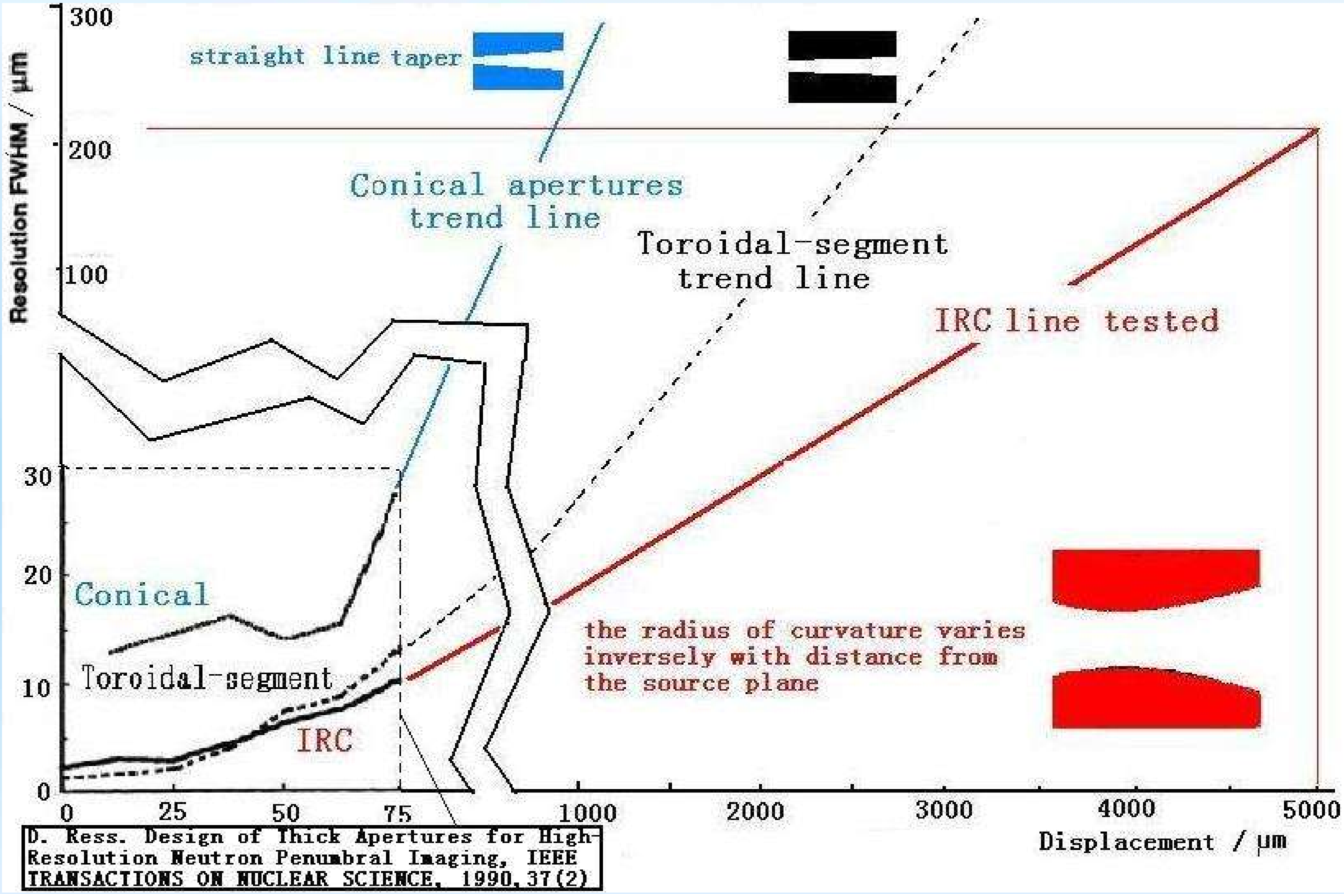


(d)point space on source plane 250 μm

(e)point space on source plane 200 μm

Absolute: 250μm

Relative: 40 lp/mm



Extrapolate the MTF of apertures designed by D. Ress, the spatial resolution reaches a consistence for a field view of 1cm .

4 Technique of penumbral apertures

- Materials

polymers 5%
- Bisphenol A epoxy resin E-51
- polyamide 650

(Bisphenol A epoxy resin E-51 : polyamide 650 = 100:60)

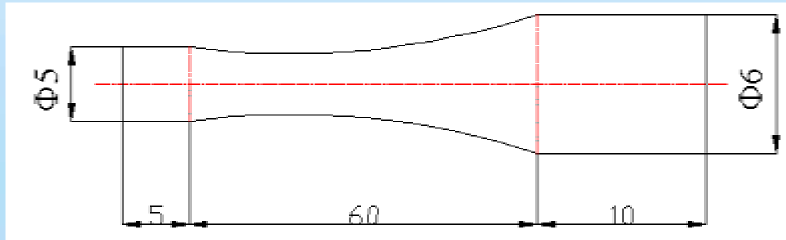
tungsten 95%

acetone: 100mL

titanium dioxide(TiO_2) 1.5g.

➢ Instruments

vacuum evacuation machine, incubator, mixer, screw jack and mold



- Procedures

(1) Design and fabrication of the mold and the "needle stick".
(2) Smear silicon oil on the inner surface of the mold and the outer surface of the "needle stick"
(3) In terms with the ratio of the materials, weigh tungsten 950g, bisphenol A 32g, polyamide 18g, titanium dioxide 1.5g.
(4) Add about 100mL acetone as dilution; mix the materials sufficiently and uniformly with the mixer.
(5) Put the well-mixed polymer-tungsten in the vacuum evacuation machine, pump air and acetone. Repeat pumping 2-3 times.

➢ Procedures

(6) Pressurize the compound materials with the screw jack. Put them wholly into the incubator to solidify.

(7) The solidification course is set on the program that the materials are bathed under 50°Cfor three hours, then one hour under 70°C and the last two hours under 130°C

(8) Separate mold.

(9) Corrode the smaller radius end of the “needle stick”. with nitrate of volume concentration 50%.

(10) Remove the mold from the aperture and clean the aperture.

- Notices

① the carbon steel is selected as material of the "needle stick" instead of the ~~stainless steel~~, which is mainly because that stainless steel cannot be corroded by acids.

② pump air at least twice. The first time of pumping air from the materials in the mold can be done without loading force upon the materials; in the second or third time, press the materials hardly with a screw jack; at the last time, push them mildly till the length of the aperture meet the needs. When air inner the materials is exhausted, put the whole instrument into the incubator.

- Notices

③ in the process of acid corrosion of the "needle stick", when we compound nitric acid solution with volume concentration 50% for use, the hot water with around 95℃ should be used.

④ separate the mold immediately the solidification course in the incubator is over. It is not easy to separate the materials from the mold and the "needle stick" when materials cool down in the air. Once cooled down, reheat them in the incubator for about 20 minutes first, and then do the separation.

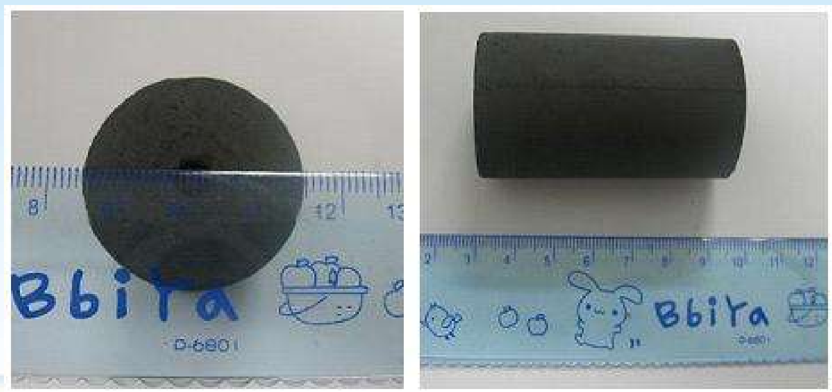
➢ Trial-produced samples

- Failure articles

Air holes in materials

Over load on materials

- Successful article



5 Summary

- Designed penumbral apertures is tested isoplanatic and has a spatial resolution of 250 μm over a 1 cm field of view through simulation.
- The once formation technique with polymer-tungsten composite materials was established by trials and experiments.

- More quantitative studies on the technique.
- Further study of imaging experiments.

Thanks for your attention!