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Diagnostics of Alcator C-MOD**

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# The X-ray Imaging Diagnostics on Alcator C-MOD

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## Abstract

Two separate x-ray imaging systems will be installed on Alcator C-MOD: a set of photodiode arrays in a poloidal cross-section for tomography and a tangentially-viewing 2-D camera. The tomographic imaging system consists of five linear photodiode arrays, each array containing 38 detectors, for a total of 190 channels. Slit apertures and fixed beryllium filters ( $50 \mu\text{m}$ ) result in the usual 'fan'-shaped chord projections. The detectors and associated signal cabling are ultra-high vacuum compatible, enabling installation of the arrays on the interior wall of the vacuum chamber. Reconstructed images will have a radial resolution of  $\Delta r/a \leq 0.1$  and a poloidal resolution of at least  $m = 4$ . All of the channels can be simultaneously digitized at rates up to 100 kHz. The 2-D camera system uses pinhole apertures and foil filters to project an x-ray image onto a thin scintillating surface ( $\text{CdWO}_4$ ) deposited on the vacuum side of a fiber-optic faceplate. The visible image is optically coupled by a coherent fiber bundle to a standard MCP-intensified CCD camera. 64 frames at rates up to 250 Hz can be recorded during a discharge. Several different foil filters and pinhole sizes can be selected remotely, which permits imaging in different spectral ranges. Information from the two different x-ray imaging systems can be used to check for self-consistency of both the data and the reconstruction algorithms.

## Brief Description of Alcator C-MOD

Alcator C-MOD is the newest experiment in a long history of high field ( $B_\phi \leq 9$  Tesla), high current ( $I_p \leq 3.0$  MA), high density ( $\langle n_e \rangle \leq 10^{21} \text{ m}^{-3}$ ) tokamak research at MIT. However, there are major differences between this machine and its predecessors, and x-ray imaging will be a useful diagnostic tool to help study many of the new physics issues that will arise. For example, C-MOD will have highly-elongated, shaped equilibria, and x-ray imaging will provide independent information on the shape of the innermost flux surfaces, possibly helping to determine the  $q$ -profile near the magnetic axis<sup>[1]</sup>. Highly elongated equilibria are unstable to the axisymmetric vertical instability, and sequences of x-ray images will shed light on the growth rate and behavior of the plasma shape during these disruptions. With its capability for divertor operation, C-MOD may achieve an H-mode with both ELM's and changes in the density and temperature profiles reflected in the x-ray emission. ICRF minority heating of H and/or He<sup>3</sup> will possibly lead to sawtooth stabilization and 'monster' sawteeth, a phenomena for which fast x-ray imaging is invaluable<sup>[2]</sup>.

In addition, the multiple-pellet injector on C-MOD (up to 20 per discharge) will probably produce MHD oscillations, changes in sawtooth behavior, impurity accumulation<sup>[3]</sup>, 'snakes'<sup>[4]</sup>, ablation x-rays<sup>[5]</sup>, etc.

### The X-ray Tomography Arrays

Since many of the C-MOD ports are large enough to permit manned access, miniature x-ray arrays can be mounted on the interior wall of the vacuum vessel as long as they are compatible with ultra-high vacuum. This allows for a relatively large number of arrays, resulting in good poloidal resolution, and has the added advantage of not blocking access to any of the horizontal ports for other diagnostics. The detectors we are using are linear photodiode arrays manufactured by EG&G (#PDA-38-3, with the glass cover removed). Our tests have shown that they are vacuum compatible ( $10^{-7}$  Pa) and can tolerate the vessel bakeout temperatures ( $\leq 170^\circ$  C). This simplifies the engineering design significantly, since the detectors do not have to be sealed in a secondary vacuum, and they do not have to be actively cooled. In fact, experience on JET indicates that periodic baking of solid-state detectors at these temperatures helps to anneal out radiation damage.

The C-MOD tomography system consists of 5 arrays, each with 38 detectors (total of 190 channels), installed at one toroidal location (the same one as the pellet injector). An additional array may also be installed at another toroidal location at a future time. There are several possible array configurations that are being considered. The most desirable is shown in fig. 1, but it would require a sizeable gap in the divertor tile hardware, so other configurations are being looked at in case this is not feasible. Partly because of this uncertainty, we are using the modular design shown in fig. 2 for the construction of the x-ray arrays in order to have more flexibility in their placement. The detectors can be moved to different locations and still have excellent field-of-view and spatial resolution. This is achieved by being able to change the aperture-to-detector distance using different numbers of 'spacers', and by offsetting the aperture with respect to the center of the detector array using simple insertable aperture pieces and a sliding filter foil holder. Relative alignment between the aperture and detector is critical, and accuracy is ensured with precision-machined alignment pins and holes in the associated mounting pieces. This modular design also allows for replacement of radiation-damaged detectors in situ (i.e. from inside the vessel during a vacuum break). This may become necessary every year or so during high-performance deuterium operation. The x-ray filters, which will be  $50 \mu\text{m}$  beryllium foils initially, can also be changed in-situ. These foils must be light-tight, but do not need to be vacuum-tight since all the detector hardware is vacuum compatible. This means that more complicated shapes for the foil are feasible, and in fact, for our arrays we

have designed a recessed, moveable, semi-circular shaped foil holder. This means that all chord lines of sight have the same attenuation thickness. The signals from the detectors, which will be in the range of 0.1 to 100  $\mu\text{A}$ , are shielded by solid coax cables (vacuum compatible), with shields at circuit ground. An additional shield, grounded to the vessel, will surround the detectors and cables of each array. The circuit ground and vessel ground are electrically isolated. Linear amplifiers with computer-controlled gains will be used instead of logarithmic amplifiers because they are much less sensitive to high-power ICRF pickup (which was a problem with the Alcator C system).

Extensive image reconstruction tests have been done to determine the angular and radial spatial resolution of this system, and to specify the tolerances for noise and calibration accuracy. In these tests, an arbitrarily complex 2-D x-ray emission profile is specified, usually as a function of  $\psi$  on a Grad-Shafranov equilibrium. Using a given detector and aperture geometry, the radiated power incident on each detector is calculated. Random noise is added to each signal ( $\sigma = 2\%$  for the cases shown here) and then they are passed to the tomography reconstruction program, along with a specification of the plasma boundary. The emissivity is reconstructed using the Fourier/Zernicke harmonic expansion algorithm<sup>[6]</sup> and compared to the original source function. Improvements in this linear least squares algorithm have been made so that even the high poloidal and radial harmonics are well-behaved in the outer regions. Two examples of this procedure are shown in figs. 3 and 4. Note that the differences between a displaced crescent-shaped core (often seen during the sawtooth crash) and a rigidly displaced core can be accurately distinguished. The radial resolution has been determined by using a source function consisting of two narrow rings of emission. The radial separation between the rings is decreased until they are just barely resolved in the tomographic reconstruction. The result is that with a 1.0 mm wide aperture slot, the radial resolution is about 2.6 cm, or  $\Delta r/a \approx 0.1$ . Other tests of the poloidal resolution have shown that  $m \leq 4$  will be well resolved using the configuration of fig. 2. The radial resolution can be improved somewhat by using a narrower aperture, which may be feasible depending on the actual x-ray emission levels in C-MOD. The effect of the 2% noise is definitely noticeable in figs. 3 & 4, and raising this to 4% produces significant degradation. It is concluded that the combined errors due to calibration and noise should be no worse than 2%, and preferably even better.

### The Tangential X-ray Camera

The tangential x-ray camera on Alcator C-MOD is shown in fig. 5. It is based on the PBX design<sup>[7]</sup>, with several improvements. The x-ray-to-visible conversion is accomplished by a thin layer of cadmium tungstate scintillator deposited on the vacuum side of

a fiberoptic faceplate.  $\text{CdWO}_4$  has a high efficiency in the energy range of interest and a fast decay time, thereby providing good temporal response. The camera design includes a rotatable filter wheel with six positions, having filters for both soft and hard x-rays, a  $50 \mu\text{m}$  beryllium foil to match the tomography arrays, and even an  $\text{H}_\alpha$  filter for looking in the visible spectrum (in this case the scintillator would act only as a translucent screen). The wide dynamic range required may surpass the capabilities of the scintillator, so a second wheel with six different pinhole sizes, ranging in diameter from  $100$  to  $400 \mu\text{m}$ , is included in the design. The alignment between the rotatable pinhole wheel and the faceplate is critical—an error of  $\leq 60 \mu\text{m}$  is desired. This tolerance is achieved by use of a clever device called a Geneva mechanism, shown in fig. 6. A driveshaft turns the smaller wheel, which in turn rotates the pinhole wheel via a small post near its edge and mating slots in the pinhole wheel. The specially-shaped hub eventually fits into the semi-circular notch in the edge of the main wheel. The Geneva mechanism provides extremely accurate positioning, and also serves as a positive lock. The driveshaft position is no longer critical. For design simplicity, the filter wheel is also designed with a Geneva mechanism, even though its positioning is not as critical as the pinhole wheel.

The visible image from the scintillator is transmitted through the faceplate, which acts as a vacuum window, and coupled into a 3-meter long coherent quartz fibre bundle with an image reducer. The bundle is routed out of the igloo neutron shield and the image is optically coupled to a Reticon CCD camera ( $128 \times 128$  detector pixels) preceded by an ITT image intensifier. Additional neutron shielding will surround the camera. Using a standard video digitiser, images can be acquired at intervals as short as 4 msec, with enough memory to store up to 64 frames per discharge. However, the temporal resolution will be controlled by the duration of the high-voltage gate to the image intensifier, and this could be much less than a millisecond, depending on photon statistics.

Image reconstruction tests have been done for the tangential camera, in a similar manner as the tomography arrays. A source emission function is specified and assumed to be axisymmetric. The calculation of the radiated power incident on each detector pixel involves an integration over tangential chords. Random noise is added to each pixel, but in this case, the noise is due to photon statistics, and therefore  $\sigma$  is proportional to the square root of the signal. In order to improve the statistics, the  $128 \times 128$  signals can be reduced to a  $32 \times 32$  image by averaging neighbouring pixels. The reconstruction is done by solving a grid of emission pixels (which are actually toroidal rings) for the least squares fit to the chord signals. An example of the reconstruction of an elongated equilibrium on a  $9 \times 15$  emission grid is shown in fig. 7. For this image, signal amplitudes have been chosen so that the statistical noise on the maximum pixel has  $\sigma = 2\%$  (i.e. maximum detector has

2500 photons). The relative noise on lower-signal pixels is considerably higher. As with the tomographic reconstructions, the effects of this noise are noticeable, and higher noise levels result in significant degradation.

### Present status of diagnostics

The Alcator C-MOD tokamak is presently well into the assembly phase, with major systems tests scheduled for the first few months of 1991, followed shortly by first plasma operation. The x-ray tomography arrays will be installed before operations begin and will be working for first plasma. The details of the housing design are being finalised and nearly all components have been procured, with the exception of the linear amplifier circuits. The tangential x-ray camera is not planned to be installed until well after operation begins, and its design details have not yet been addressed. An intense x-ray tube has been built for calibration purposes and it is already operational, yielding maximum signal levels even higher than those expected from typical C-MOD plasmas.

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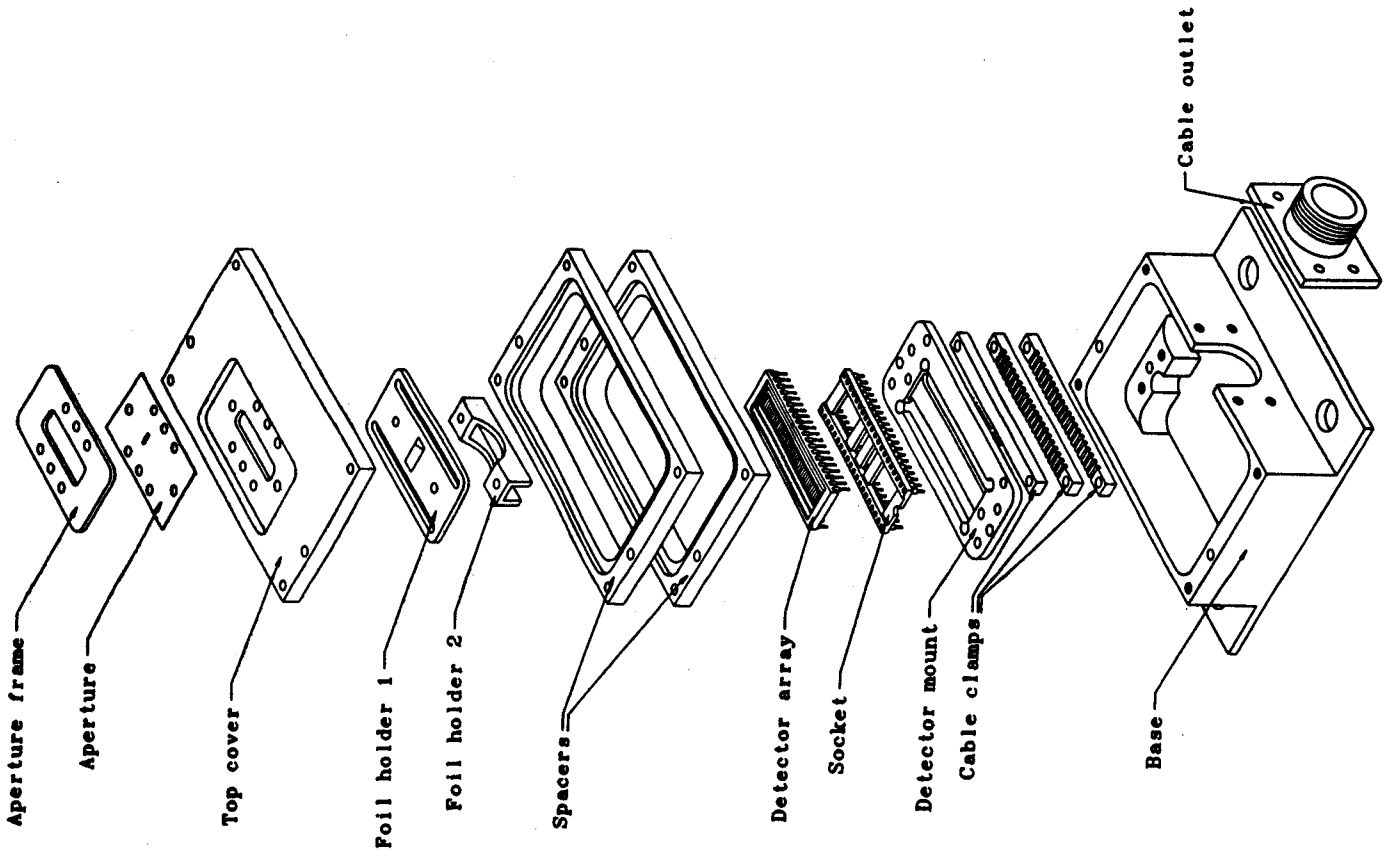


Figure 2—Exploded diagram of the x-ray array assembly.

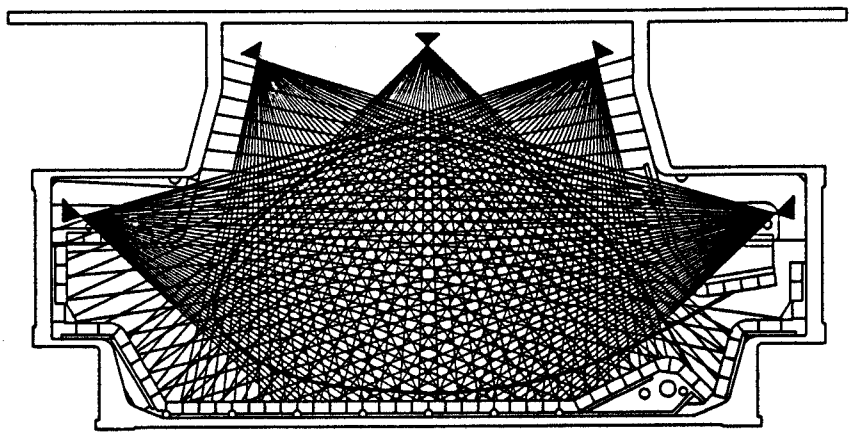


Figure 1—One of several possible detector configurations for the Alcatraz C-MOD x-ray tomography system.

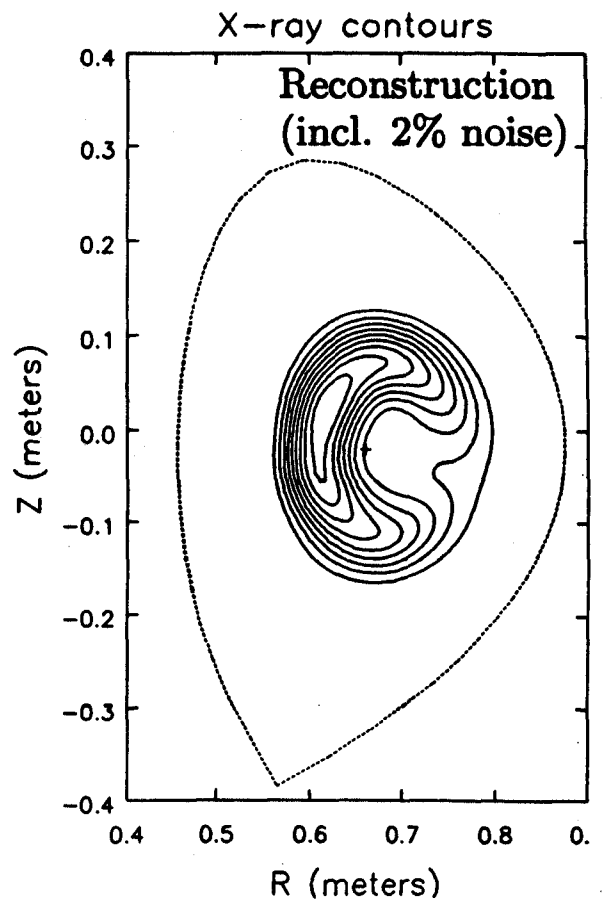
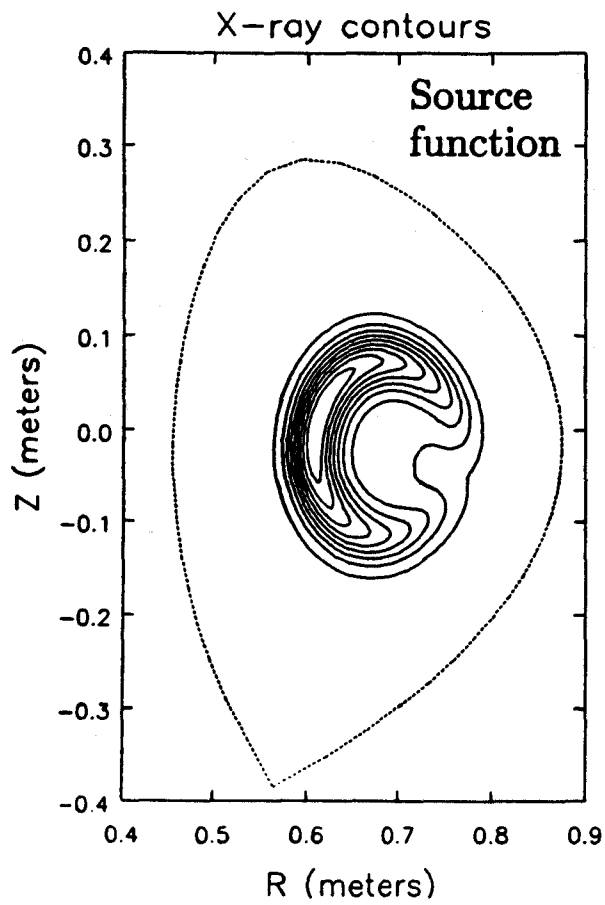


Figure 3—Reconstruction test of shifted crescent-shaped core. Random noise has been added to the signals.

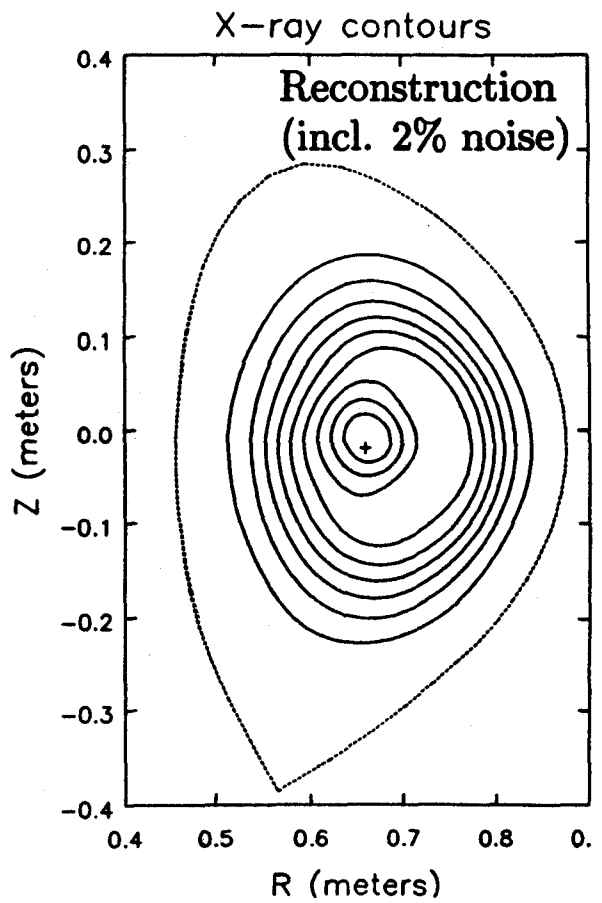
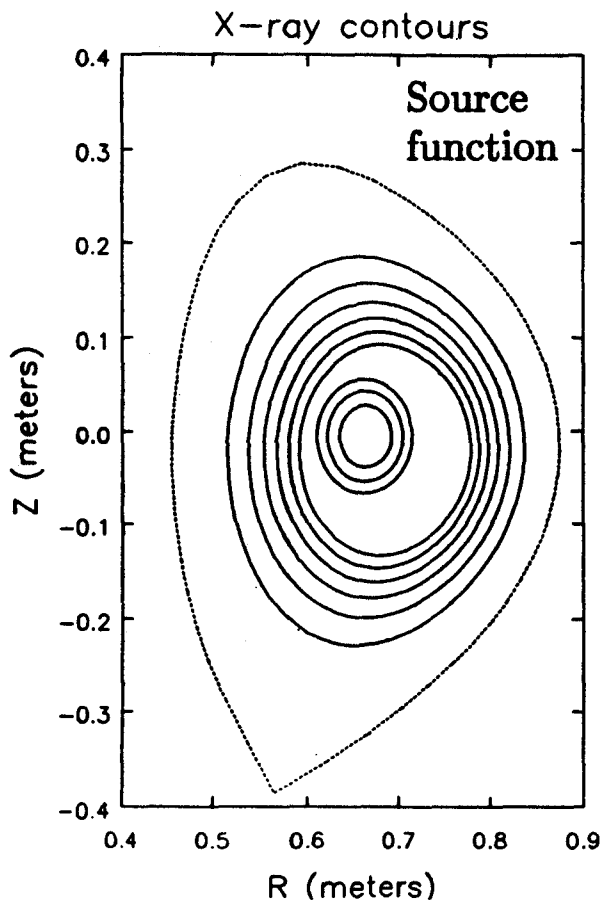


Figure 4—Reconstruction test of rigidly shifted core. Random noise has been added to the signals.



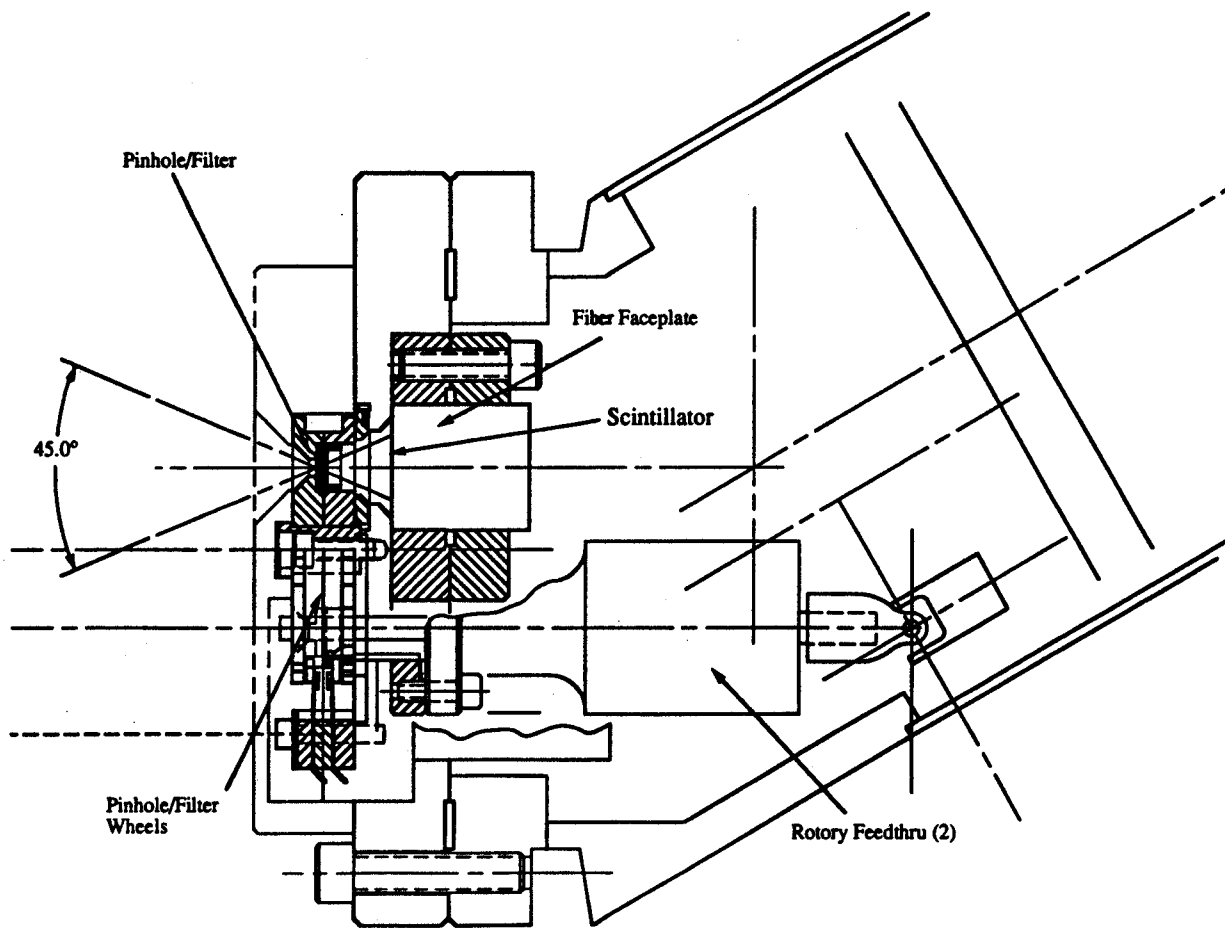


Figure 5—The tangential x-ray camera design on Alcator C-MOD.

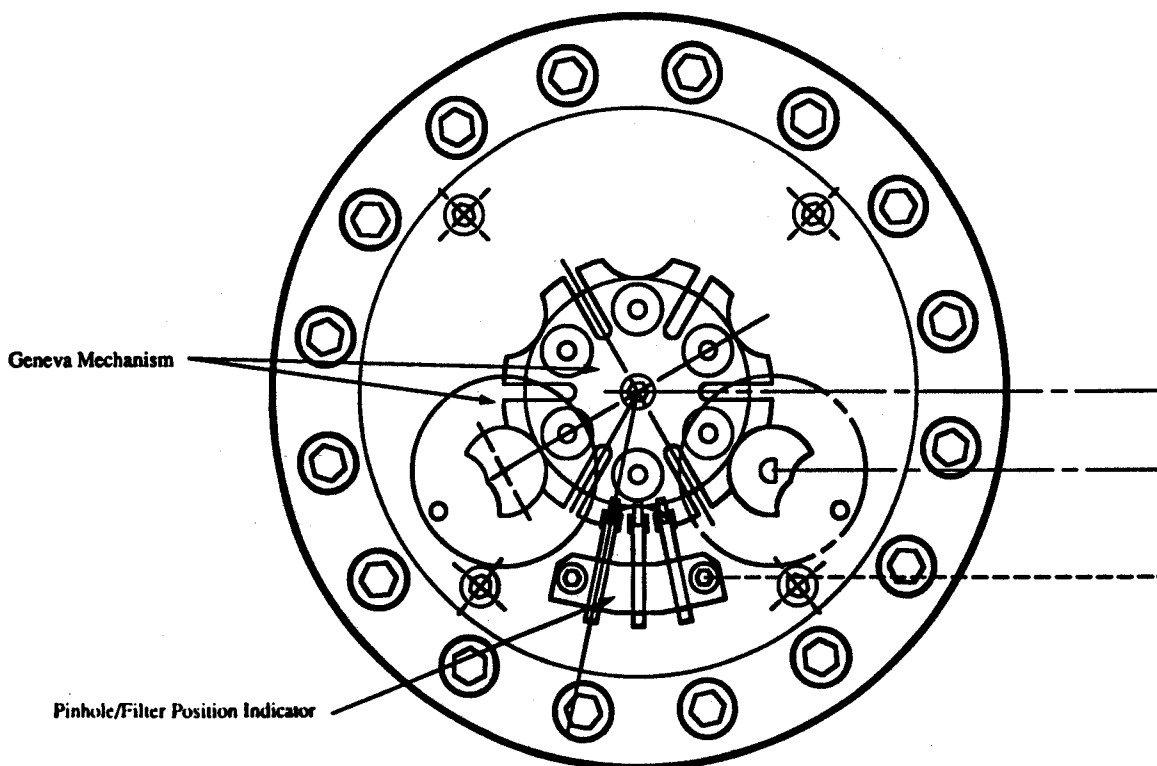


Figure 6—Details of the Geneva mechanism for rotating and aligning the filter wheel and pinhole wheel.

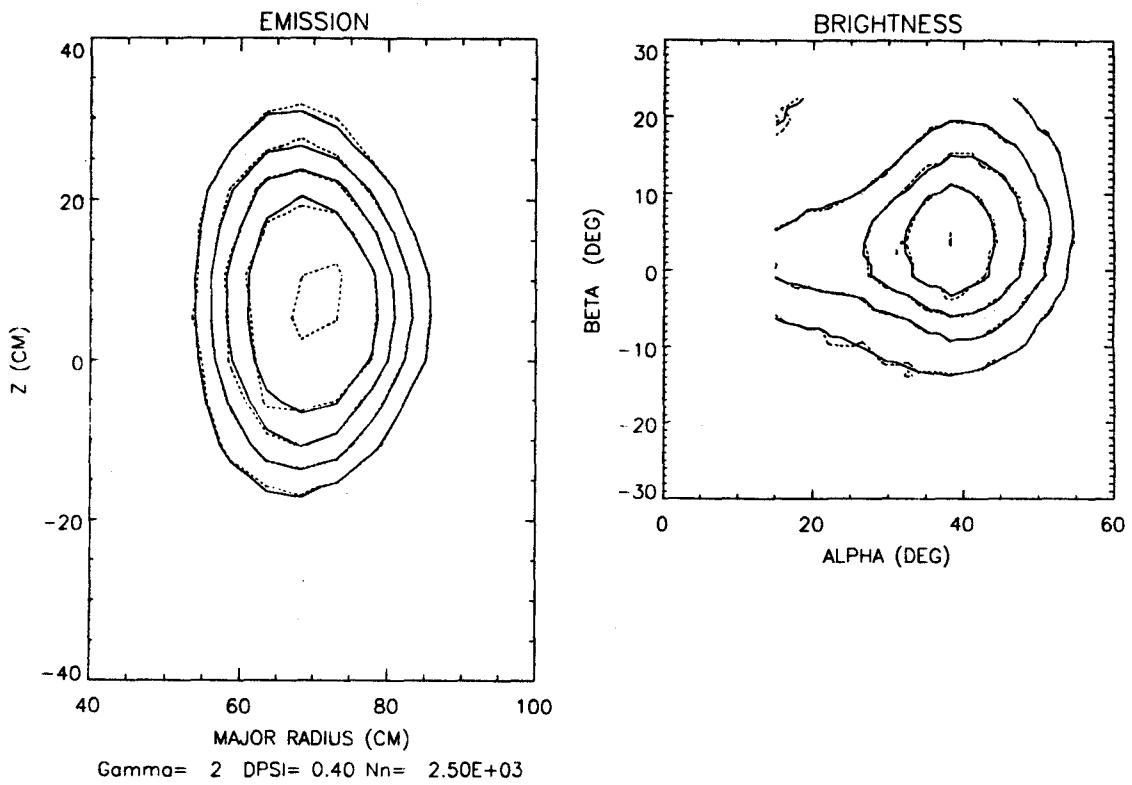


Figure 7—Reconstruction test of the tangential camera for an elongated emission function. The solid lines are the source function, the dashed lines show the reconstruction. Statistical noise has been added to the signals.