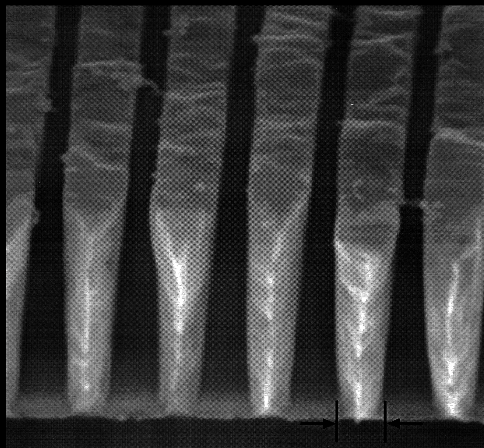
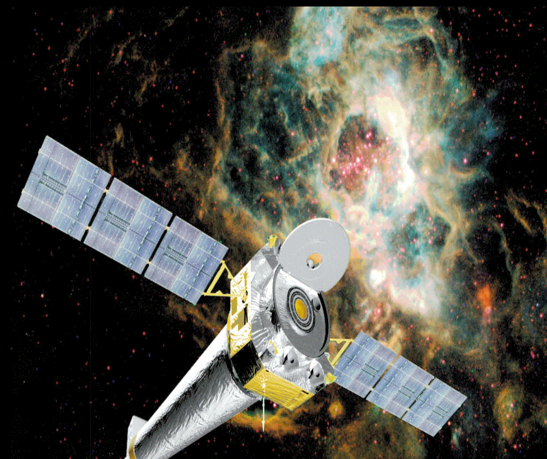



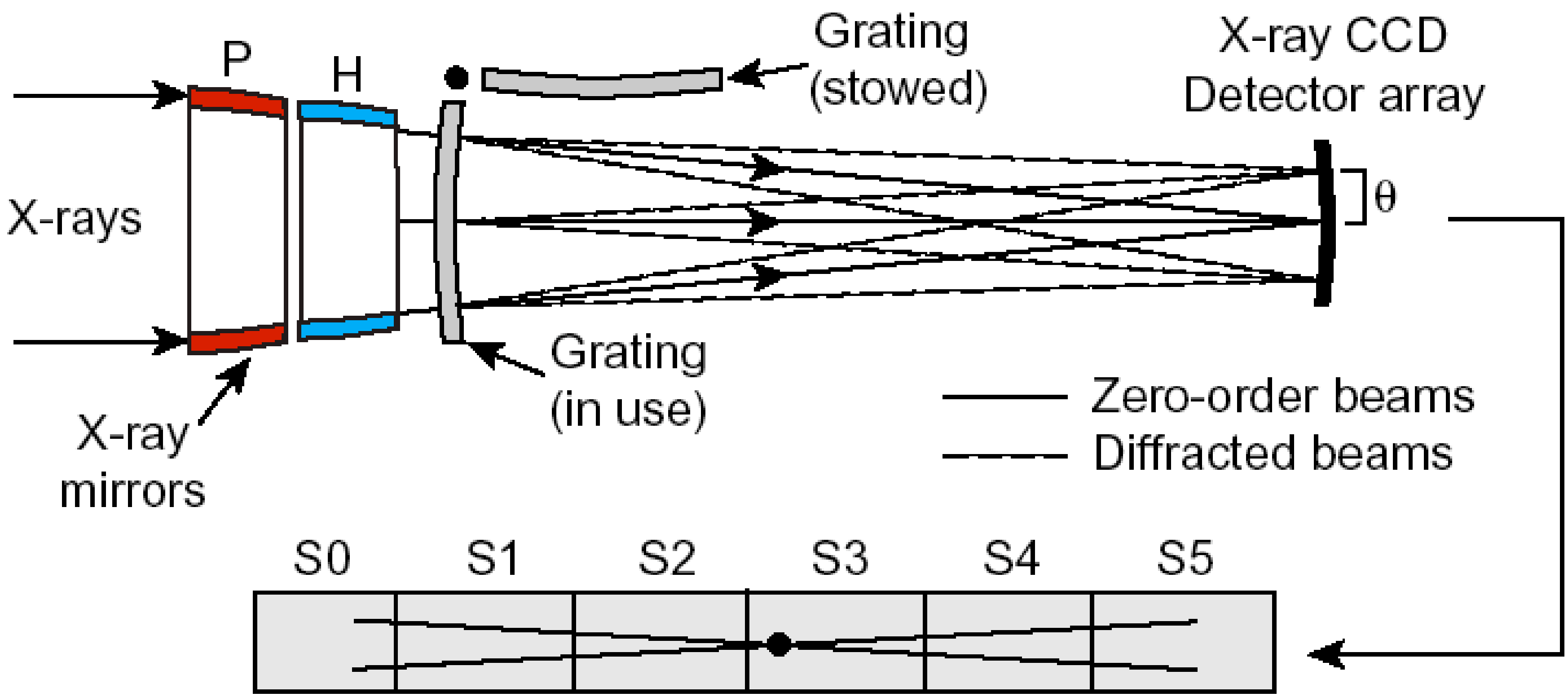

Nanometers to Megaparsecs: The Inside Story Behind the Making of the Chandra HETG

Claude R. Canizares

Chandra Fellows Symposium

October 2004

Chandra HETG Schematic

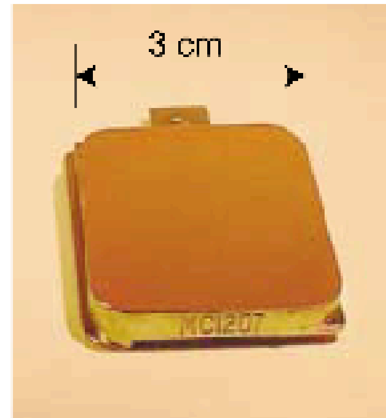


NASA *Chandra X-ray Observatory*
High Energy Transmission Grating Spectrometer (HETGS)

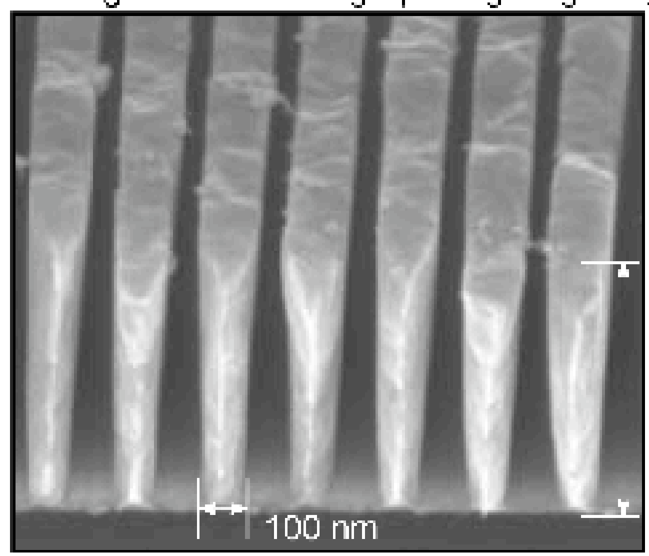
HETGS instrument.

1.1 meter

Invar grating frame.



Scanning electron micrograph of gold grating.



550 nm

MLS-2001-05-11.01tpv

HETG Timeline

1979-80 CRC & Mark Schattenburg begin collaboration with Henry I. (Hank) Smith

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HETG Timeline

1989 BCS deselected; revised BCS proposed & accepted
1992 AXAF Restructured to AXAF-I and AXAF-S; BCS dies final death

1993 HETG Systems Requirements Review (SRR)
1993 Hampshire Instruments ceases operations; X-ray lithography abandoned
1994 Preliminary Design Review (PDR)
1995 Critical Design Review CDR
1996 Complete HETG facet fabrication

1996 Deliver & Calibrate Completed HETG

1999 Chandra Launch!

"To Disperse or Not To Disperse"
That is THE Question

(wave-particle duality in X-ray spectrometers)

$E = h\nu$

Non-Dispersive

- ΔE ~ fixed
- Resolving Power ~ $E/\Delta E$

Instruments

- Prop Counters ➜ IPC
- Gas Scint PC ➜ IGSPC
- Si(Li) ➜ CCD
- μCalorimeter
- STJ/TES

$\lambda = c/\nu = hc/E$

Dispersive

- $\Delta\lambda$~fixed
- Resolving Power ~1/E

Instruments

- Bragg spectrometers
- Transmission Gratings
- Reflection Gratings

Einstein Observatory 1978-1981

Spectrometers

- Focal Plane Crystal Spectrometer (FPCS)
- Objective Grating Spectrometer (OGS)
- Solid State Spectrometer (SSS)

HEAO-2 (Einstein Obs)

Objective Grating Spectrometer (OGS)

1000 lpmm (p=1 micron)

Thin wires

Support structure

Fabricated at Utrecht

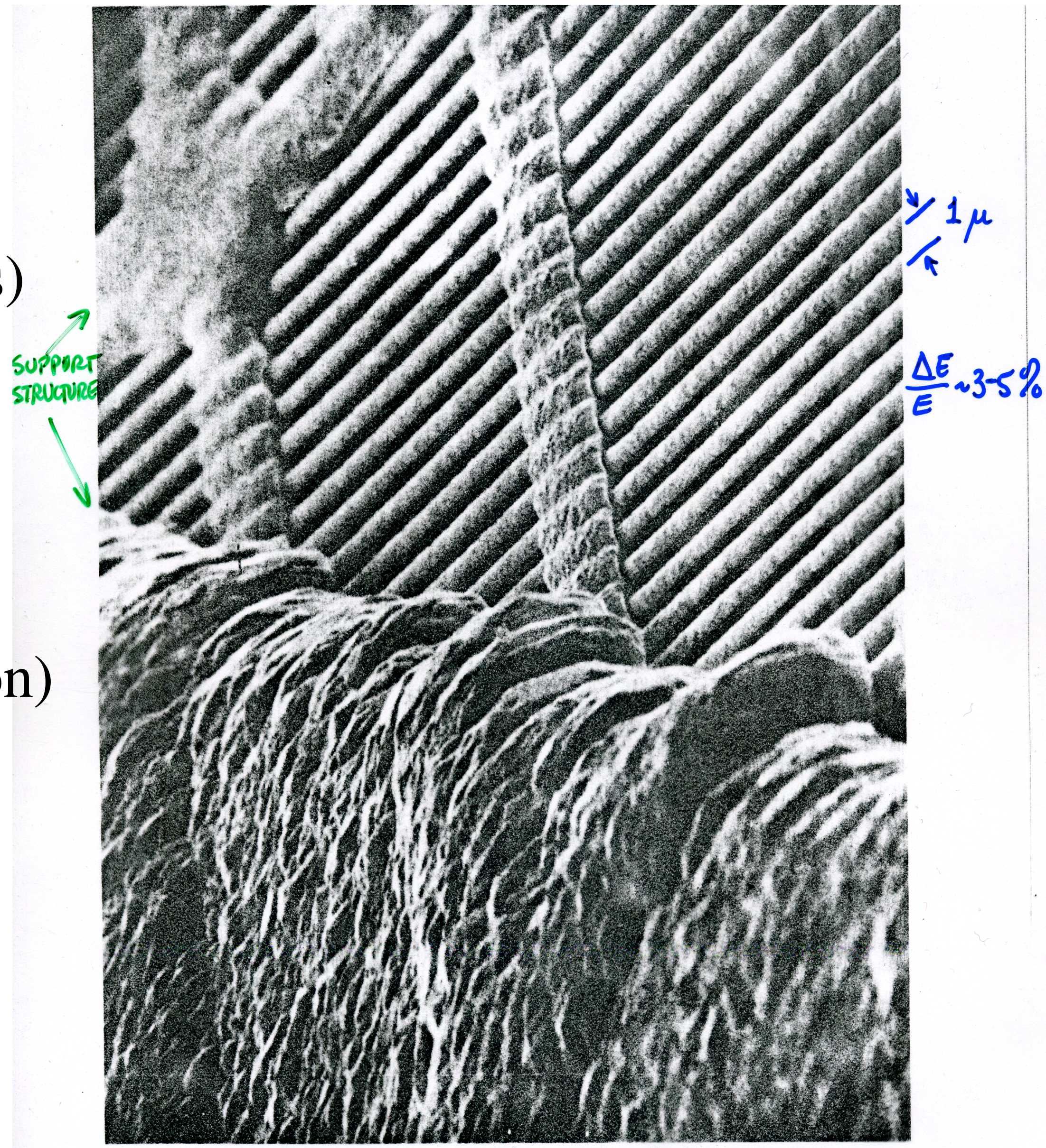


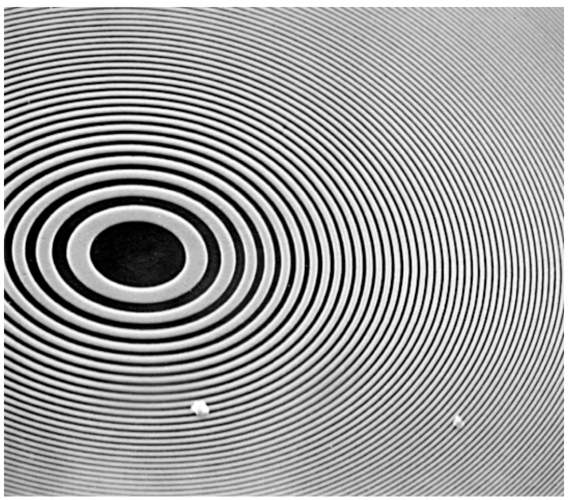
Fig. 2

Schnopper et al 1976 Applied Optics

HETG Timeline

1979-80 CRC & Mark Schattenburg begin collaboration with Henry I. (Hank) Smith (MIT EECS Dept)

X-ray Fresnel Zone Plate



LBL - CXRO

~ 1979 CRC discovers (by chance) that Hank Smith in EECS is expert in micro-fabrication of X-ray gratings and zone plates

Attempts several zone plate and grating design schemes with grad student Mark Schattenburg; settles on HETG concept

Smith very reluctant to collaborate until diminished funding makes him eager to have additional grad student

~ 1980/81 Schattenburg begins working in Smith Nanotstructures Lab to develop improved transmission gratings

Key features needed for an HETG design:

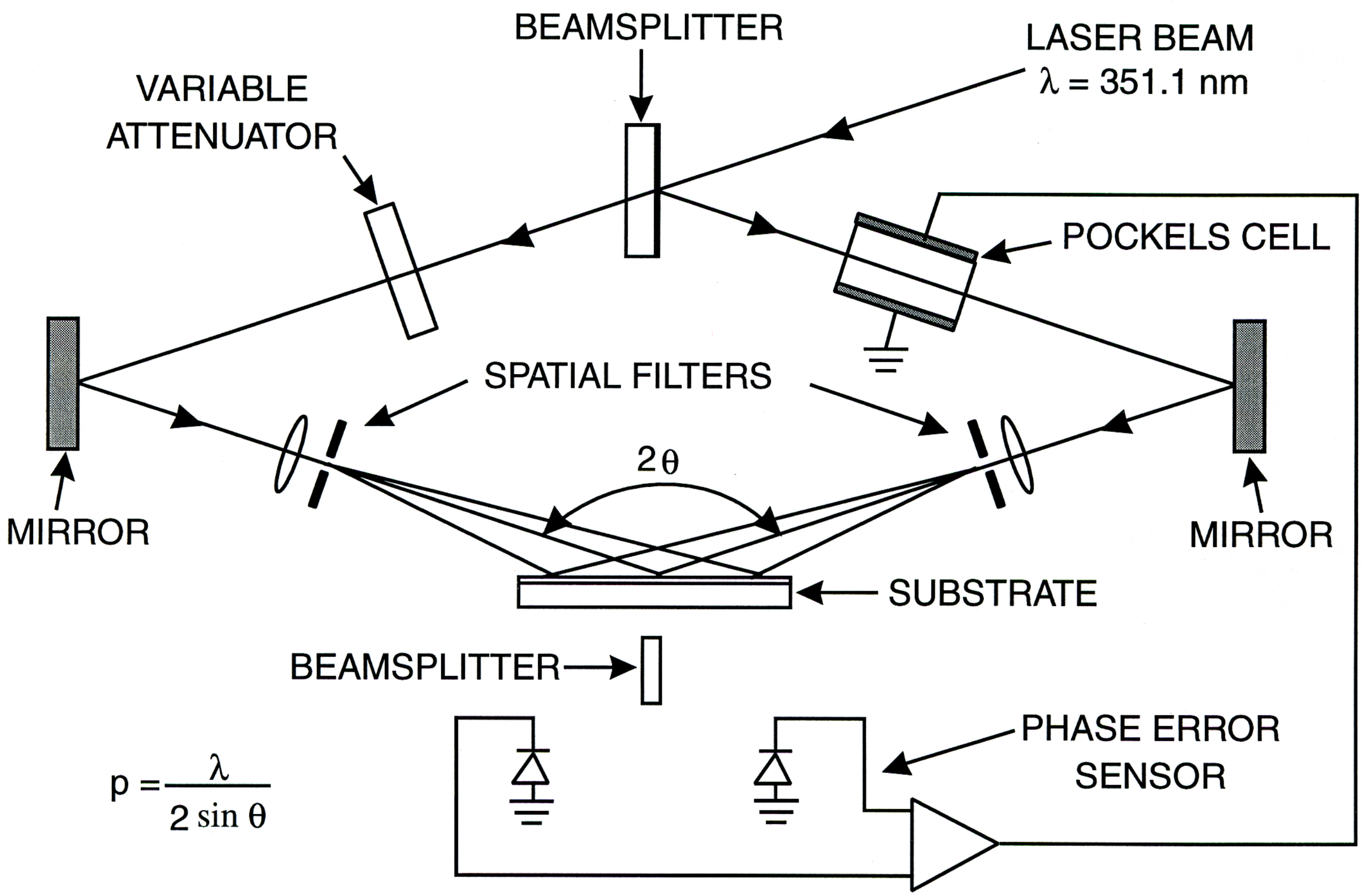
- ~5000 lpmm (p=0.2 micron) gratings

- high efficiency over 1.5 decades of energy (0.4 - 8 keV) => high aspect ratio to enable phased grating

- gratings rugged enough to withstand launch

- fabrication of hundreds of identical grating elements to tolerances of ~100 ppm

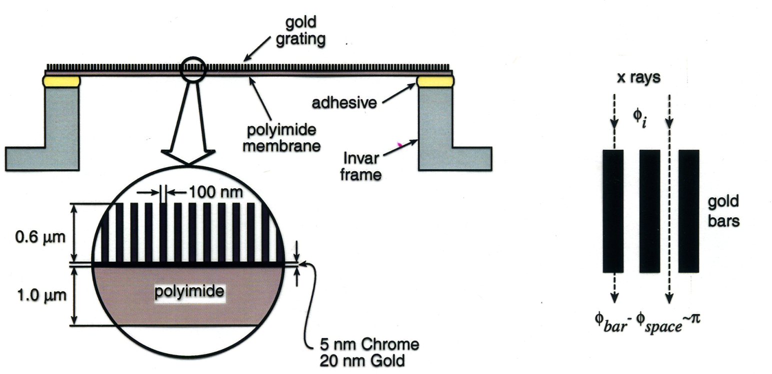
INTERFERENCE LITHOGRAPHY



$$p = \frac{\lambda}{2 \sin \theta}$$

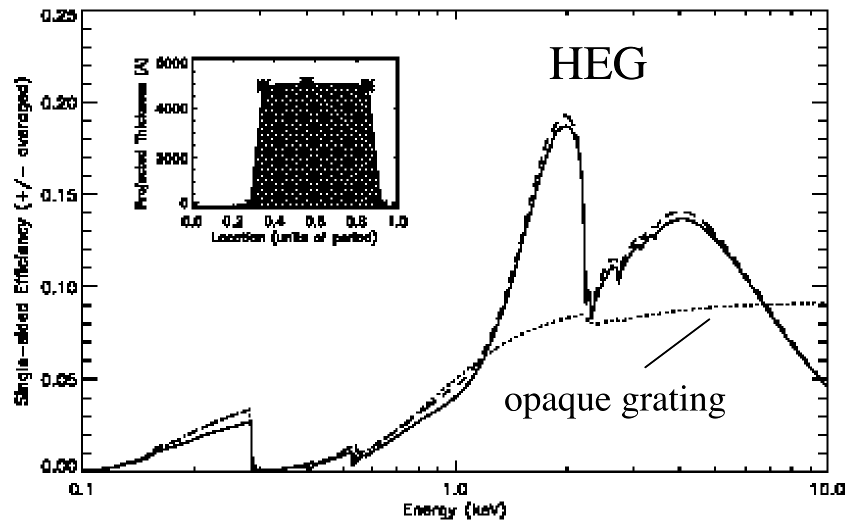
Single-sided grating efficiency (as built)

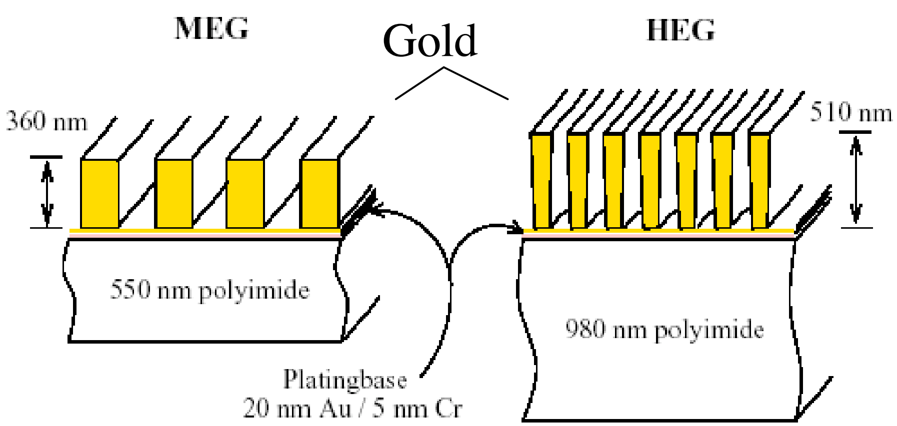
Pi-Phase-Shifting Transmission Grating Design

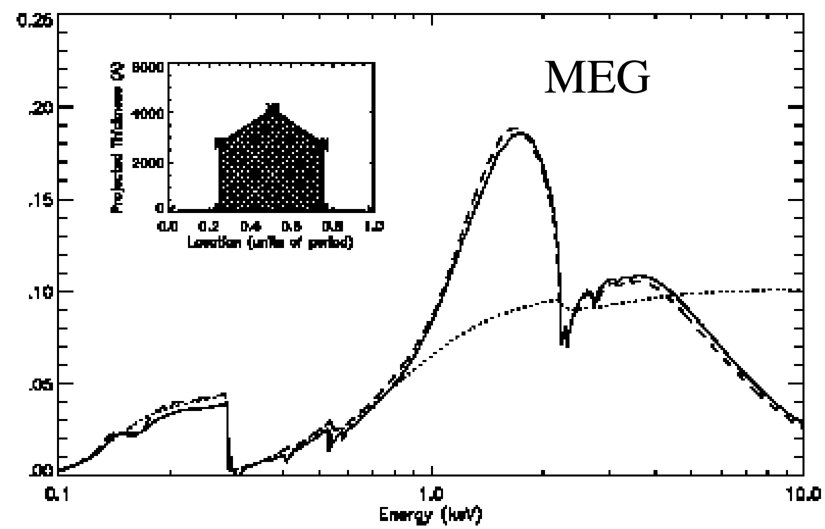


Transmission Grating Design

Bars shift phase x-rays by ~π
zero order ~0
first order maximized



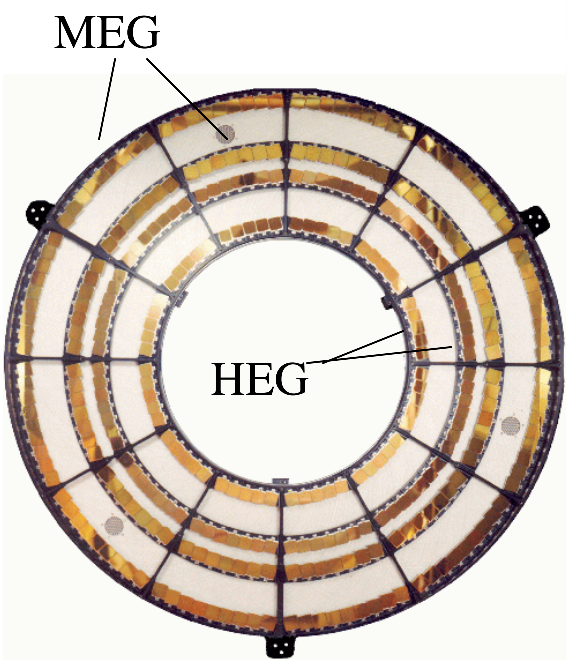


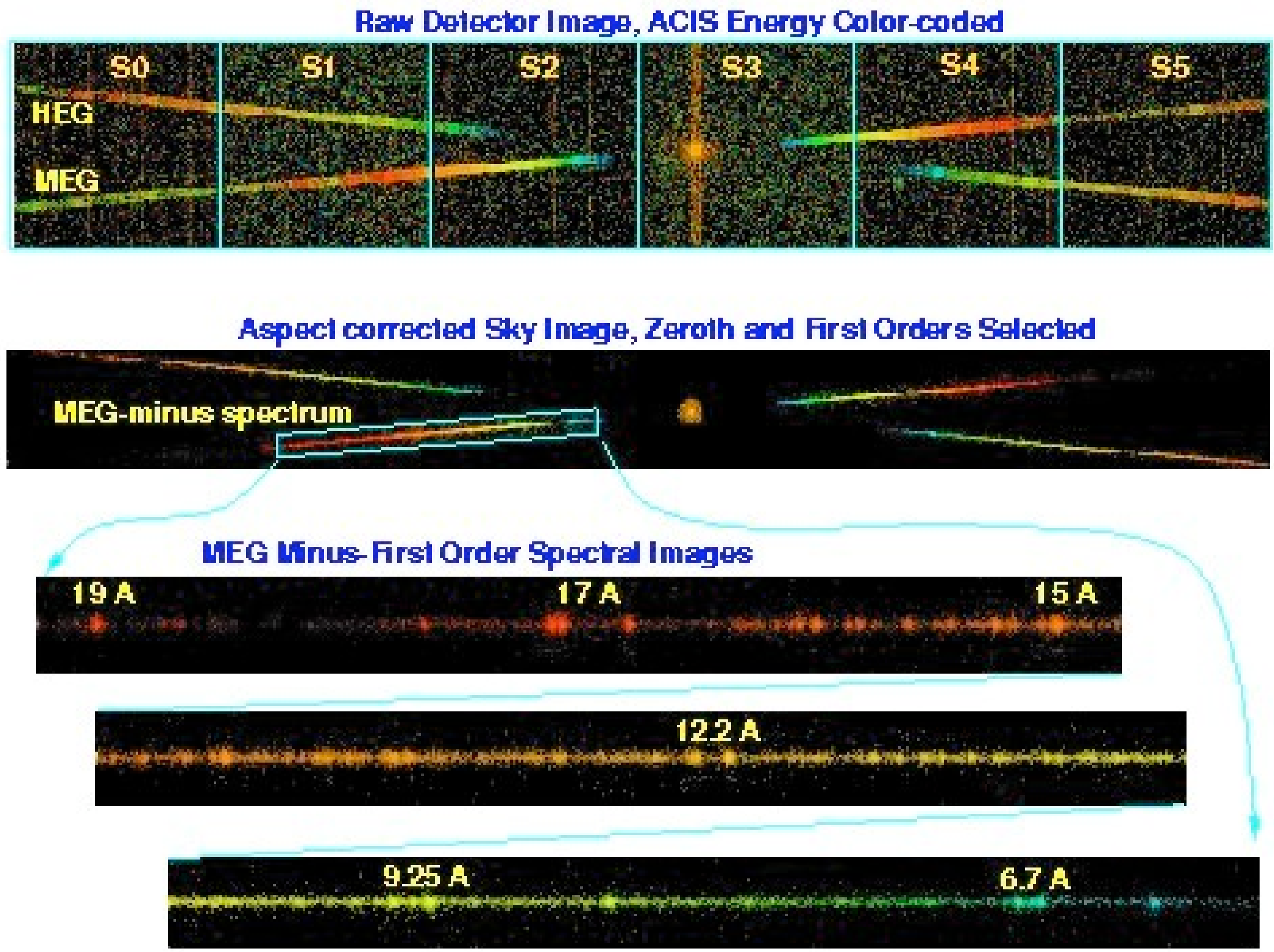


0.1 1.0 E (keV) 10.0

2500 lpmm (0.4 micron period) 5000 lpmm (0.2 micron period)

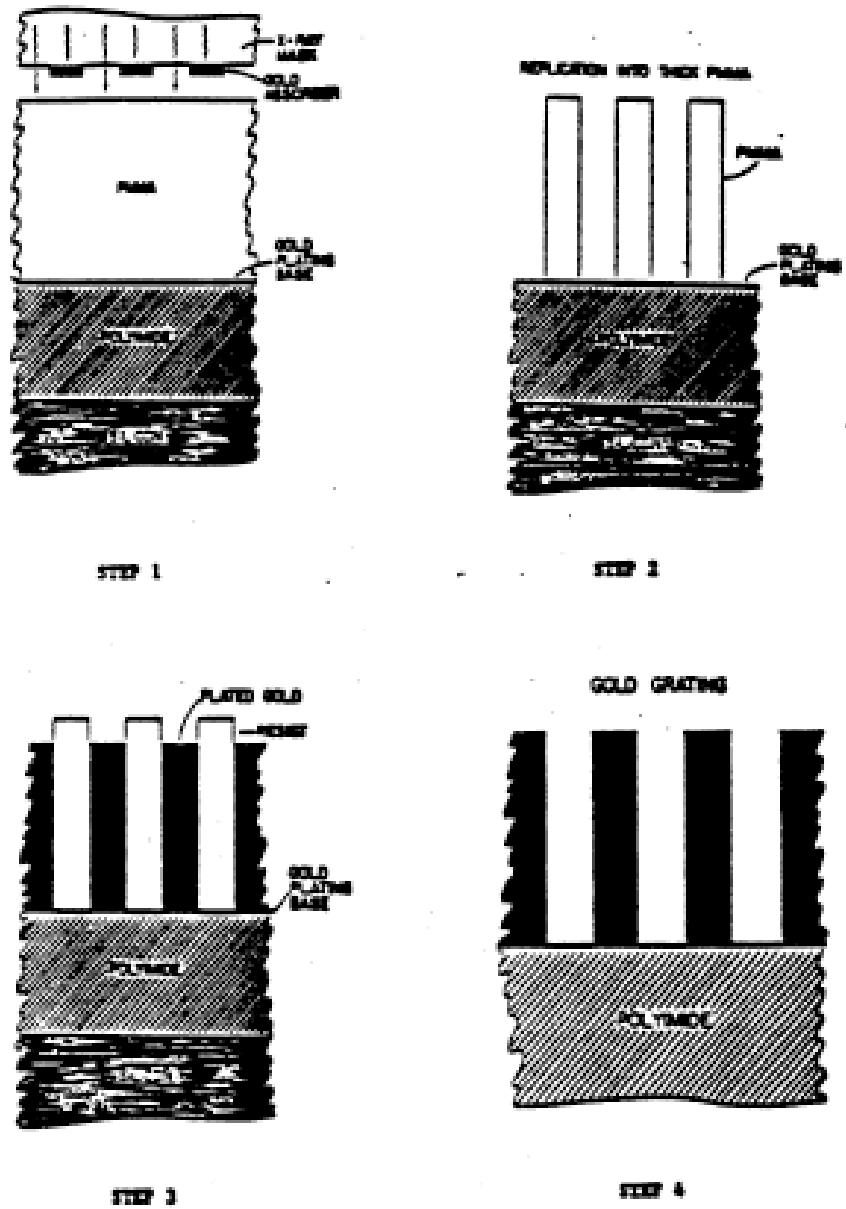
HETG observation of Capella



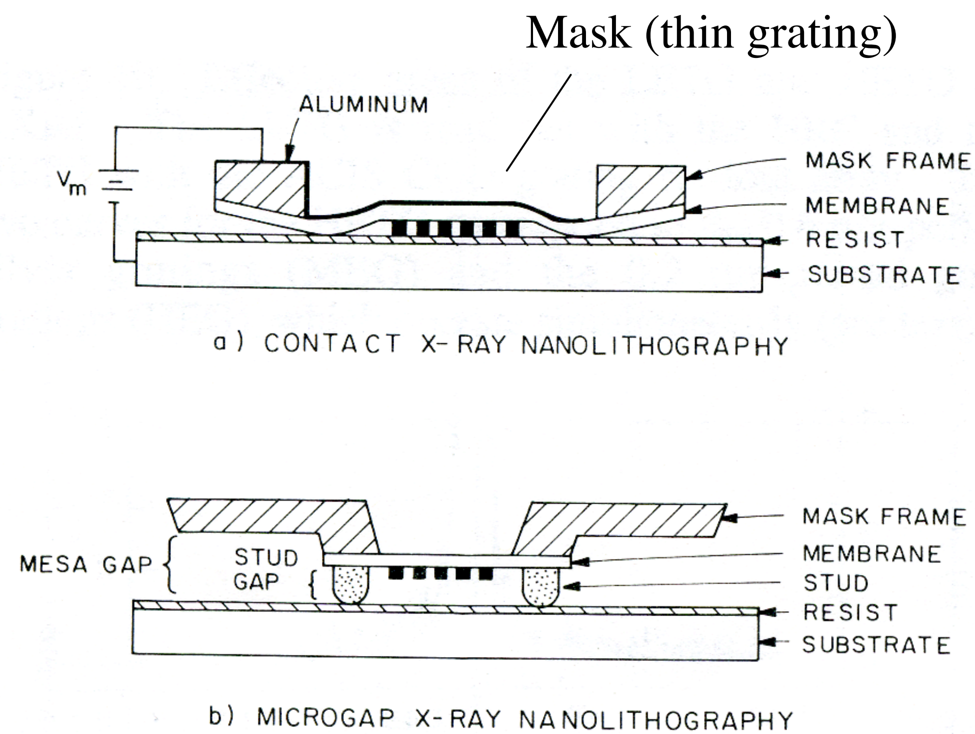


X-ray Lithography

Key technology for replicating a “thin” grating “mask” into many thick, phased gratings with the same period



Invention of Micro-gap X-ray Nanolithography



X-ray Lithography Station

Soft X-ray (Cu L line)

Exposure time ~ 24-36 hrs per grating!

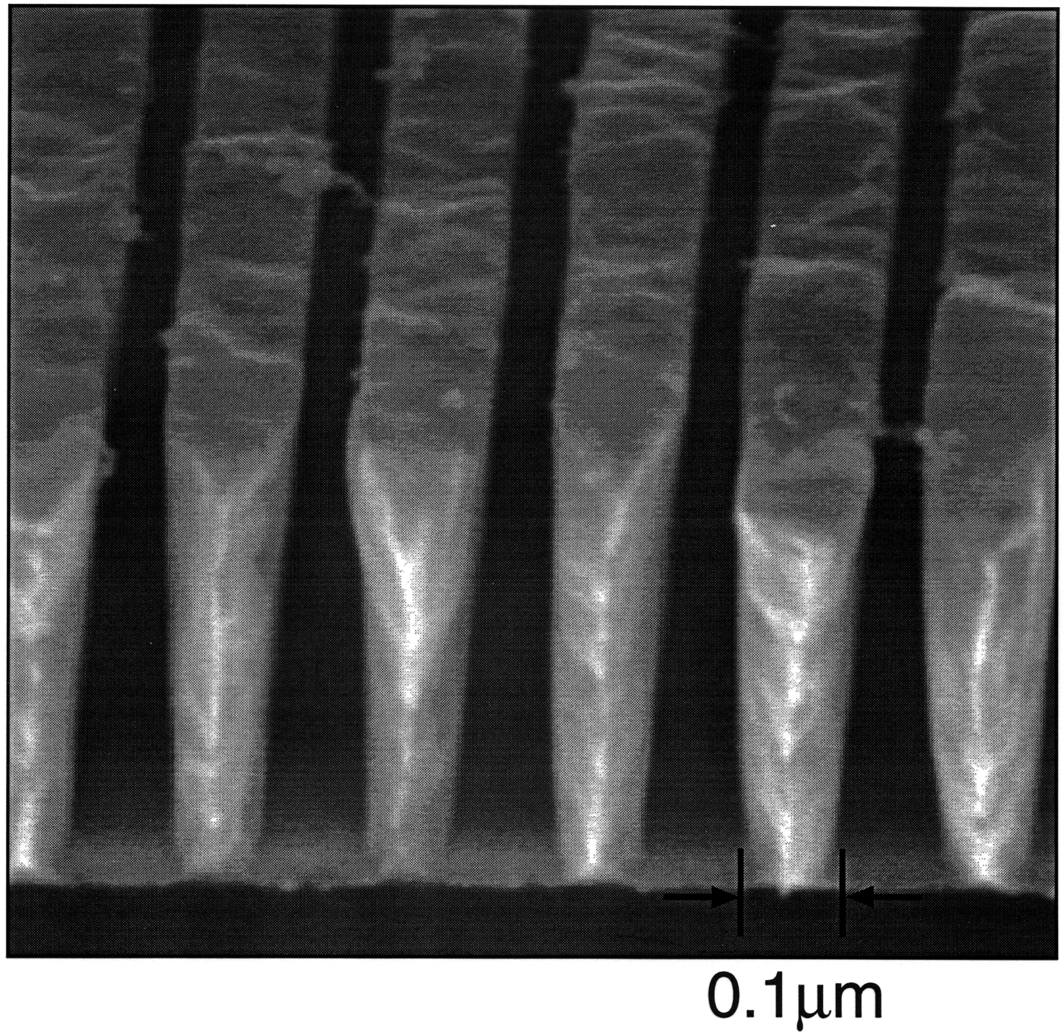
We (and industry) needed higher intensity X-ray machines…

But, note prophetic statement:

"X-ray lithography is the technology of the future… and it always will be!"

-- Mark Schattenburg

AXAF Gold Transmission Grating



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Key Proposal Strategy issue:

How can we (MIT/CSR) propose for 3 instruments ???

- CCD camera (aka ACIS),
- Bragg Crystal Spectrometer (building on Einstein FPCS)
- And HETG ????

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Strategy: Propose for even more!!!

CCD -- collaborate with Penn State (Garmire) as PI (became ACIS)

Then propose not two, but three instruments in one proposal for *High Resolution X-ray Spectroscopy Investigation:* BCS, HETG and an "optional" LETG (expecting [hoping] to lose the low energy grating)

Proposal for High Resolution X-ray Spectroscopy Investigation

Teamed with Ball Aerospace and GSFC (Bruce Woodgate) for BCS

"We propose to use AXAF to perform moderate and high resolution X-ray spectroscopy of point and extended celestial objects including stars, X-ray binaries supernova remnants, galaxies, clusters of galaxies, quasars, and interstellar and intergalactic material."

"We propose two complementary dispersive spectrometers [BCS & HETG]…

we … offer an LEG only as an option…"

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

RECEIVED

MAR 11 1985

C. R. CANIZARES

Reply to Attn of: EZ (AGO)

MAR 5 1985

Professor Claude R. Canizares
Department of Physics and
Center for Space Research
Building 37-501
Massachusetts Institute of Technology
Cambridge, MA 02139

Dear Dr. Canizares:

We have completed the review and evaluation of proposals for the Advanced X-ray Astrophysics Facility (AXAF) mission. I am pleased to inform you that the proposal "High Resolution X-ray Spectroscopy Investigation for the AXAF Mission" submitted by you and your colleagues has been accepted, in part, for definition study on AXAF. The low energy grating option, which you proposed, is not being selected. You are also appointed to the AXAF Science Working Group (SWG). Final selection for the mission will be contingent upon the definition study results and the approval of AXAF as a spacecraft new start.

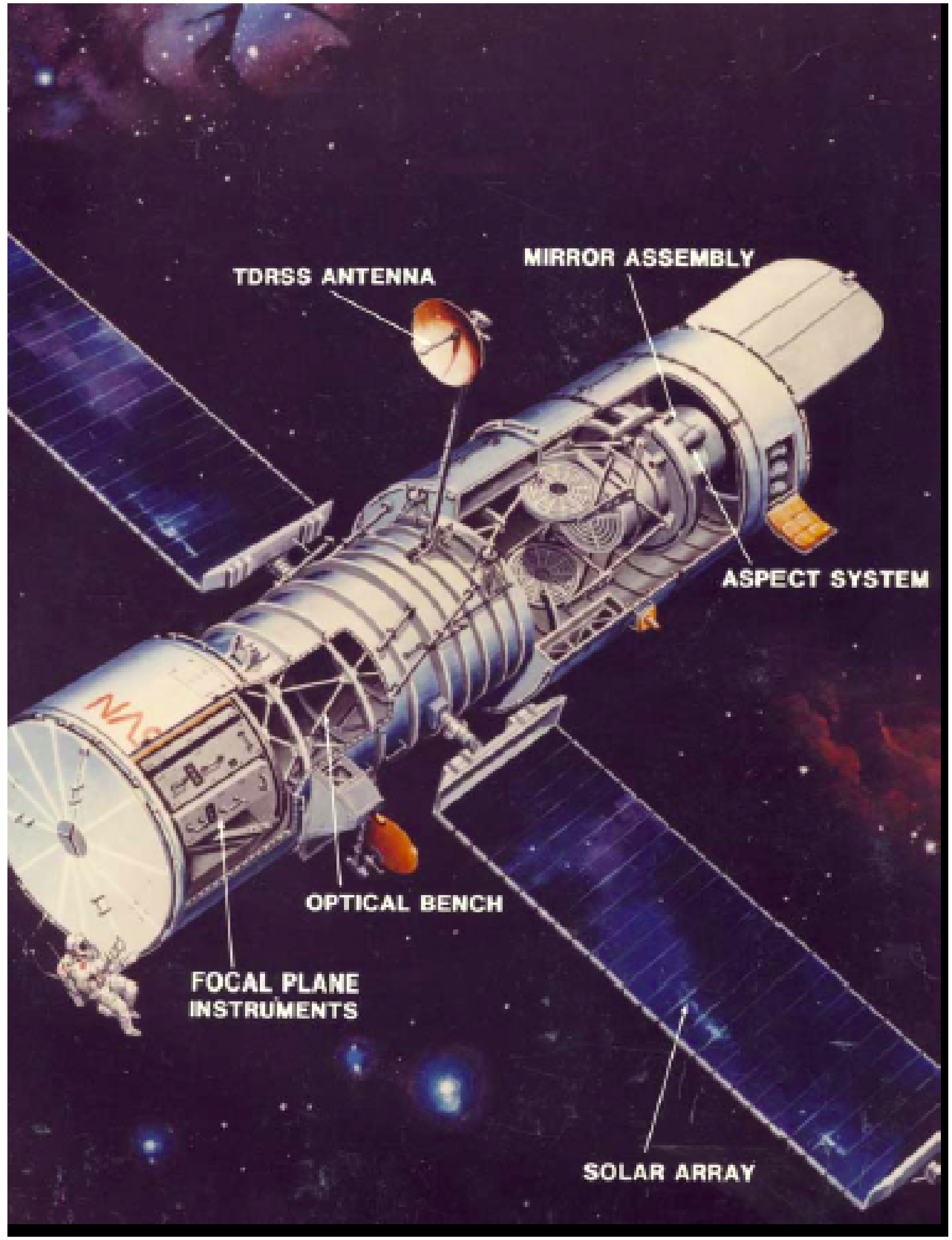
The instrument definition study will parallel and be integrated with spacecraft definition studies presently being conducted by two mission contractors and should result in a clear understanding of scientific and technical requirements of the mission. During the definition study, we expect you to work closely with the NASA AXAF Definition Team and mission definition contractors to specify mission requirements and spacecraft interfaces and to develop a detailed schedule for instrument test and delivery. We will also develop a Project Data Management Plan (PDMP).

The initiation of the development phase will depend upon, among other factors, the estimated total cost of AXAF and the confidence that the program can be completed within this estimate. During the definition study, we will estimate the cost

AXAF 1984

- 6 mirrors
- 4 focal plane instruments
- Low earth orbit
- Shuttle servicing
- "just like HST"
- launch ~1991

AXAF remained 7-8 yrs away from launch for the next 8 years!



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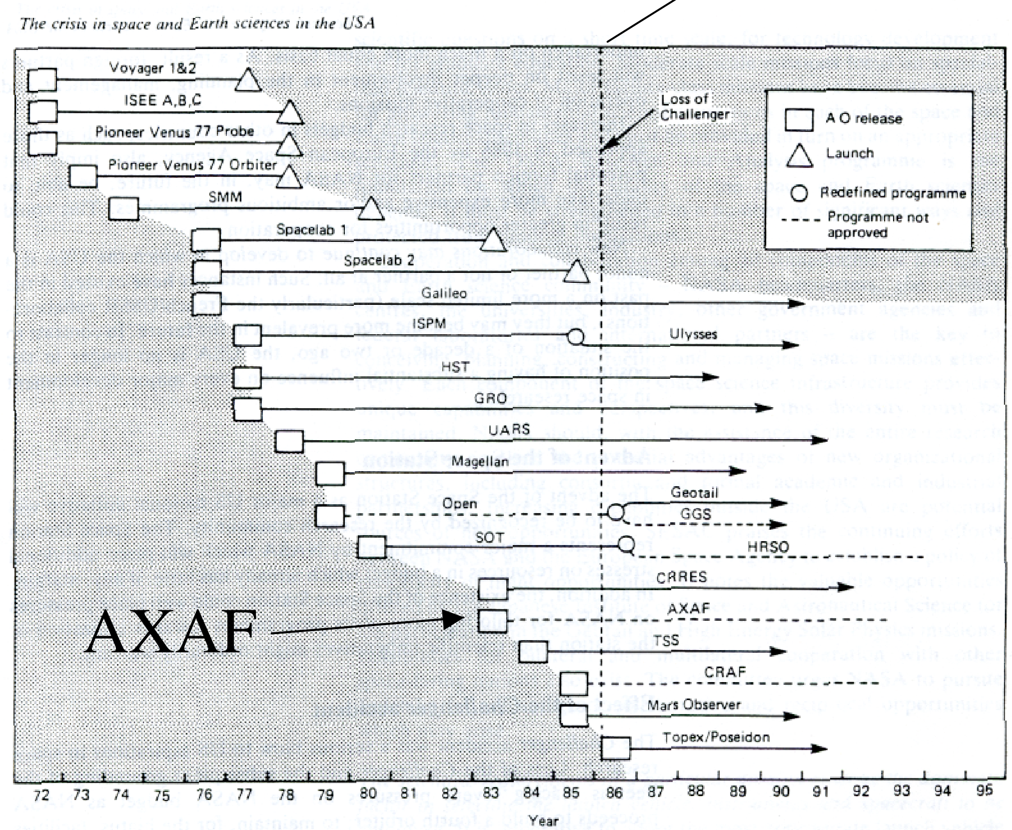
NASA Space & Earth Sciences Advisory Committee Report 1986/7

The Crisis in Space and Earth Sciences



United States Senate

COMMITTEE ON COMMERCE, SCIENCE,
AND TRANSPORTATION

WASHINGTON, DC 20510

March 17, 1988

The Honorable Donald W. Riegle
Chairman
Subcommittee on Science, Technology, and Space
105 Dirksen Senate Office Building
Washington, D.C. 20510

Dear Don:

I am writing to express my strong support for AXA Advanced X-ray Astrophysics Facility, which has been ir a new start in the President's 1989 budget request. AX constitutes a major step forward in reasserting America leadership in space science and its inclusion in this y authorization is critical.

The space science of X-ray Astronomy was pioneeer United States in the 1960's and 1970's. While numerous countries have profited from our efforts and have X-ray Astronomy missions flying at present, we do not. The l mission, the Einstein Observatory, was launched in 1978 which has been under study for a decade now by NASA, th scientific community, and industry is the follow-on to highly successful Einstein mission. To meet its mid-19 date AXAF must be funded this year.

Due to its tremendous scientific potential, AXAF listed as the most important single recommendation for program of the 1980's by the prestigious National Acade Sciences Astronomy Survey Committee and it continues to full support of the academic scientific community. Bas current estimates alone, over 1000 astronomers from 10C institutions will be involved with AXAF data and 10-20 per year will complete their thesis research during AXA fifteen-year lifetime.

The cost of AXAF development this year is $27 mil a cost of approximately $1B in current year dollars ove years. It represents a significant investment. The dev of the telescope and placement of the entire observator space is an investment in our national technological ba

Despite its relative youth, this space-based science, X-ray astronomy, has already made a very significant contributions to the technological base. Technology advances taken from instrumentation developed for X-ray astronomy have been used in a variety of important products from Medical CAT scanners to airport X-ray detectors. Other X-ray related breakthroughs in crystallography and precision optics hold promise for extraordinary advances in a number of areas.

This is an extremely important time for astronomy. A number of technological advances and unique phenomena in the universe provide an opportunity for extraordinary scientific advances. The promise of those advances will not only increase human knowledge, it will help us maintain an outstanding group of astronomers and recruit the next generation of scientists. Our scientists are our greatest edge in economic competitiveness today and we can not afford to lose these people.

The planning for AXAF is completed. The tests required have all been accomplished. The budget is well understood. The project can be done and it will have an immediate payoff for all of science.

I believe that AXAF's designation as a new start in the Space Science budget is a cornerstone of a new pride in space science and I ask for your support.

Sincerely,

John F. Kerry

JFK/nrd

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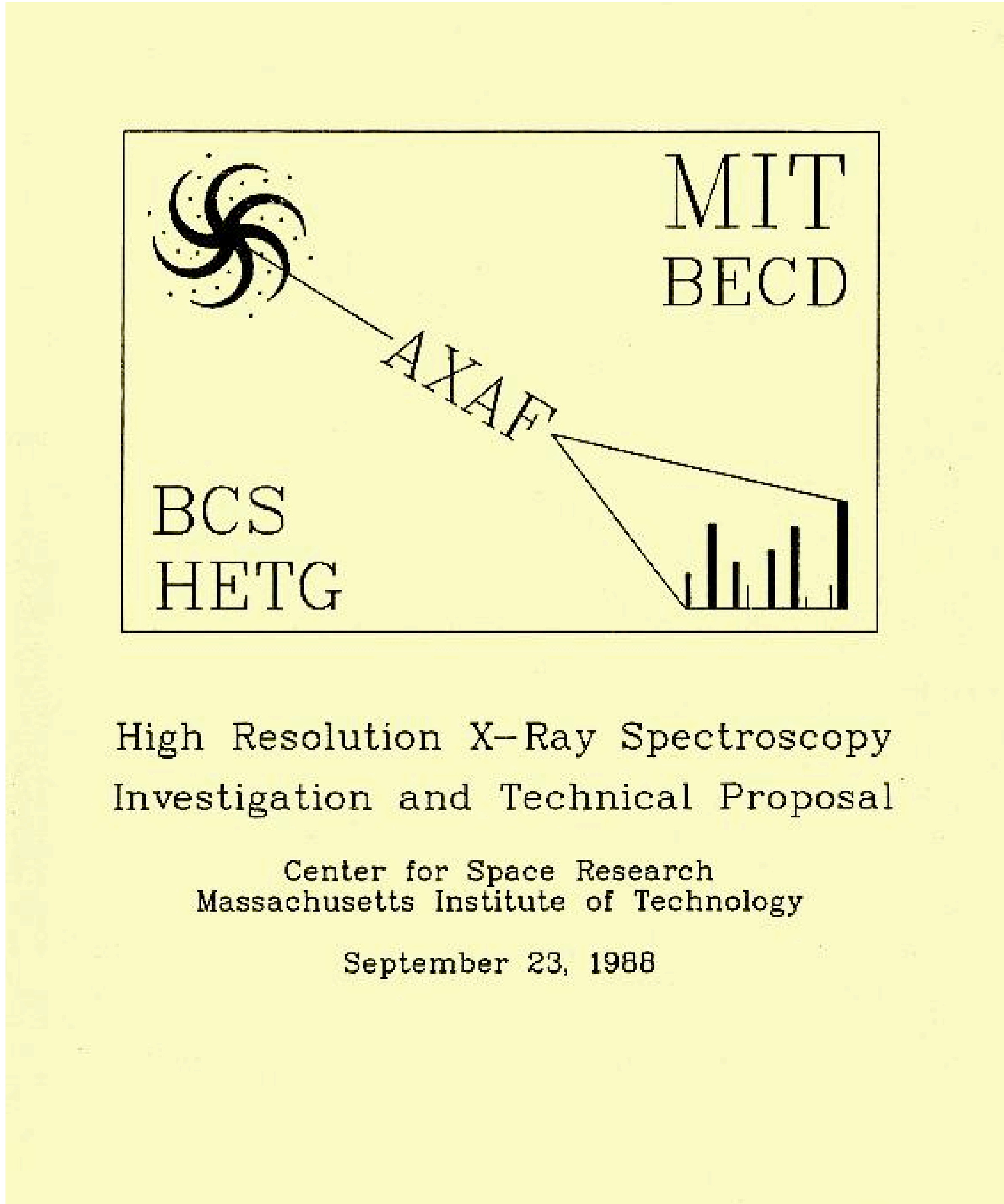
1988 Congress approves “phased new start” of AXAF optics;
1988 Deselection Process (launch 1995/6)

“Re-proposal” was the written portion,

followed by ~3 hr “stand-up oral exam” by CRC (with Bill Mayer) before AXAF deselection review board (chair: B. Margon)

CRC is optimistic

….but not for long!!


MIT
BECD
AXAF
BCS
HETG

High Resolution X-Ray Spectroscopy
Investigation and Technical Proposal

Center for Space Research
Massachusetts Institute of Technology

September 23, 1988

- In a hallway discussion at Jan 1989 Boston AAS meeting, unnamed, usually reliable source tells CRC that review board has “deselected” BCS to save cost/complexity

- CRC reaches Charlie Pellerin (NASA Astrophysics Director) that evening at AAS Hotel; asks for breakfast meeting next morning; spends sleepless night wondering what to tell him

- CRC asks Pellerin for “stay of execution” to allow proposal of revised BCS as “insurance” against problems with XRS; Pellerin agrees

- By Sept 1989 MIT/Ball team submits new proposal for revised BCS that complements XRS -- presented to Len Fisk (yet another oral exam) and accepted

- And the politics continues, year after year…..

United States Senate
COMMITTEE ON COMMERCE, SCIENCE,
AND TRANSPORTATION
WASHINGTON, DC 20510-6125

May 20, 1991

Professor Claude R. Canizares
Professor of Physics
Director
Massachusetts Institute of Technology
Center for Space Research
Cambridge, Massachusetts 02139

Dear Professor Canizares:

Thank you for your recent letter supporting the funding for continued development of the Advanced X-ray Astrophysics Facility (AXAF).

On May 14, the Committee on Commerce, Science, and Transportation met to consider the FY 1992 NASA authorization bill. I am pleased to report that the Committee approved, without objection, the Subcommittee's proposal to fully fund AXAF for the coming fiscal year. I expect our authorization bill to be ready for Senate consideration in early June.

Sincerely,

Al Gore

AL GORE
Chairman
Subcommittee on Science,
Technology, and Space

AG:spb

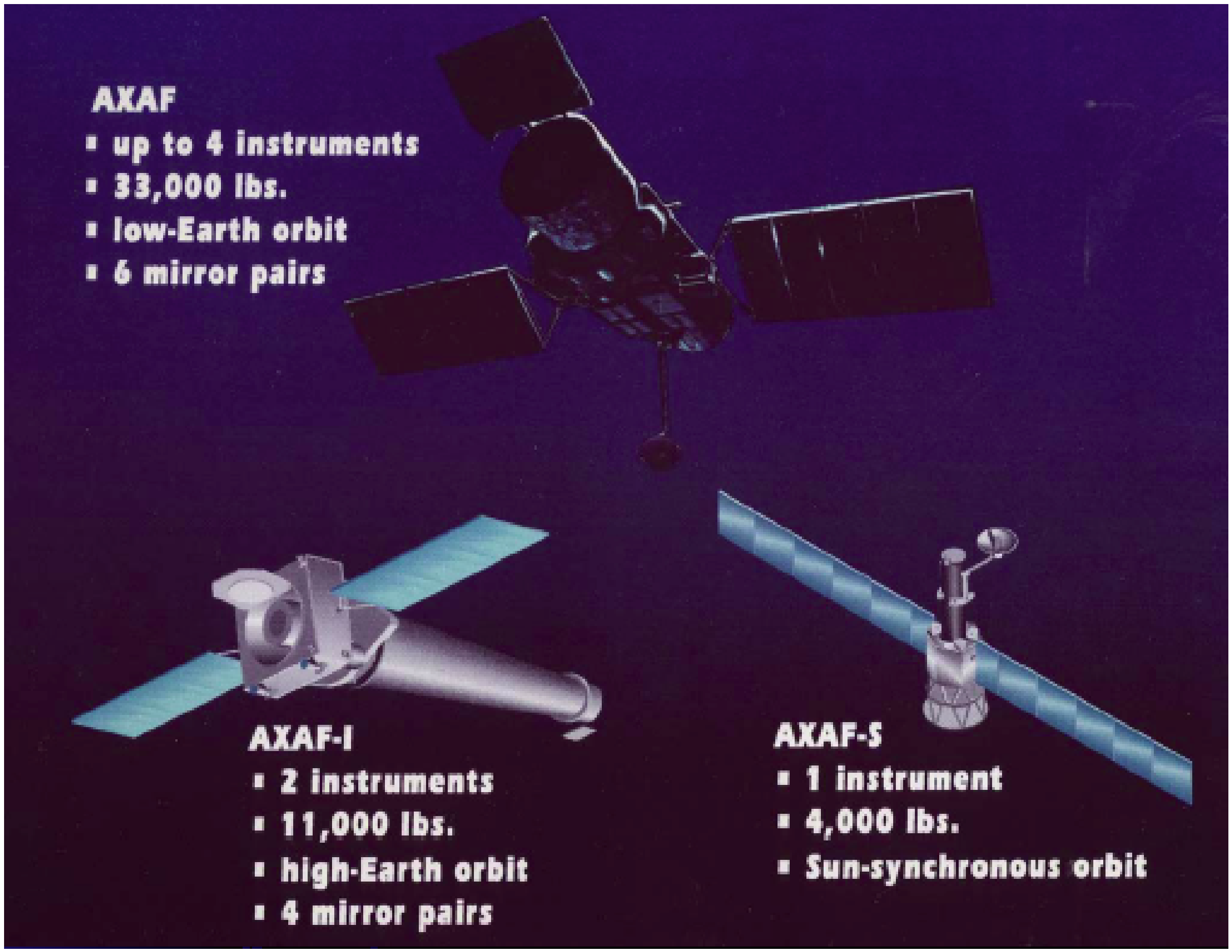
HETG Timeline (continued)

1989BCS deselected; revised BCS proposed & accepted

1992 AXAF Restructured to AXAF-I and AXAF-S; BCS dies final death; team focuses on HETG for AXAF-I; AXAF-S eventually dies also

AXAF Restructuring -- 1992

(the pictures but not the pain…)



Weiskopf 2003

So, the BCS ws dead but we still had the HETG

… until disaster struck again!

So, the BCS ws dead but we still had the HETG … until disaster struck again!

• We had subcontracted with Hampshire Instruments, a start-up company building high-intensity X-ray sources for microchip lithography, for ~$3.5M machine

• After $1.7M of progress payments, Hampshire president asks for further, accelerated payment to meet payroll

• CRC declines and exercises backup option for delivery of another, existing Hampshire machine

• Hampshire ceases operations and N.Y. State financing agency seizes all assets, including backup machine

• X-ray lithography is no longer possible, but miraculously, Schattenburg develops alternate based on precision production of multiple X-ray masks

Key breakthrough by Schattenburg:

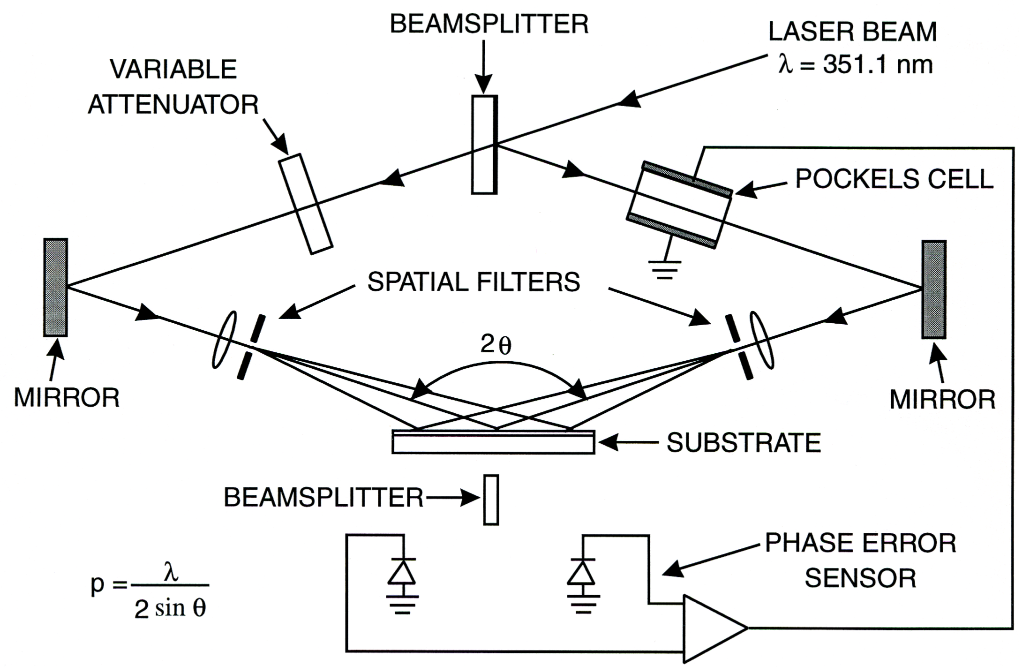
For each exposure, lock UV interference pattern to standard grating (on wafer) using Moire pattern

MLS demonstrates repeatability to less than ~200 ppm (within few weeks!)

Thinks he can achieve high aspect ratio by plasma etching rather than X-ray lithography

<u>Now the masks have become the gratings!!</u>

INTERFERENCE LITHOGRAPHY



- By the next quarterly review at NASA/MSFC, CRC announces Hampshire failure, presents recovery plan and pledges delivery of HETG on schedule and on budget; even NASA (A. Diaz) is amazed (though not as amazed as CRC himself!)
- After ~ 1 year effort, MIT lawyers unsuccessful in obtaining any recompense from liquidation; U.S. government concurs that MIT has acted responsibly and closes matter
- President of Hampshire Instruments commits suicide

But now, we need significant facilities for large-scale production of hundreds of gratings

• Plan devised for stand-alone Class 100-1000 clean-room facilities in CSR building to permit production of HETG facets

• Requires several $M investment by MIT

• Provost Mark Wrighton reviews request and denies it

• By phone (from NASA HQ) CRC asks for “stay of execution” and chance to appeal

• CRC makes personal appeal to Provost, who reverses decision

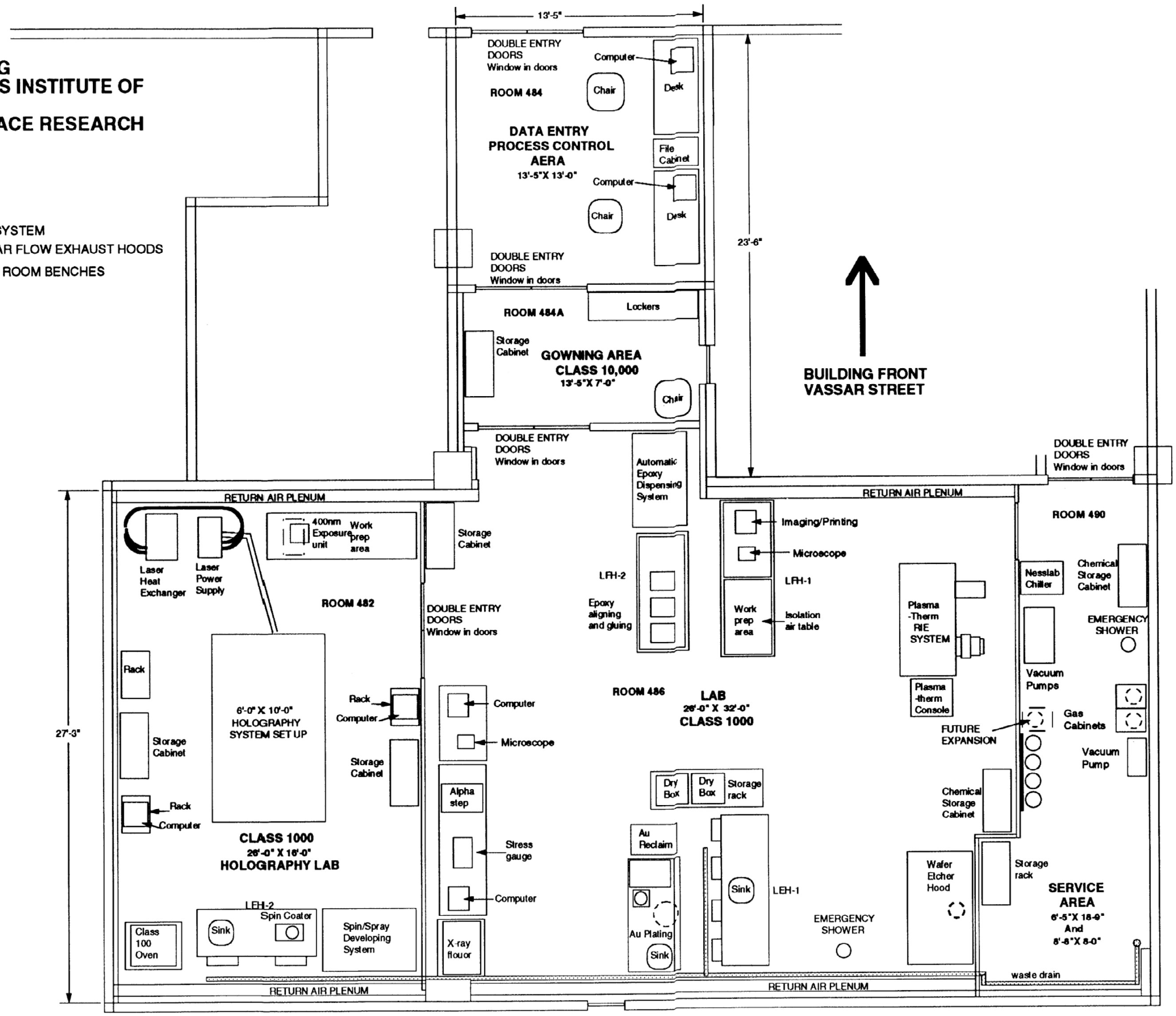
• CSR facility is constructed at cost of ~$3M and loaded with ~$5M of specialized equipment

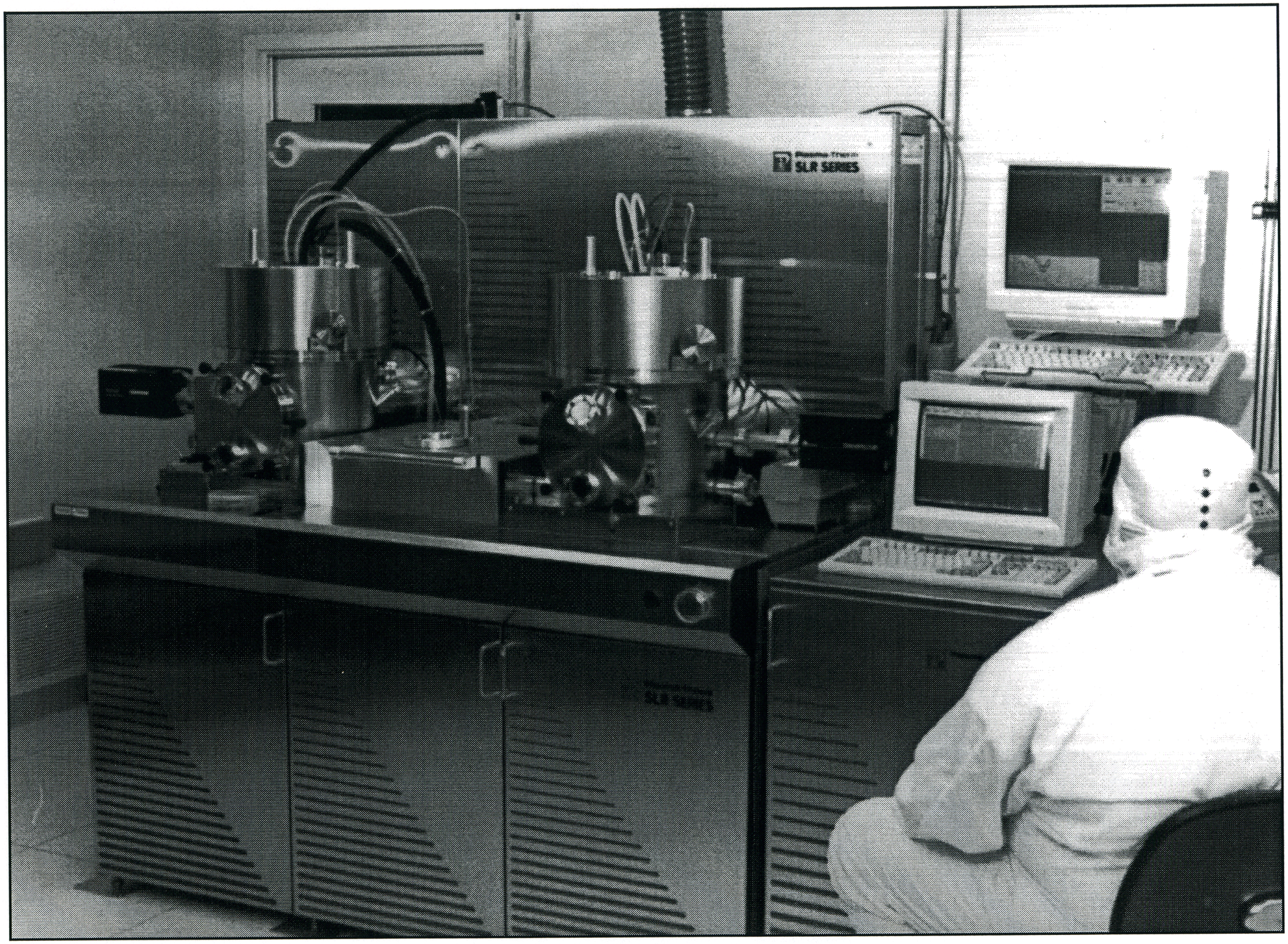
BUILDING 37 GRATING FABRICATION LAB
REV-17D

RCF 94-3-31

ROBERT FLEMING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CENTER FOR SPACE RESEARCH
(617) 253-3130
JUNE 8, 1994

▭ =CLEAN ROOM WALL SYSTEM
LEH-1,2 CLASS 100 LAMINAR FLOW EXHAUST HOODS
LFH-1,2 CLASS 100 CLEAN ROOM BENCHES

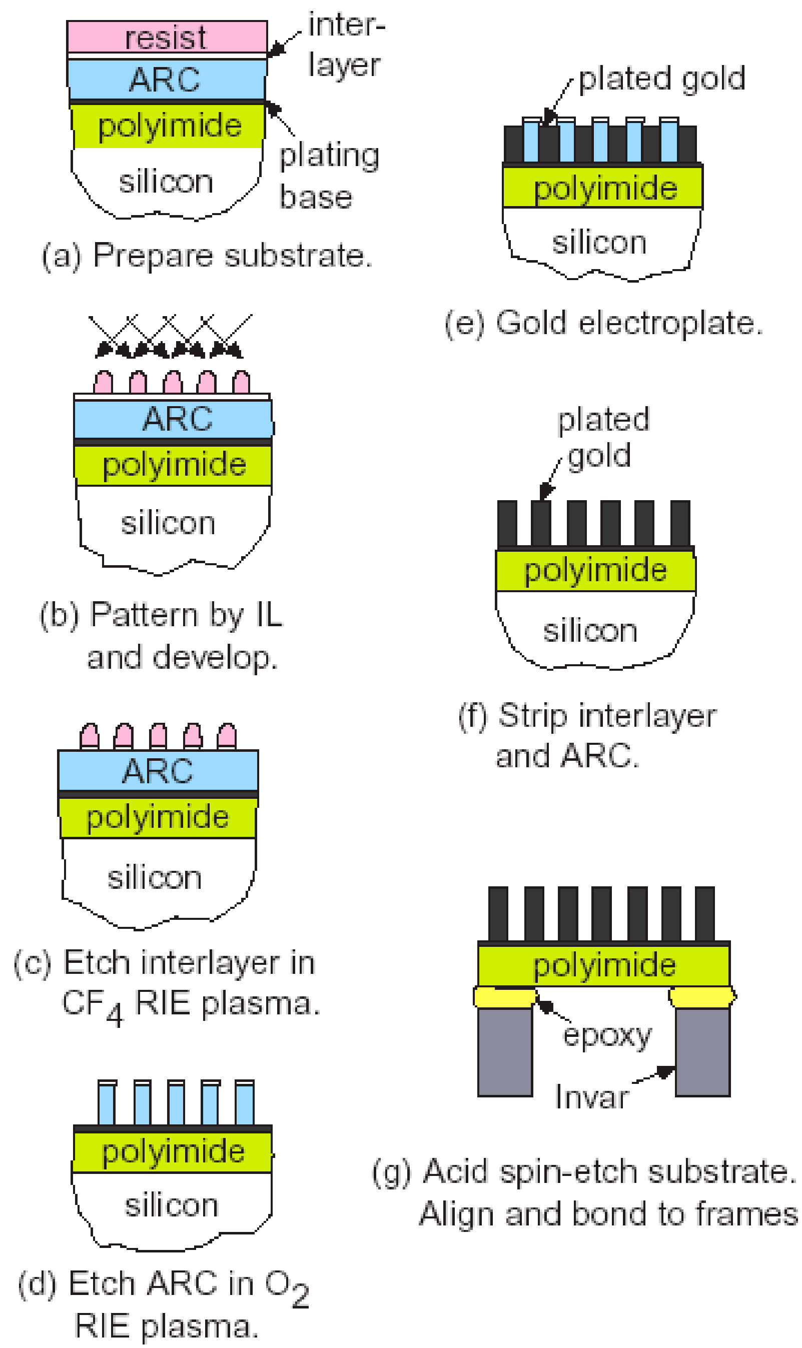




Plasma Therm 770
Reactive Ion Etcher

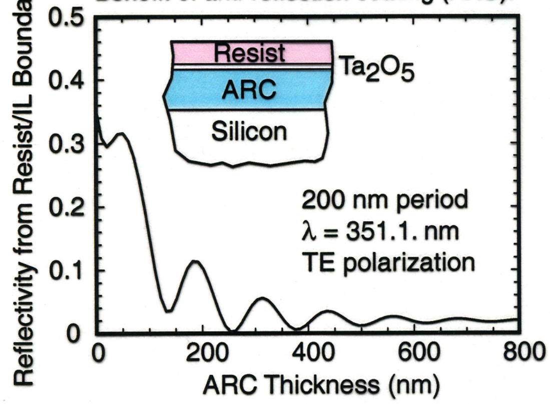
Simplified HETG Fabrication Process

Dozens of technological innovations by Schattenburg and his team; several key pattents for processes now widely in use by VLSI industry

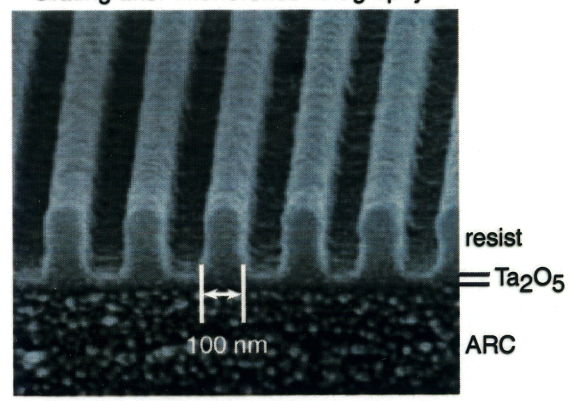


Gold Transmission Grating Fabrication Process

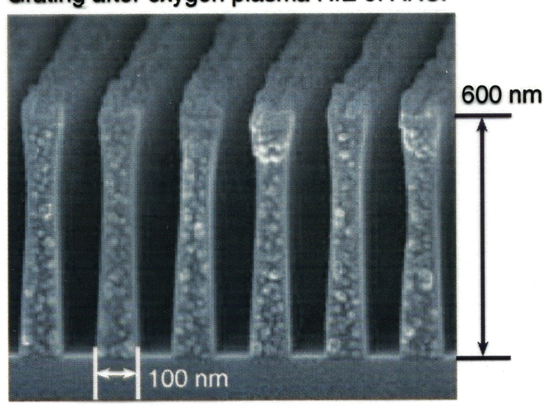
Benefit of anti-reflection coating (ARC).



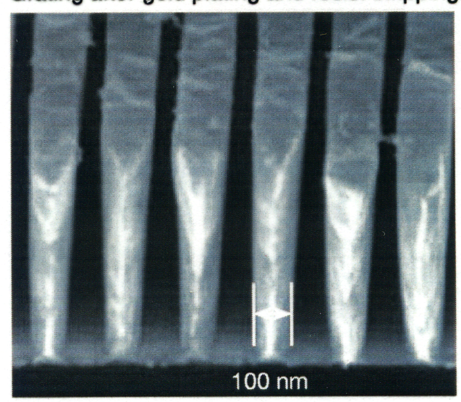
Grating after interference lithography.



Grating after oxygen plasma RIE of ARC.



Grating after gold plating and resist stripping.



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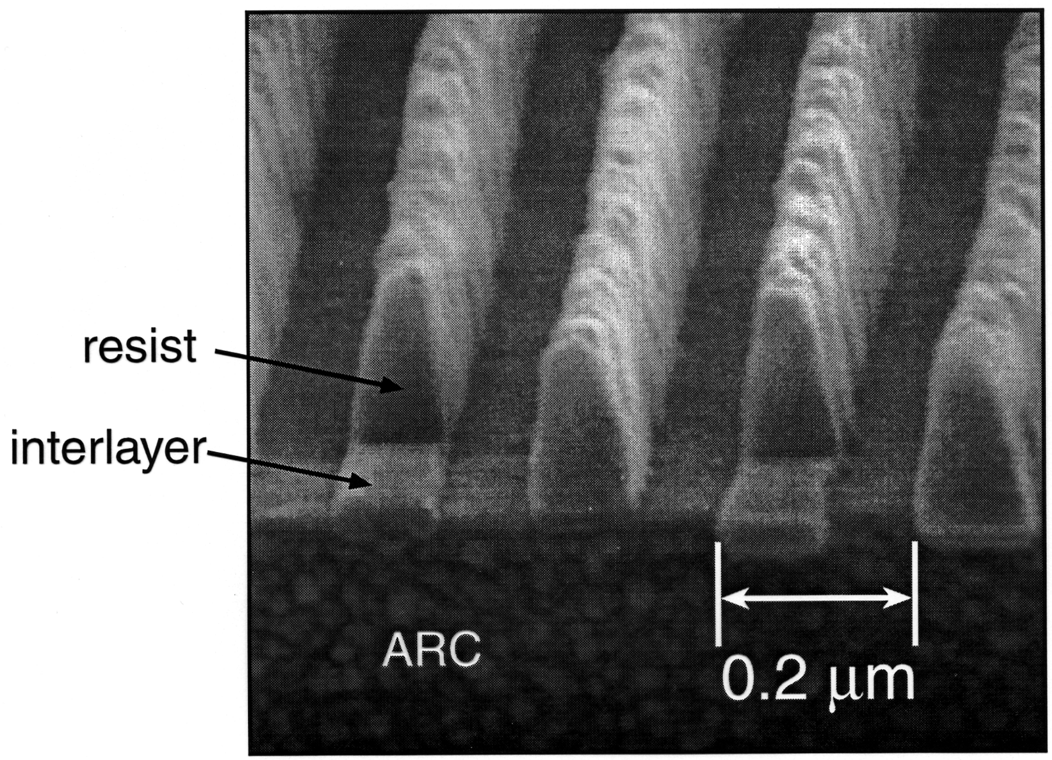
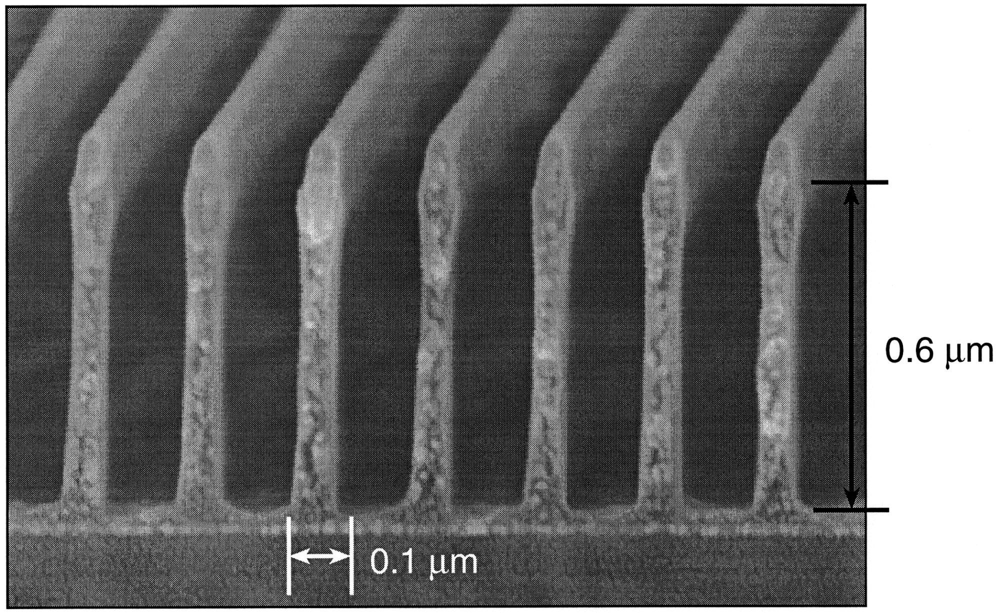
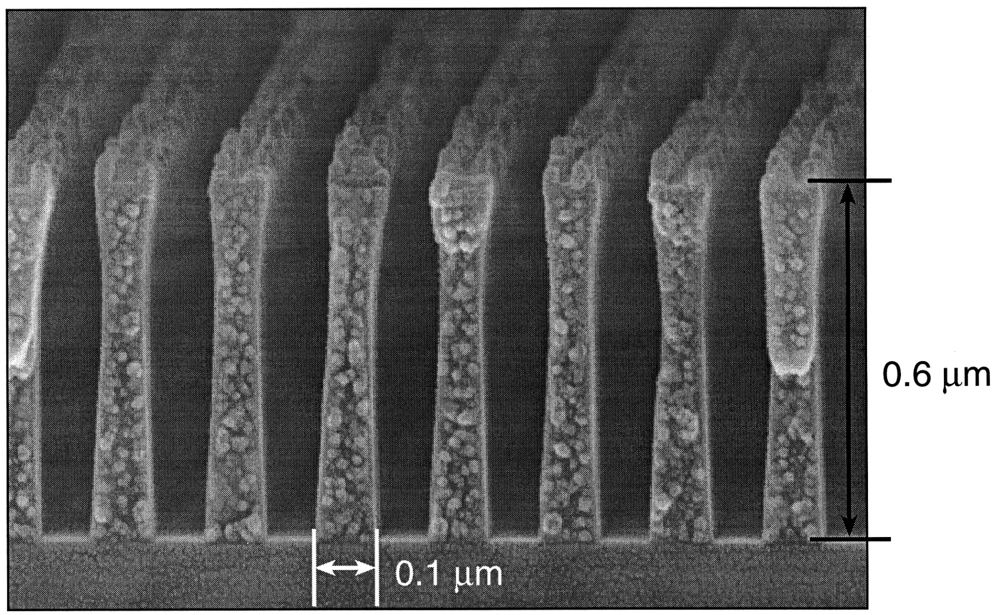
GRATING AFTER INTERLAYER ETCH



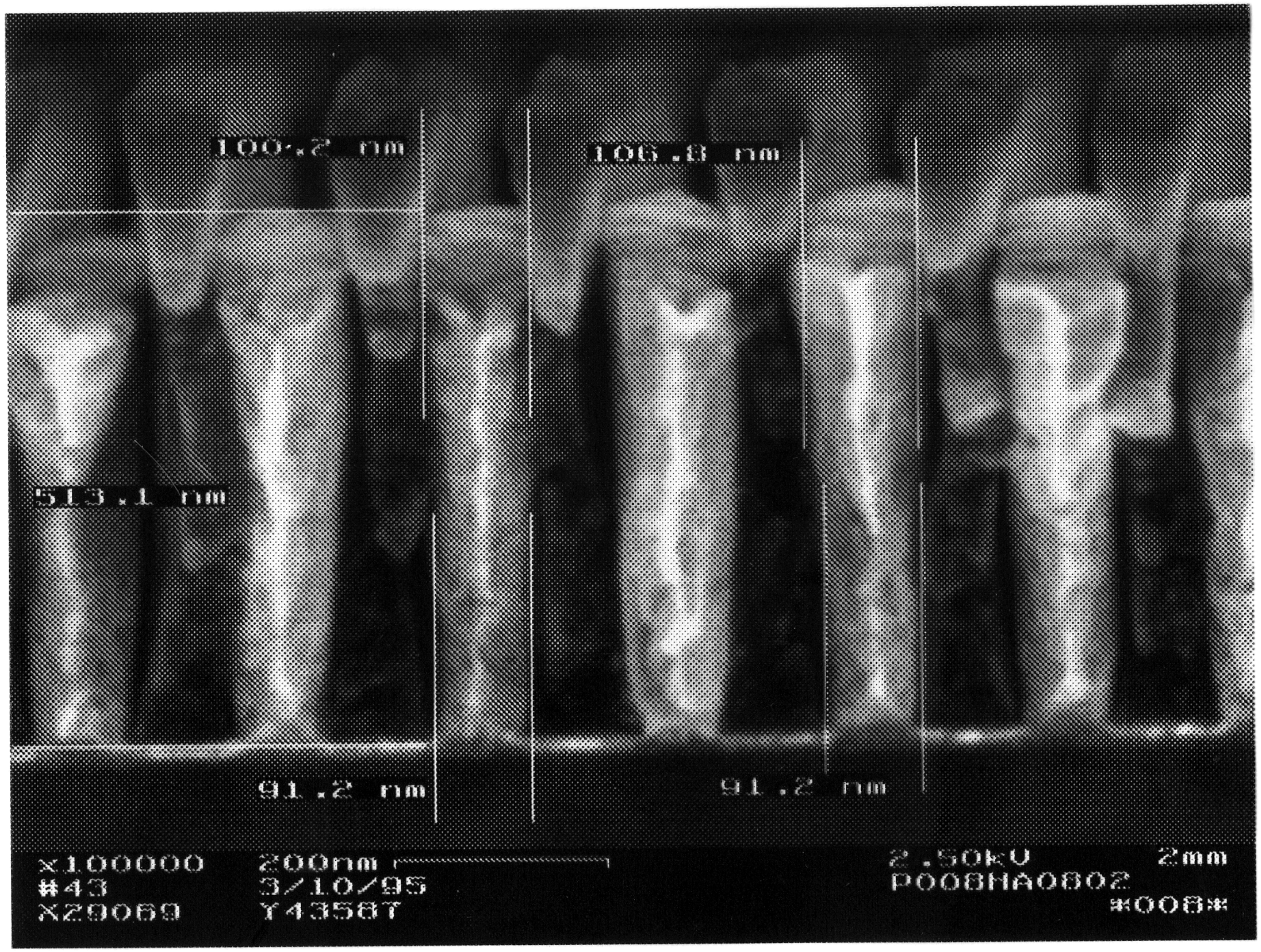


a) SiO_2 Interlayer



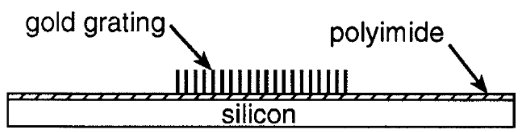
b) Ta_2O_5 Interlayer

MLS-95-05-28.04


100.2 nm
106.8 nm
513.1 nm
91.2 nm
91.2 nm
x100000
200nm
2.50kV
2mm
#43
3/10/95
P008MA0802
X29069
Y43587
008

Spin-Etch and Mount
(Steps 11 and 12)

11) Spin-Etch Wafer
  etch in acid(s)
  rinse & dry



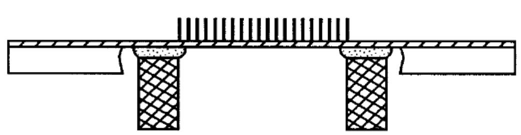
Before Spin Etch

After Backside Spin Etch

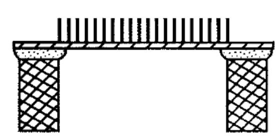
12) Mount
  period map baseline (optional)
  clean frames
  apply glue to frames
  align & join frames to membrane
  soft-cure glue (time)
  cut out frames
  oven hard-cure glue (optional)
  optical inspection
  period map final

Clean Invar Frame

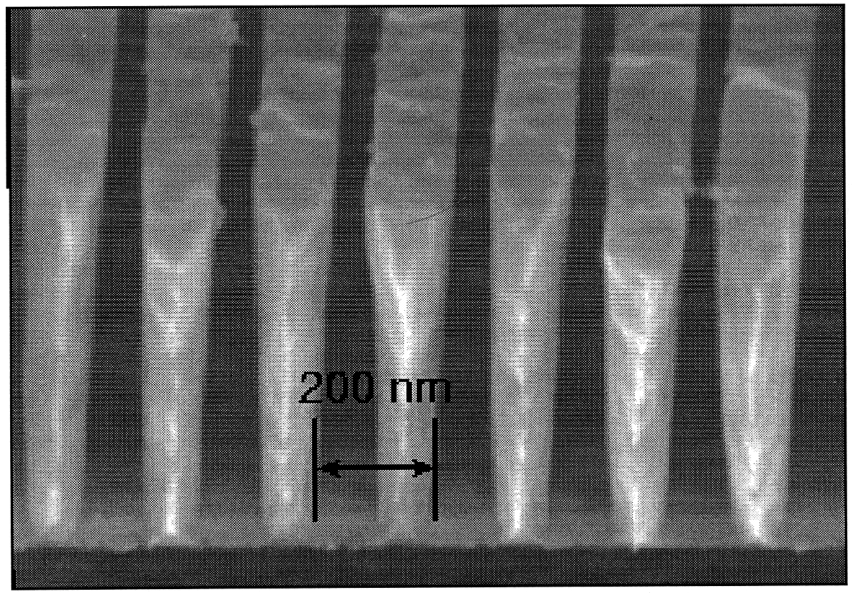
Apply Adhesive



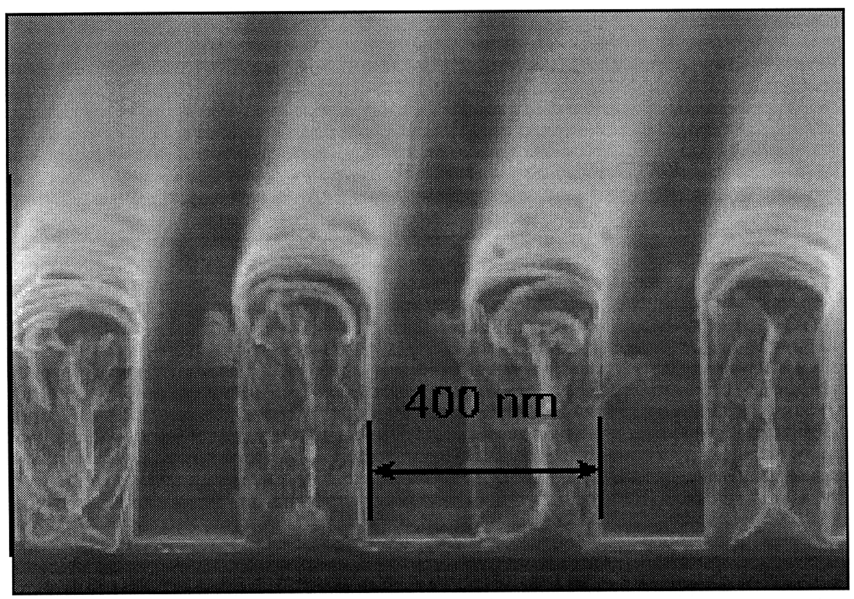
Align and Join Frame to Membrane



Cure and Cut Away



(a) High Energy Grating (HEG).



(b) Medium Energy Grating (MEG).

Fabricating hundreds of gratings is only part of the job

Dozens of scientists, engineers, technicians and students invented a whole host of new ways to measure, hold, calibrate, test, protect, model, etc. the grating spectrometer

Here are just a few examples:

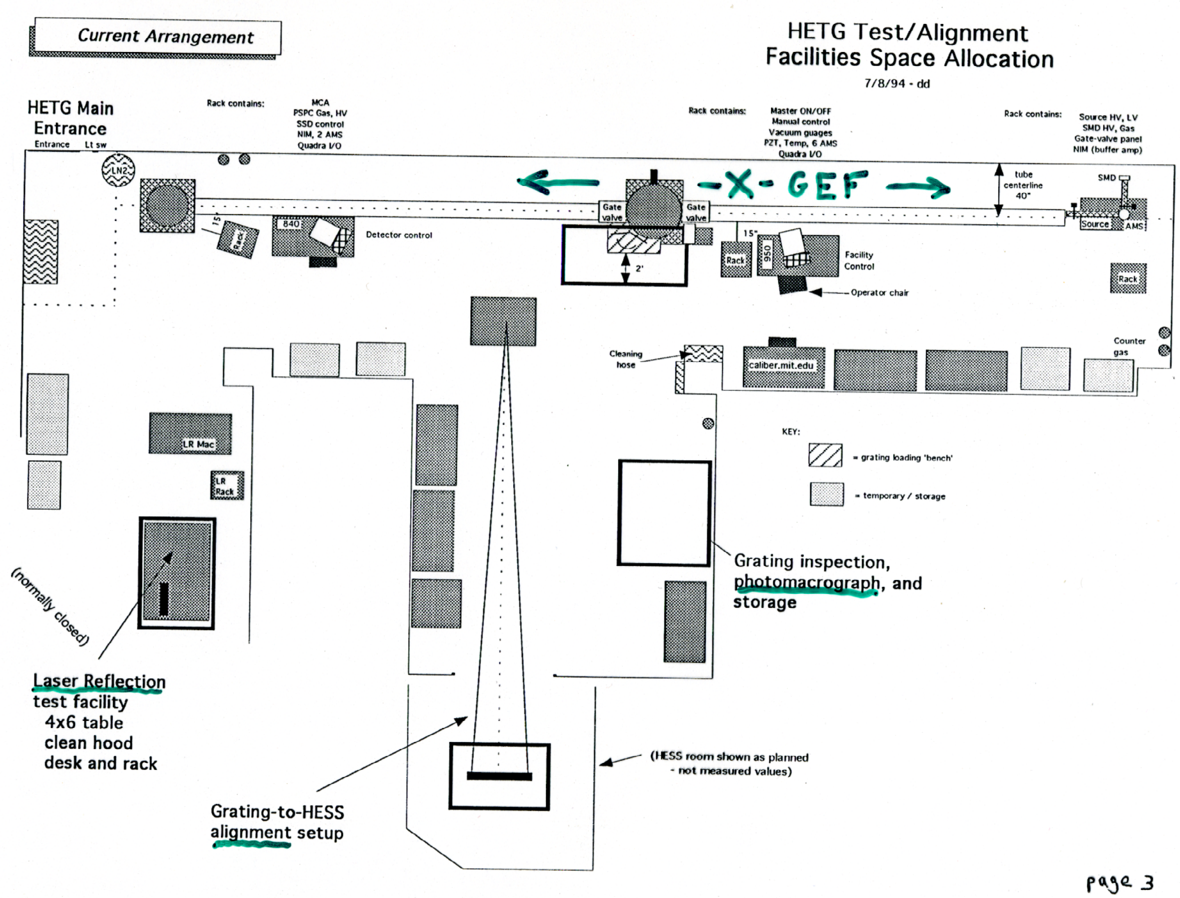
How do we map grating periods to <100 ppm across grating and from one grating to another for ~1000 gratings? *Use automated laser reflection system (Dewey)*

How do we test each grating's efficiency? Test some gratings at synchrotron facilities, test all gratings in *automated X-ray test system at MIT (Flanagan, Elder, …)*

How do we align gratings? *Use polarizing property of gratings for white light (Levine)*

HETG
Test/Alignment
Facilities

Bldg NE80 (Draper)



How do we assure gratings will withstand launch? *Perform individual and system level acoustic, shake, and thermal-vac tests (McGuirk, Dewey)*

How do we know if gratings are humidity sensitive? *Dip one in a glass of water at a Science Working Group meeting*

How do we hold gratings in torroidal "Rowland Circle" geometry to required tolerance? *Design precision HETG Support Structure (HESS) fabricated by numerically-controlled milling machine (Pak)*

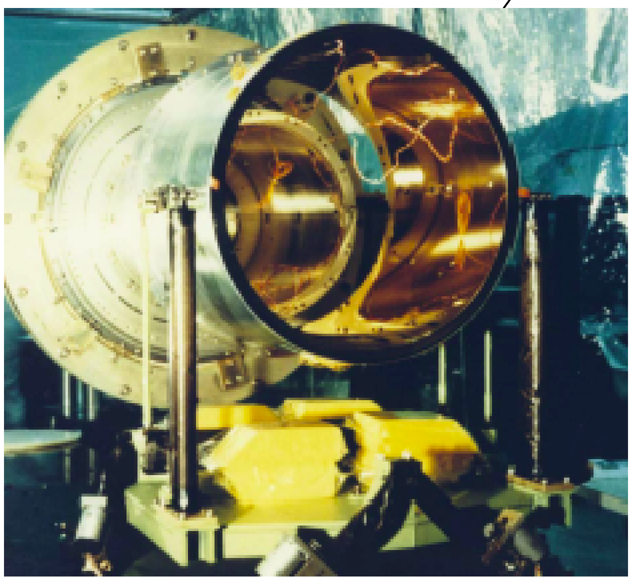
How do we avoid thermal/mechanical stresses from distorting gratings? *Use INVAR frames held to HESS by a single screw (Pak, Manino)*

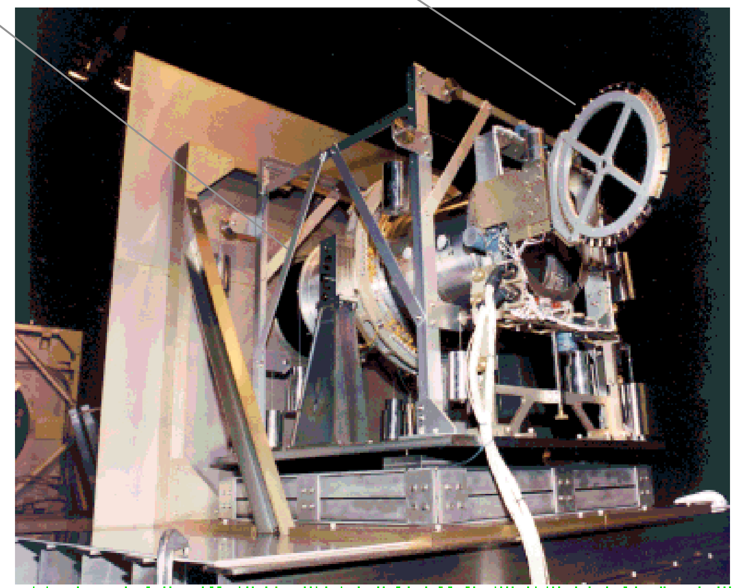
How do we know if HETG will survive truck shipment to MSFC? *Send truck on dry run with shipping container instrumented with accelerometers*

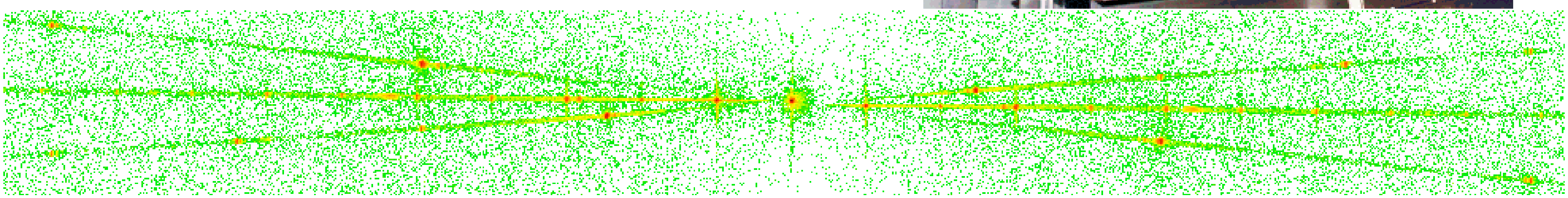
How do we know if our gratings will achieve the required resolution? *Test them with the "test mirror assembly (TMA)" in the MSFC X-ray Cal facility (Galton, Dewey)*

Test Mirror Assembly (TMA)

Grating facets on wheel (in open position)



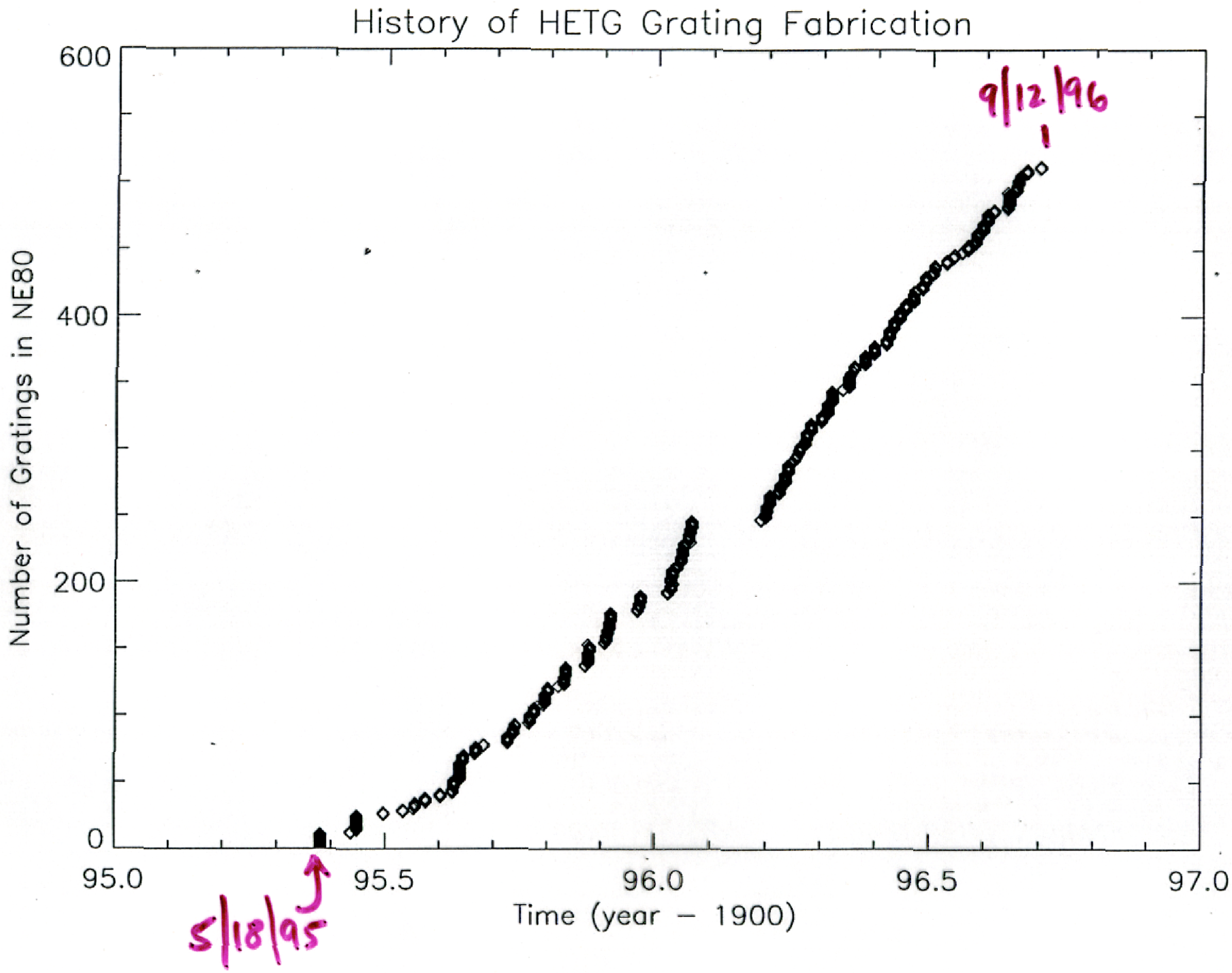




1996 TMA Objective Grating Assembly (TOGA) test at MSFC/XRCF

Twelve years after initial proposal, the first real evidence that grating assembly would perform as expected!!

"[expletive deleted]!!! I might even use the gratings!" --- Leon van Speybroeck


History of HETG Grating Fabrication
Number of Gratings in NE80
600
400
200
0
95.0
95.5
96.0
96.5
97.0
Time (year – 1900)
9/12/96
5/18/95

HETG Timeline

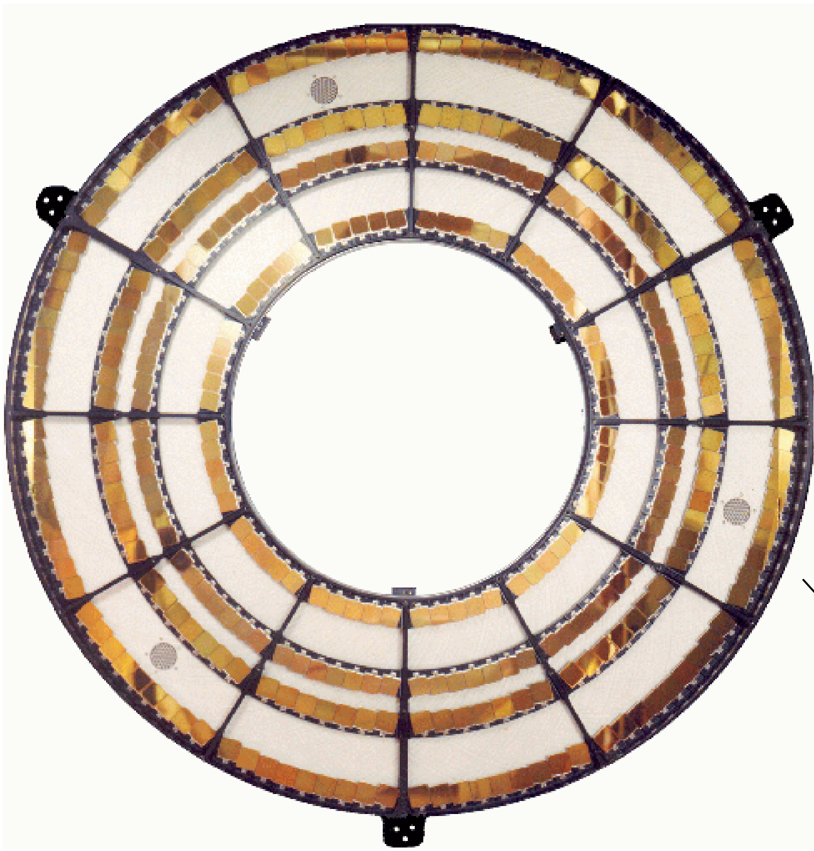
1989 BCS deselected; revised BCS proposed & accepted
1992 AXAF Restructured to AXAF-I and AXAF-S; BCS dies final death

1993 HETG Systems Requirements Review (SRR)
1993Hampshire Instruments ceases operations; X-ray lithography abandoned

1994 Preliminary Design Review (PDR)
1995 Critical Design Review CDR

1996 Complete HETG facet fabrication
1996 Deliver & Calibrate (XRCF) Completed HETG

1999 Chandra Launch!!! (only 20 years had passed)

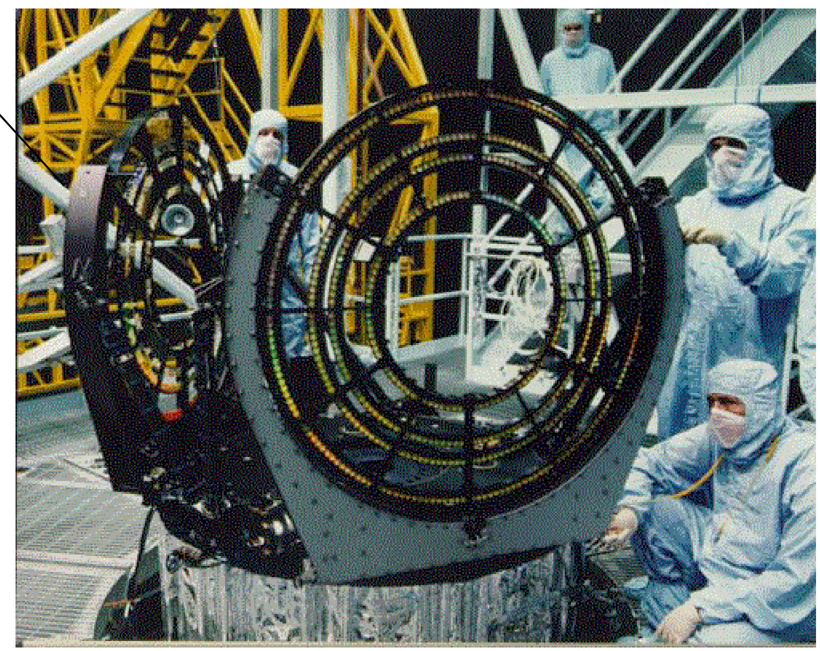


High Energy Transmission Grating

336 grating facets aligned to <1 arc min tolerance

HEG: inner two rings

MEG: outer two rings




July 23, 1999

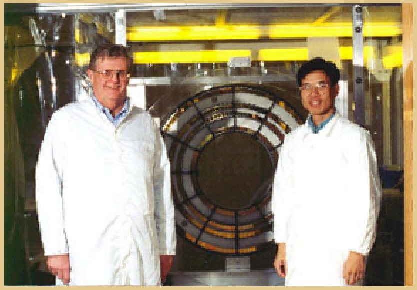
Fabrication

Back row:
Bob Fleming, Mark Schattenburg, Roger Millen, Bob Sisson, Hank Smith.
Front row:
Rich Aucoin, Jeanne Porter, Jane Prentis, Pat Hindle.

Testing

Dick Elder, Bill Forbes, Bob Laliberte, Ed Warren, Mike Enwright.

Mechanical

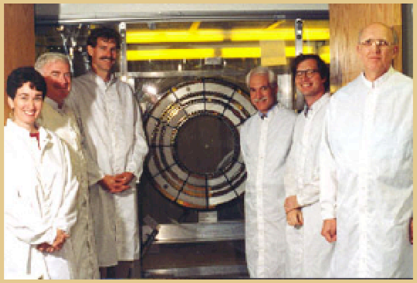


Don Humphries, Chris Pak

Support

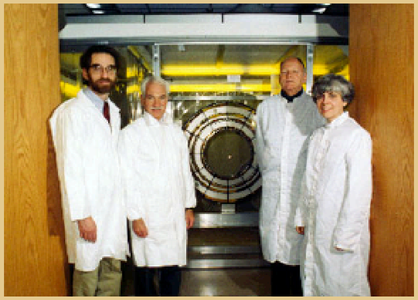
Kim Farrell, Dave Breaslau.

Science



Kathy Flanagan, Mike McGuirk, Mark Schattenburg, Claude Canizares, Dan Dewey, Dick Elder.

Inspiration



Al Levine, Claude Canizares, Gene Galton, Angie[for Tom] Markert

Tom Markert

1948-1996

With deep gratitude to the Incomparable HETG (and BCS) Team

HETG Instrument Team:
Daniel Dewey
Kathryn Flanagan
Allen Levine
Thomas Markert
Mark Schattenburg

Henry I. Smith

Engineers
Eugene Galton (Proj Mgr)
William Mayer (Former PM)
Michael McGuirk (Dpty PM)
Richard Aucoin
Len Bordzol
George Czernienko
Richard Elder
Robert Fleming
Patrick Hindle
Don Humphries
Christopher Pak
Irving Plotkin
Edward Warren

Technicians
David Breslau
Michael Enright
William Forbes
Robert Laliberte
Joseph Mannino
Roger Millen
James O'Connor
Jean Porter
Jane Prentiss
Leo Rogers
Robert Sisson

BCS Scientist & Engineers
Bruce Woodgate (GSFC)
Robert Goeke
Peter Tappan

CXC/MIT
Glenn Allen
David Davis
John Davis
John Houck
David Huenemoerder
Bish Ishibashi
Joel Kastner
Herman Marshall
Michael Nowak
Irena Porro
Norbert Schulz
Michael Wise

Chris Baluta
Lane DeNicola
Amy Fredricks
Sara-anne Taylor

Plus a dozen undergraduate UROP & senior thesis students…

Postdocs
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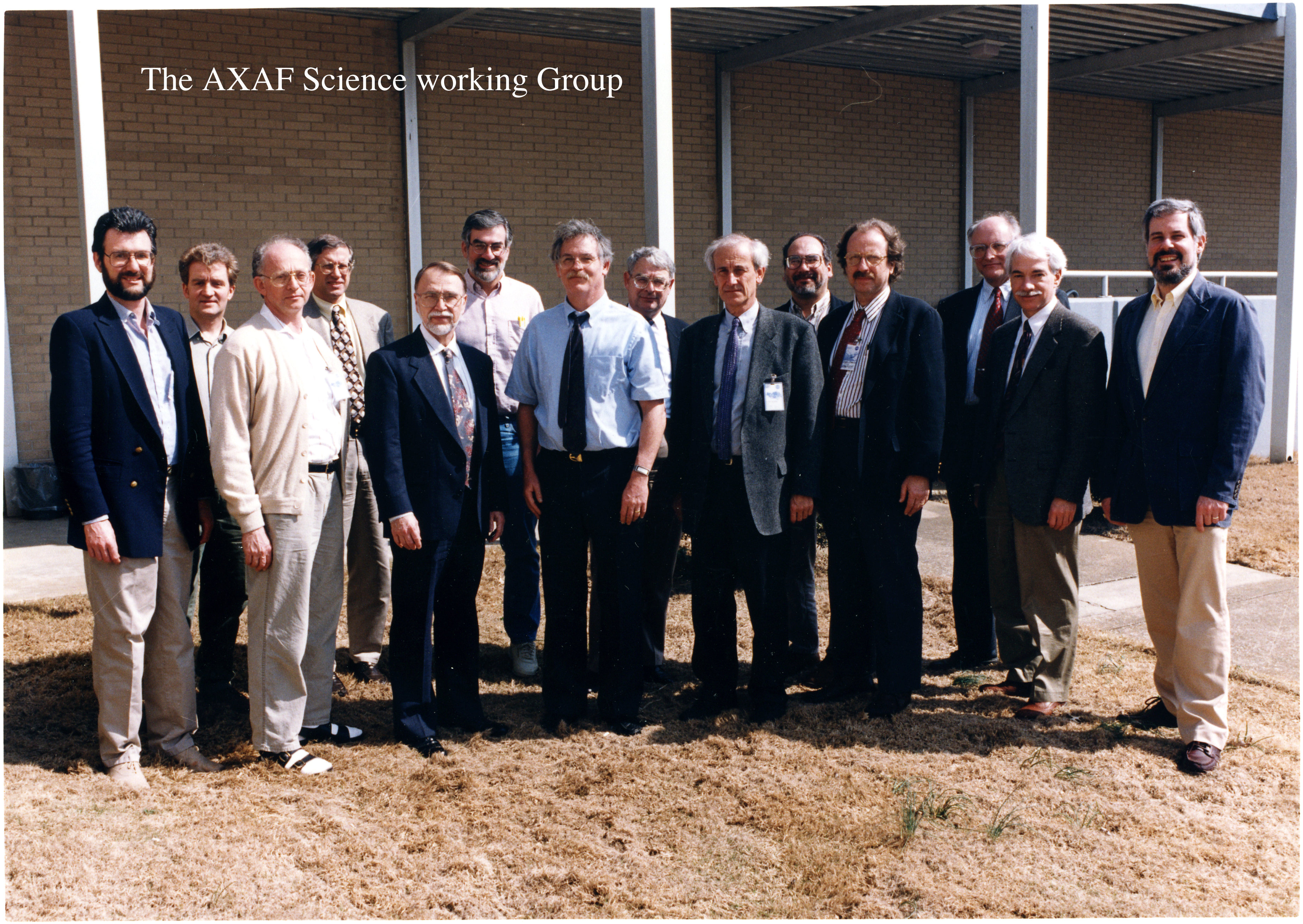
Mario Jimenez
Julia Lee
Sera Markoff
Patrick Ogle
Patrick Wodjowsky

Graduate Students
David Buote
Kathleen Early
Yao-Ching Ku
Taotao Fang
Maya Farhoud
Rob Gibson
Amalia Hicks
Una Hwang
Tesla Jeltema
Joshua Migliazzo
Alberto Moel
Gabrielle Owen
Mark Schattenburg
Michael Stage
David Um


The AXAF Science working Group

HEG Spectrum of Capella at Mg XI

Now which ones of you are going build a truly high resolution spectrometer!!