Microfabrication Techniques for Accelerators

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Argonne National Laboratory

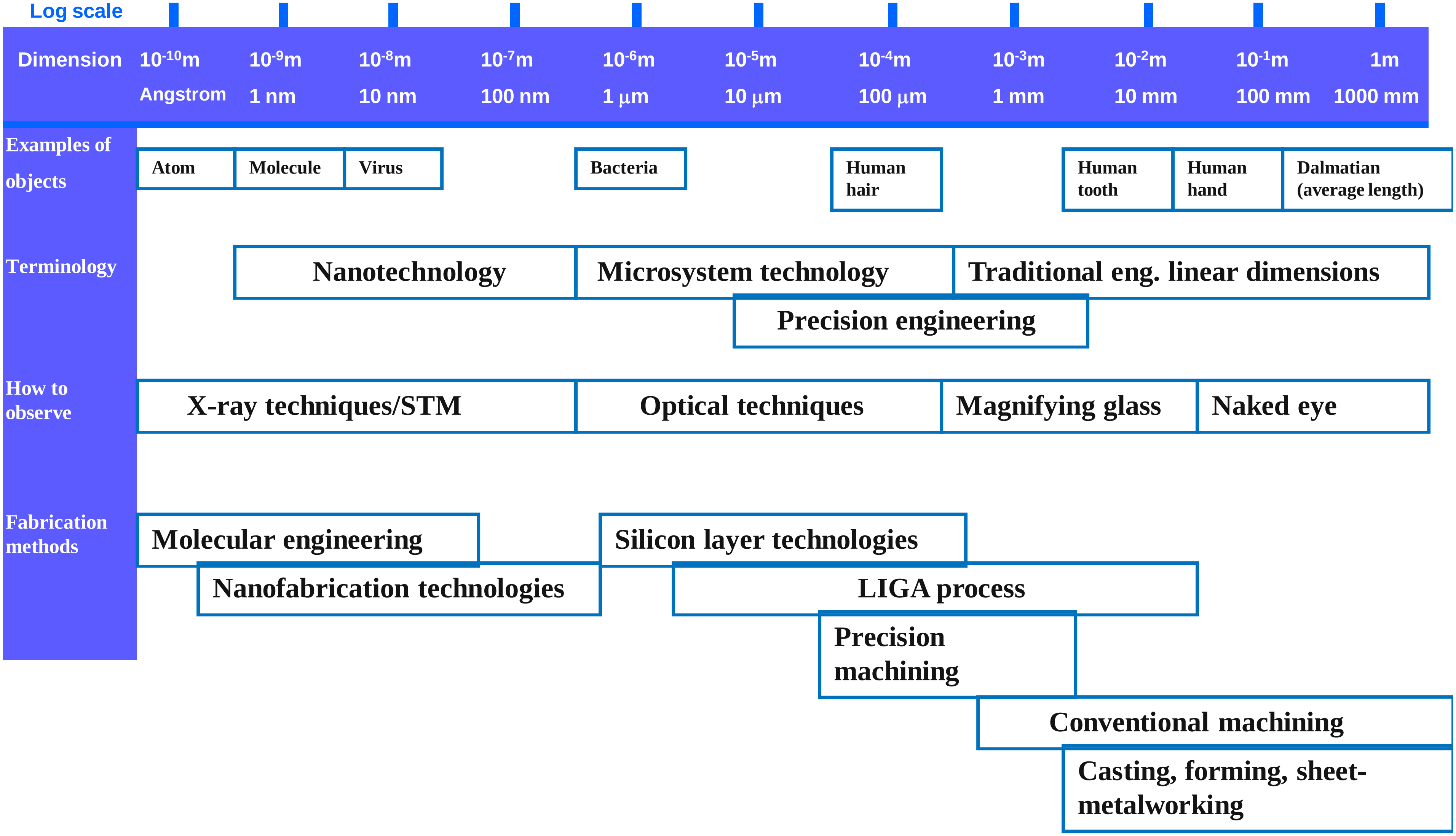
Symposium in Memory of Robert H. Siemann

and ICFA Mini-Workshop on Novel Concepts for Linear Accelerators and Colliders

Outline

- Terminology
- Microfabrication methods and tools
- DXRL at APS
- Summary

Terminology and relative sizes



Log scale

Dimension	10^{-10}m	10^{-9}m	10^{-8}m	10^{-7}m	10^{-6}m	10^{-5}m	10^{-4}m	10^{-3}m	10^{-2}m	10^{-1}m	1m
	Angstrom	1 nm	10 nm	100 nm	1 µm	10 µm	100 µm	1 mm	10 mm	100 mm	1000 mm

Examples of objects

- Atom
- Molecule
- Virus
- Bacteria
- Human hair
- Human tooth
- Human hand
- Dalmatian (average length)

Terminology

- Nanotechnology
- Microsystem technology
- Traditional eng. linear dimensions
- Precision engineering

How to observe

- X-ray techniques/STM
- Optical techniques
- Magnifying glass
- Naked eye

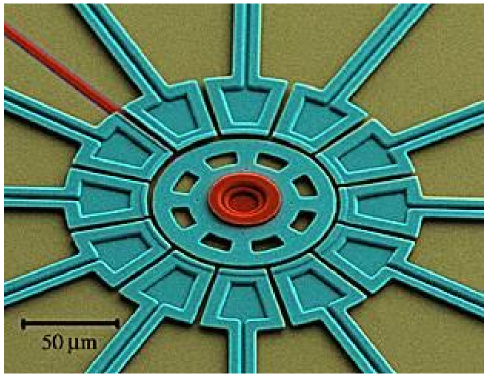
Fabrication methods

- Molecular engineering
- Nanofabrication technologies
- Silicon layer technologies
- LIGA process
- Precision machining
- Conventional machining
- Casting, forming, sheet-metalworking

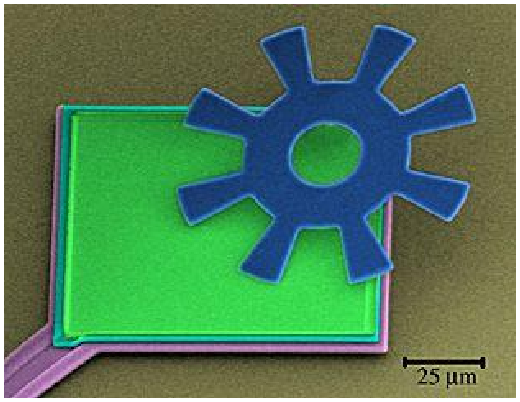
Microfabrication methods and tools - MEMS

Basic idea is to find a way to circumvent the limitations imposed by normal machining.

- MEMS (Micro-electrical-mechanical systems)
  - Fabricated at micron to millimeter sizes using a single silicon substrate
  - Used to fabricated sensors, motors, actuators, mirrors
    - *Wide range of industrial and consumer applications*
      - MEMS accelerometers for automobile airbag systems
      - MVED applications
        - *MEMS-based reflex klystron (JPL)*



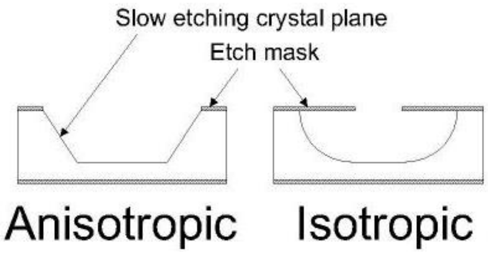
A salient-pole electrostatic ally actuated micromotor made from polycrystalline silicon using surface micromachining techniques.

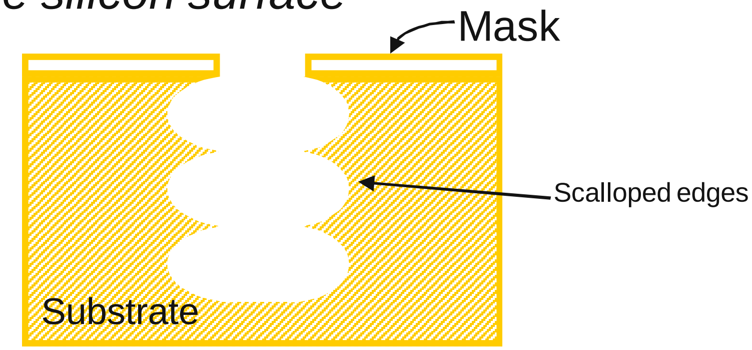


A mechanical gear which is smaller than a human hair

MEMS fabrication process

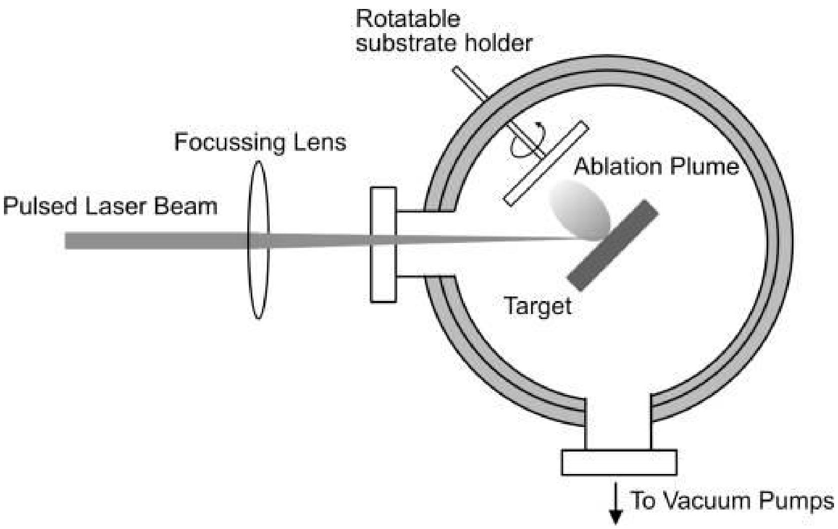
- Wet Etching
  - Isotropic wet etching uses solutions of hydrofluoric, nitric, and acetic acid, HNA.
  - It produces hemispherical shaped cavities below the mask aperture.
  - Lateral etch rate is about the same as vertical etch rate
  - Anisotropic wet etching of silicon is done using either potassium hydroxide, KOH, or a solution of ethylene diamine and pyrocatechol, EDP
- Dry Etching
  - It provides a better control and faster etch rates than either isotropic or anisotropic wet etching.
  - It refers to the process of reactive ion etching (RIE)
    - *Ionization of fluorine-rich reactive gas in a plasma chamber*
    - *Energetic fluorine ions attack the silicon surface*



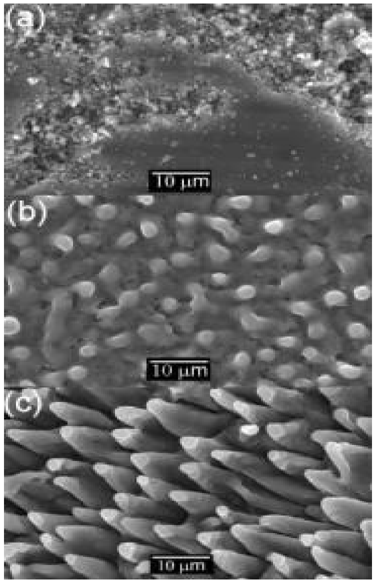


Microfabrication methods and tools – Laser Ablation

- Laser ablation micromachining uses the very high power density and very short pulse of the laser to vaporize the surface of a material without transferring heat to the surrounding area.
- It can be applied to a a wide variety of materials including metals, ceramics, semiconductors and plastics.
  - The depth of the etch can only be done by knowing the material removal rate per pulse and counting pulses or by external measurement.



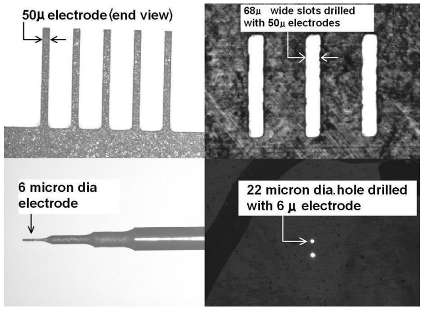
a) Pre-ablation
b) After ablation with one pulse
c) After ablation with 10 pulses



SEM images of an MgB_2 ablated at 193 nm @12 J/cm^2

Microfabrication methods and tools – EDM

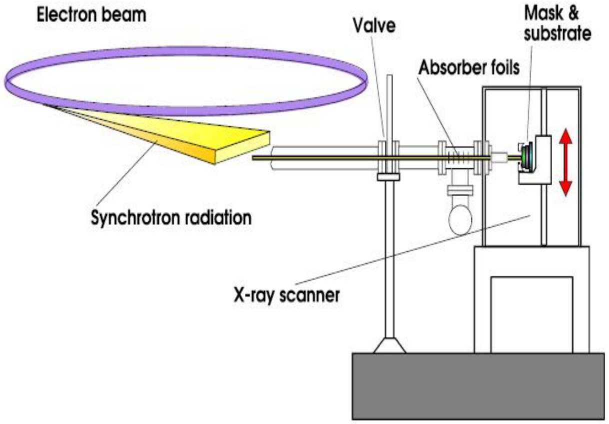
- Electric Discharge Machining uses large electric field arcs across the gap between the two metal surfaces.
- The arc raises the local surface temperature to between 8,000C and 12,000C and melts a roughly hemispherical volume on both the electrode and the work piece.
- Since the surface is formed by millions of small craters, it has a very poor surface finish.
- This can be improved considerably with finishing cuts, smaller wire diameter, lower electric fields.
- It needs additional treatment for low RF loss applications.
- Dimensional accuracy for EDM is roughly the same as precision machining.
- EDM gains in accuracy from its noncontact material removal, compared to normal machining.
- Disadvantage: variation in height of the crater-defined surface.
- New wire-handling and tensioning systems have allowed EDM wire diameters to ~ 20μm (as compared to 0.3 mm – 0.03 mm), μEDM.

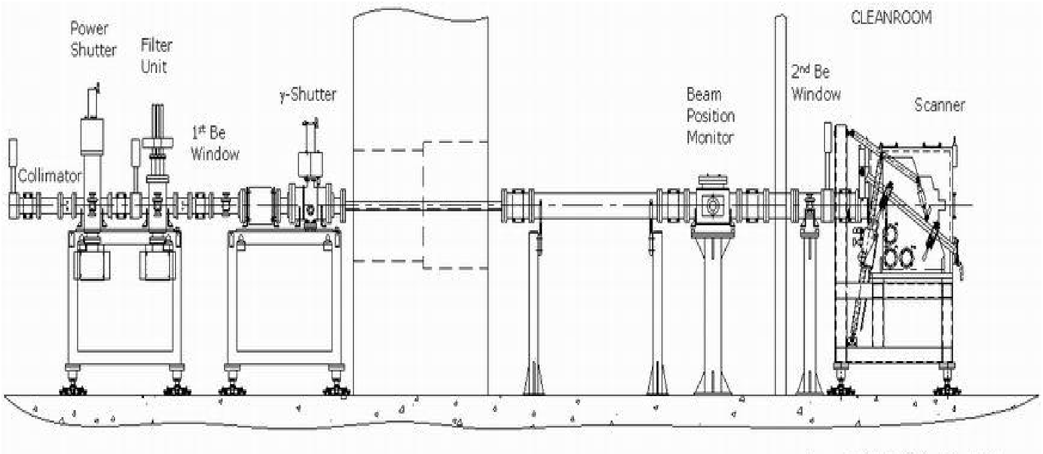


Slide courtesy: MicroBridge Services, Ltd

Microfabrication methods and tools – LIGA

- LIGA is a process in IC fabrication which involves lithography, electroplating, and molding on a given substrate. (Lithographie, Galvanoformung und Abformug)
- LIGA allows structures to have heights of over 100 μm with respect to the lateral size.
- LIGA fabricates High Aspect Ratio Structures (HARMS).
- The ratio between the height and the lateral size is the aspect ratio (e.g. 100:1)
- Ideal for fabrication of RF resonant cavities with frequencies from 30 GHz to 1 THz.
- Unlike semiconductor lithography, LIGA uses very thick resist films.





Source: Oxford-Danfysik, Oxford, UK

Deep X-ray Lithography and Electroforming

⬛ Silicon wafer, 250-µm-thick

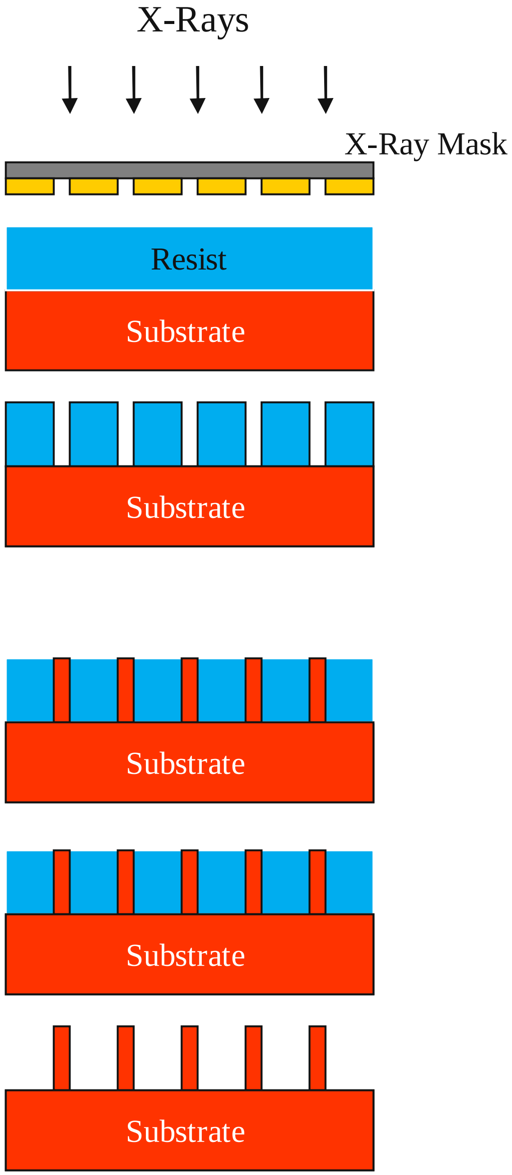
🟨 Gold absorber, 45-60-µm-thick

🟦 PMMA, 1 -3-mm-thick

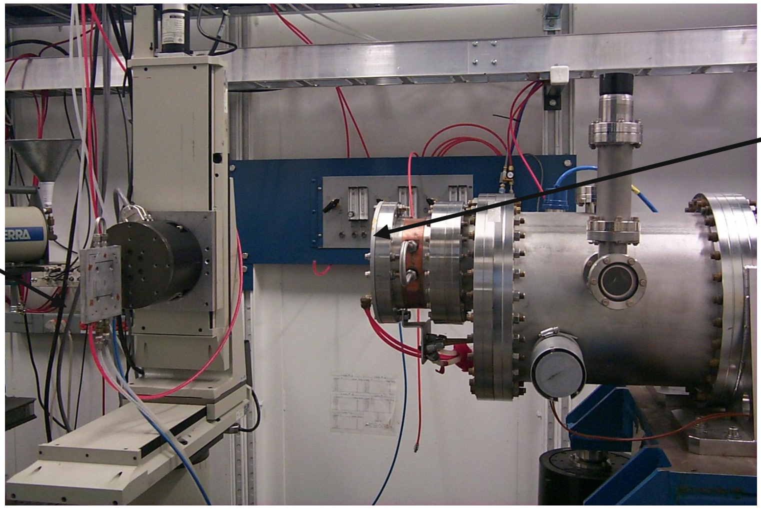
🟥 Copper base, 50-mm-thick

🟥 Copper plating

- SU-8 LIGA
  - An alternative to PMMA
  - For X-ray LIGA applications, it has a significant advantage:
    - *About 200 times more sensitive to X rays than PMMA*
    - *This drops exposure times by two orders of magnitude.*
    - *Disadvantage: The etchants that attack the exposed SU-8 also attack the metal surface of the LIGA part.*



X-ray Exposure Station at the Advanced Photon Source of Argonne National Laboratory


Scanner

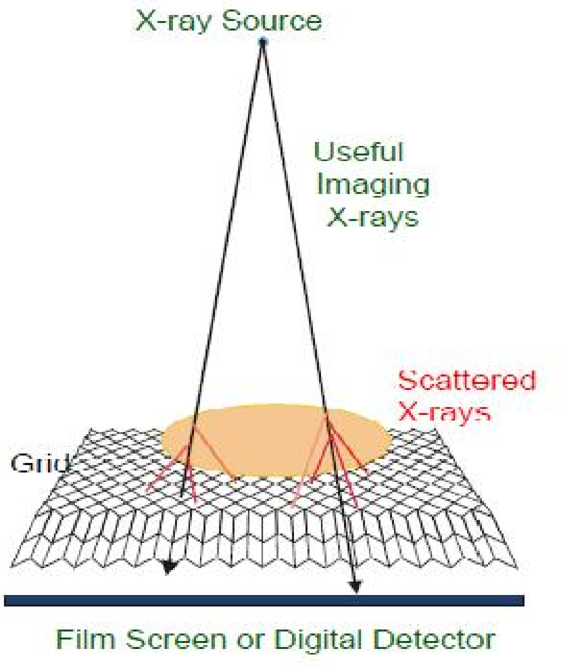
X-ray beam outlet

APS Lithography beamline:

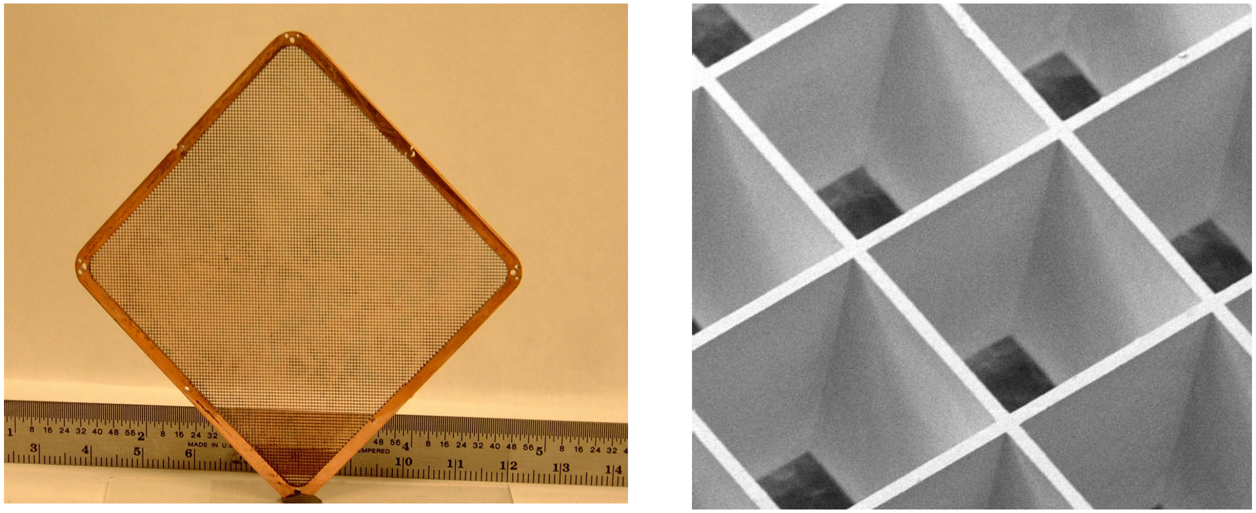
- 19.5 keV
- Highly collimated beam (< 0.1 mrad)
- Beam size @exposure station: 100 (H) x 5 (v) mm^2
- Using a high-speed scanner (100 mm/sec) for uniform exposure.
- Precision angular (~0.1 mrad) and positional (<1 micron) control of the sample.
- exposure time:
  - 1-mm thick PMMA (100 x 25 mm^2) ~1/2 hr
  - 10-mm thick PMMA ~ 2-3 hrs

Antiscatter Grid for Mammography

- Scatter
  - Produces slowly varying background fog
  - Reduces subject contrast
  - Reduces the ability to identify diseased tissues



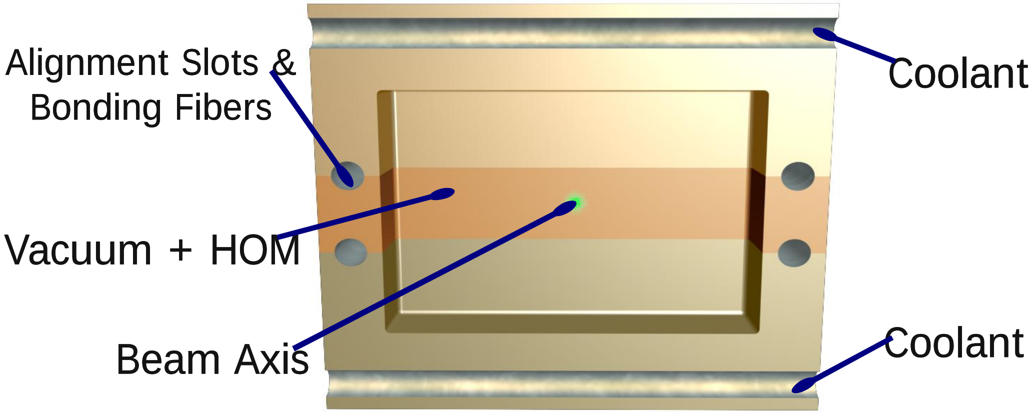

Detail of x-ray mask used for obtaining freestanding copper antiscatter grid

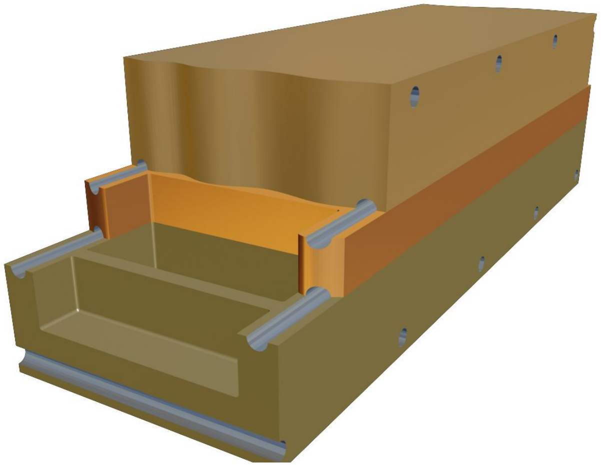

Freestanding focused to the point copper antiscatter grid 60 mm x 60 mm in size with 25-µm-wide septa walls and 550 µm period and 2.8 mm tall (grid ratio 5.3).

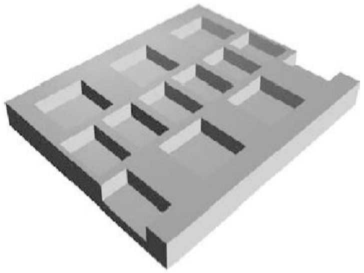
Unique benefits of ANL

- APS is one of the very few light sources worldwide suitable for micromechanics with a unique possibility of dynamic exposure for very tall (1-3mm) structures.
- Knowledgeable and experienced staff provides excellent user support.
- X-ray lithography station in Sector 10 is fully operational on a shared bend magnet beamline.
- Long experience in fabricating copper high-aspect ratio microstructures.

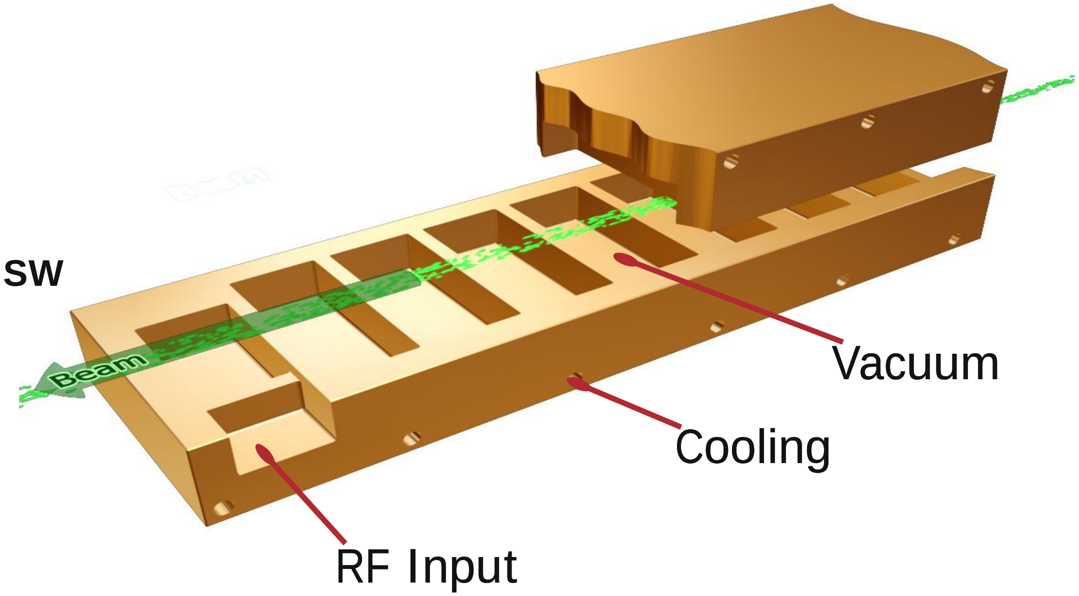
3-D Conceptual Planar Structure

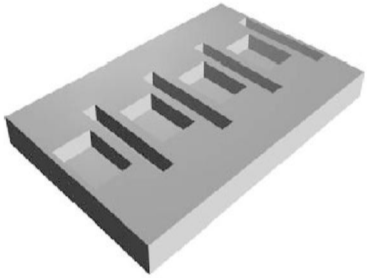






Lower half of a Side-coupled planar SW Structure

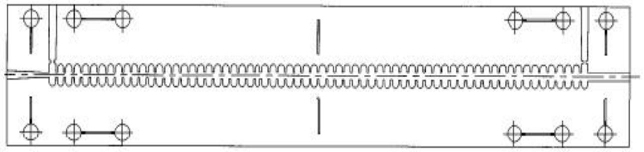


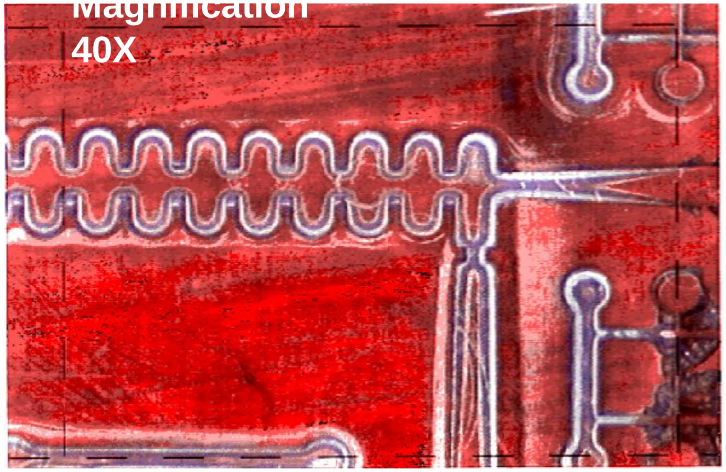


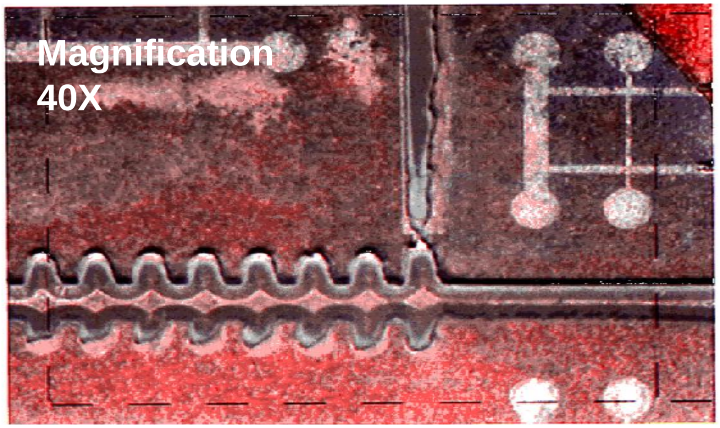
Lower half of an on-axis planar SW structure

PMMA Masks with DXRL: 94 GHz CG [1]

- Long structure (66 cells)







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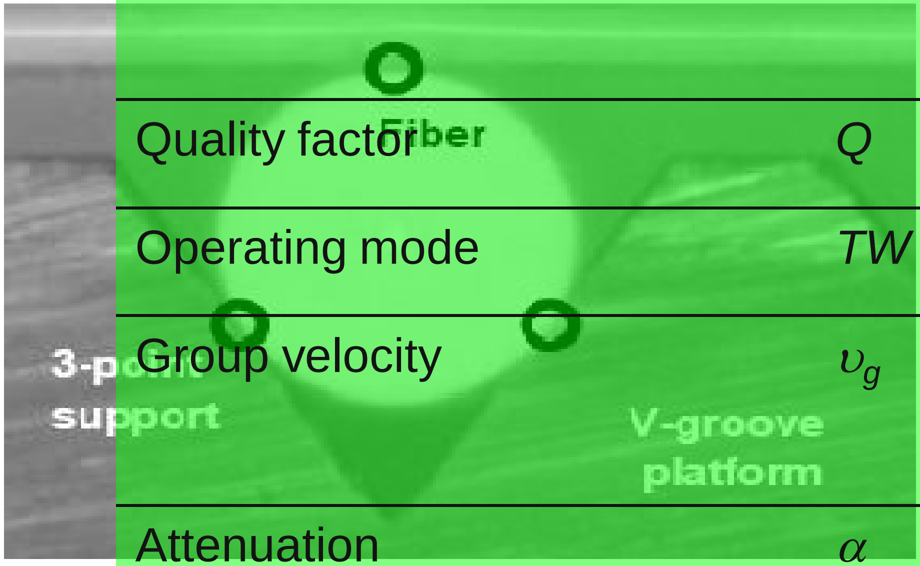
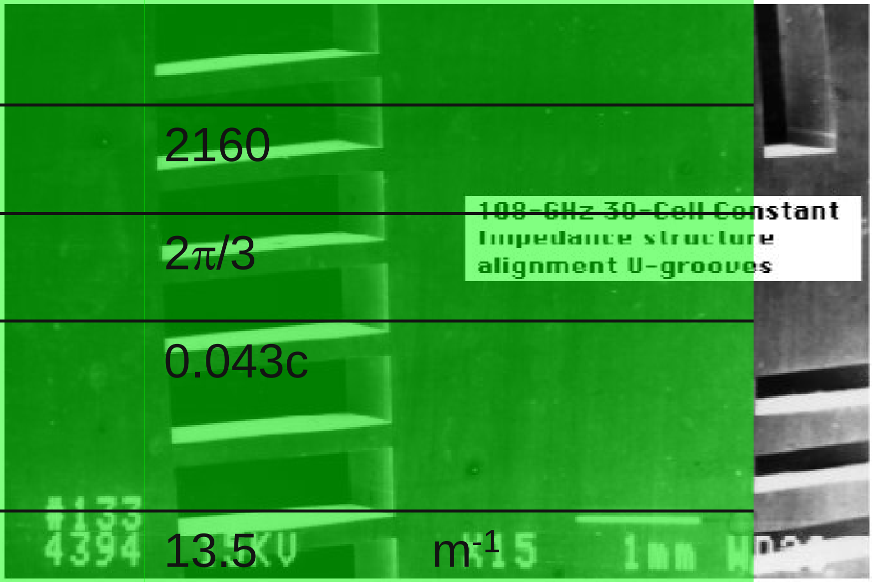
[1] **J. Song, at al., Proc. Particle Accel Conf., Vancouver, B.C., Canada, 1997**

Constant impedance cavity[1]

- High aspect ratio
- Surface roughness <50 nm
- High accuracy < 1 μm

Muffin-tin cavity RF parameters			
Frequency	f	120	GHz
Shunt impedance	R_0	312	MΩ/m
Quality factor	Q	2160	
Operating mode	TW	$2\pi/3$	
Group velocity	υ_g	0.043c	
Attenuation	α	13.5	m^{-1}
Accel. Gradient	E	10	MV/m
Peak power	P	30	kW





SEM image of 108-GHz CI structure.

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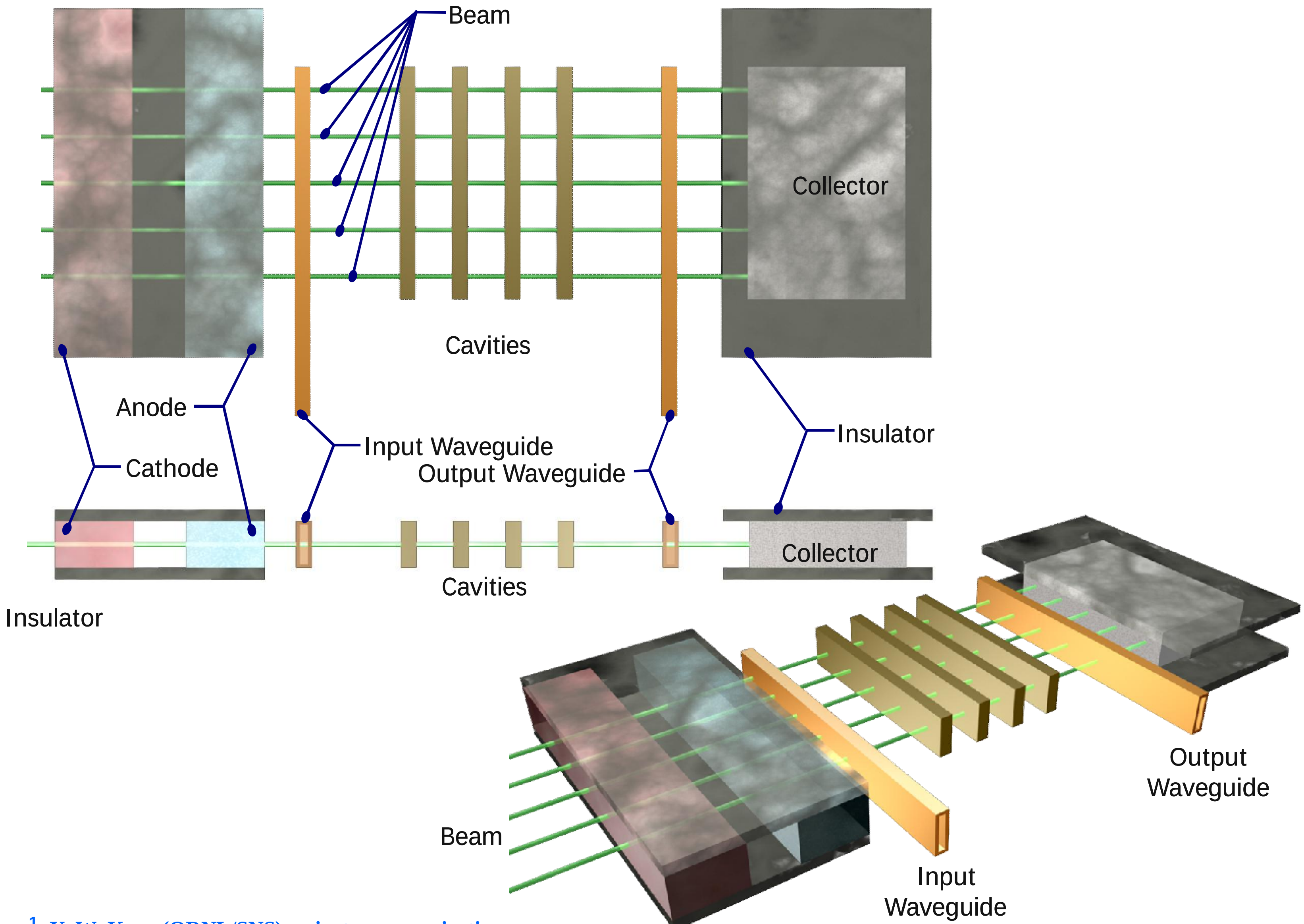
[1] A. Nassiri, at al., Proc. Int. Electron Devices Meeting, Washington, DC, December 1993

Multi-beam Planar Klystron[1]



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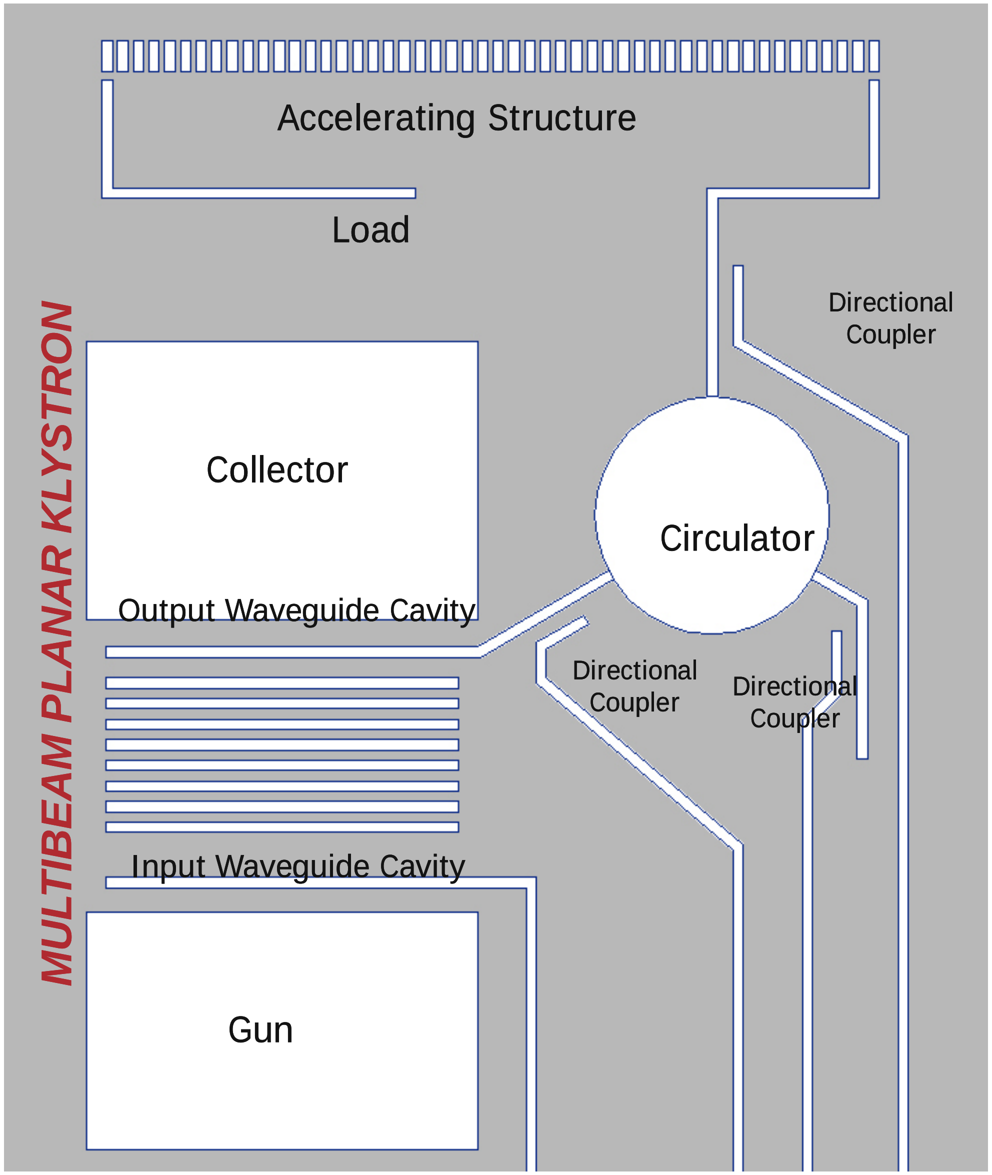
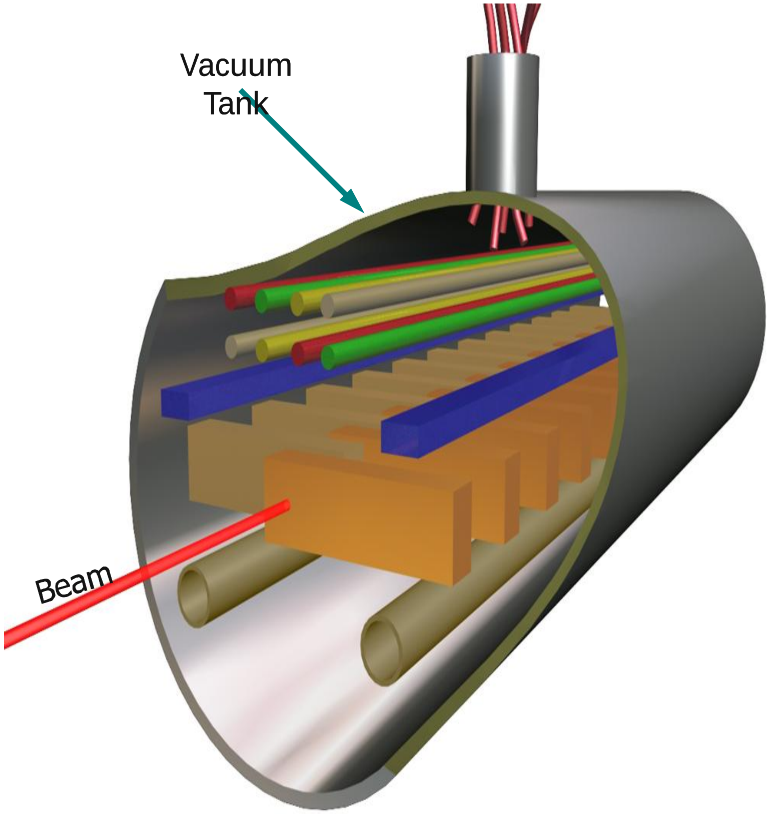
[1] **Y. W. Kang (ORNL/SNS): private communication**

Accelerator on a Substrate





Comparison of Microfabrication Methods for RF Structures

- Each fabrication method discussed has specific advantages for different materials and geometries.
- Normal machining can produce RF structures up to several hundred gigahertz as long as surface finish and consequent surface losses are not important.
- In resonant structures where surface losses drastically degrade the performance, normal machining is limited to less than 100-GHz structures.
- EDM has similar issues regarding surface losses
  - Can handle hard-to-machine materials. Only conductive materials
- LIGA is effective in a range of frequency defined by
  - Depth to which the photoresist can be exposed
    - *6-mm thick PMMA "routine"*
    - *10-mm thick PMMA soon*
  - Dimensional accuracy limits of the mask and the diffraction of the light source.
    - *Smallest lateral size is 0.2 μm.*
    - *Aspect ratios can range up to 500.*
    - *Surface roughness is small (~30 nm).*

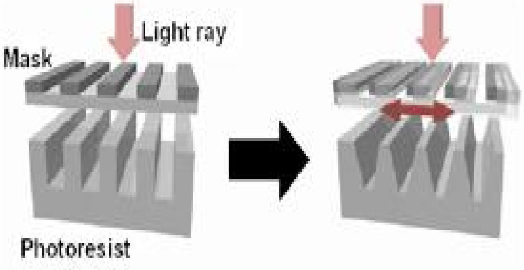
$$\boxed{f \geq 25\ \text{GHz}}$$

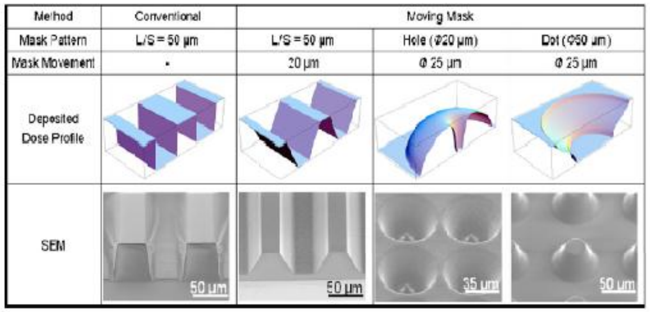
Characteristics of Microfabrication Methods

	Dimensional Accuracy (μm)	Surface Finish (nm)	Compatible Materials	Litho or Serial Process	Cost per Part	Frequency Range (GHz)
LIGA PMMA	±1	< 200	Metals	Litho	Low	25 - 600
LIGA SU-8	±1	< 200	Metals	Litho	Low	25 - 600
MEMS(WE)	±0.5	< 50	Silicon	Litho	Low	300-3000
MEMS (DRIE)	±0.5	< 50	Silicon	Litho	Low	300-3000
Laser ablation	±2	200-500	Almost any materials	Litho/Serial	High	100-300
EDM	±2	<1000	Conductors	Serial	High	0-300
Normal machining	±8	<1000	Almost any materials	Serial	Medium/High	0-100

Can a “true” 3D structure be realized?

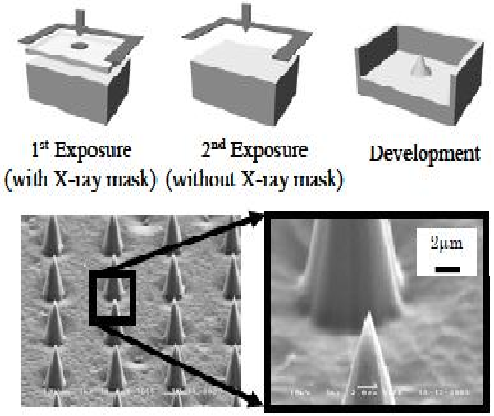
- As attractive DXRL is, it can only fabricate microstructures with vertical wall, which limits their application.
- Although 3D structures can be realized by various LIGA techniques, structures have walls parallel to the incident X-ray.
- To overcome these limitations with the conventional lithography techniques, Two recently new techniques have been developed:
  - A moving mask deep X-ray lithography (M^2DXL)[1].
    - *M^2DXL is a technique to fabricate microstructures with controllable inclined or curve wall.*
  - A double X-ray exposure technique[2]
    - *3D is realized by controlling the propagation direction of the PMMA dissolution front. This is achieved by irradiating the whole PMMA surface again without the X-ray mask after the first exposure.*





Method	Conventional	Moving Mask		
Mask Pattern	L/S = 50 µm	L/S = 50 µm	Hole (Ø20 µm)	Dot (Ø50 µm)
Mask Movement	-	20 µm	Ø 25 µm	Ø 25 µm
Deposited Dose Profile				
SEM	50 µm	50 µm	35 µm	50 µm

3D microstructure fabricated by moving mask UV lithography techniques.



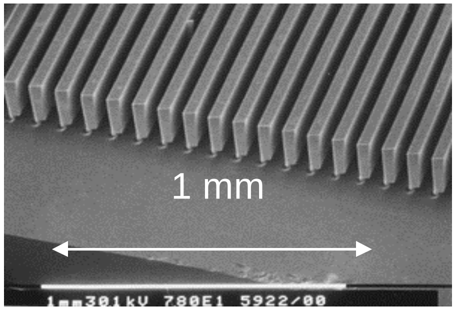
[1] Y. Hirai, et. al, J. Micromech. 17 (2007)

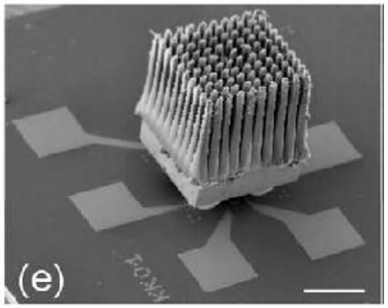
[2] N. Matsuzuka, et. al, 17th IEEE MEMS, 2004

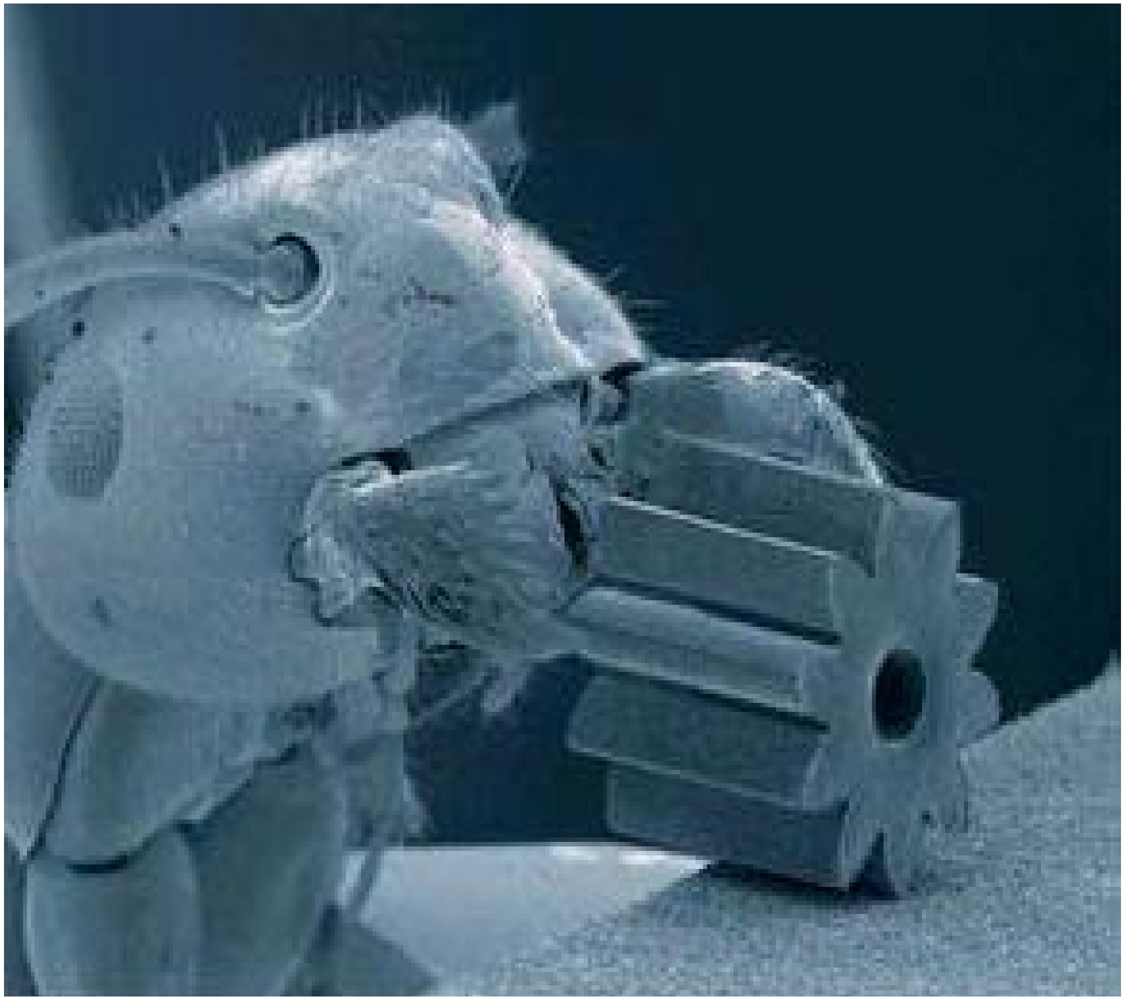
Summary

- Technology for a fully integrated design in not (yet) available and not likely in the near future.
- Hybrid design, ala hybrid integrated-electronic circuits, is closer to being available, requires considerable R&D.
- Fabrication challenges of RF structures and circuits
  - Vacuum-sealing and vacuum pumping of circuit with sub-millimeter beam apertures
  - RF losses due to surface roughness
    - *δ = 200 nm @95 GHZ and 66 nm@1THz for copper*
    - *Need surface roughness less that the skin depth*
  - Dimensional accuracy of cavities/circuits and alignment
    - *Dimensional accuracy required $\propto$ 1/BW*
  - Beam transport and magnetic focusing
  - Heat transfer and structure cooling (microchannel/ nanotubes)
    - *CW and pulse heating*

Microchannel array formed by silicon DRIE







Thank you.