Development of Hybrid “Fluid Jet / Float” Polishing Process

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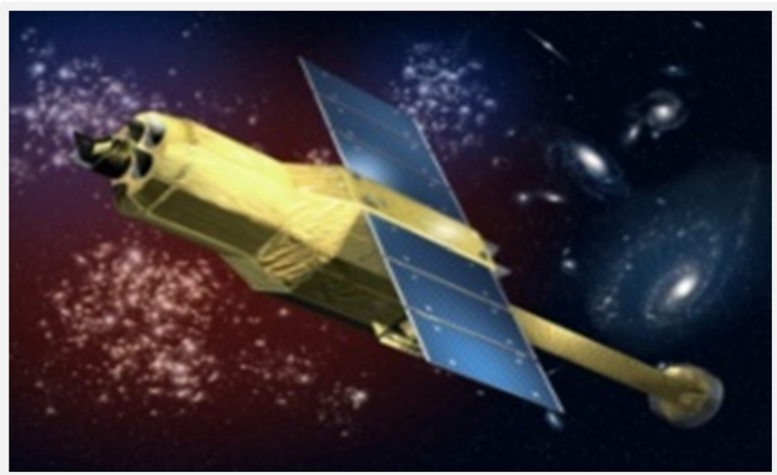


Research supported by Japan Society for Promotion of Science

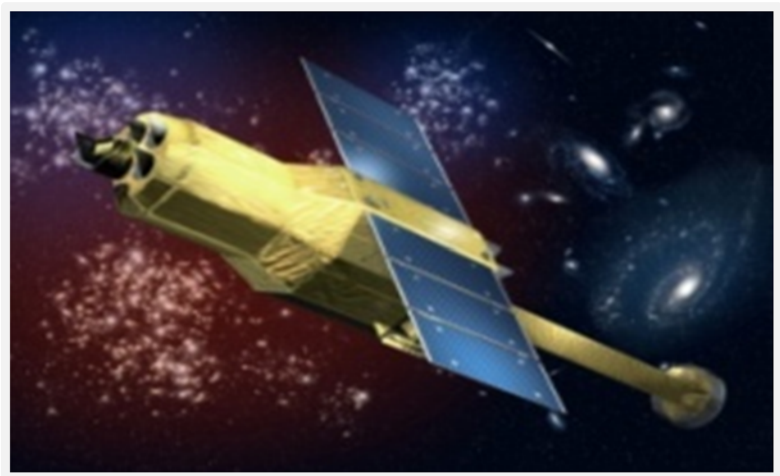
Outline

1. **Background Information**
   (X-ray telescopes, Thin mirror replication methods,
   Fluid Jet Technology)

2. **Modeling and Optimization of Fluid Jet Polishing**
   (Numerical Method, Optimization Method,
   Experimental Results)

3. **Hybridization of Float and Fluid Jet Polishing**
   (Rationale for research, Scalability of FJP,
   Float polishing, Hybridization)

4. **Conclusions**



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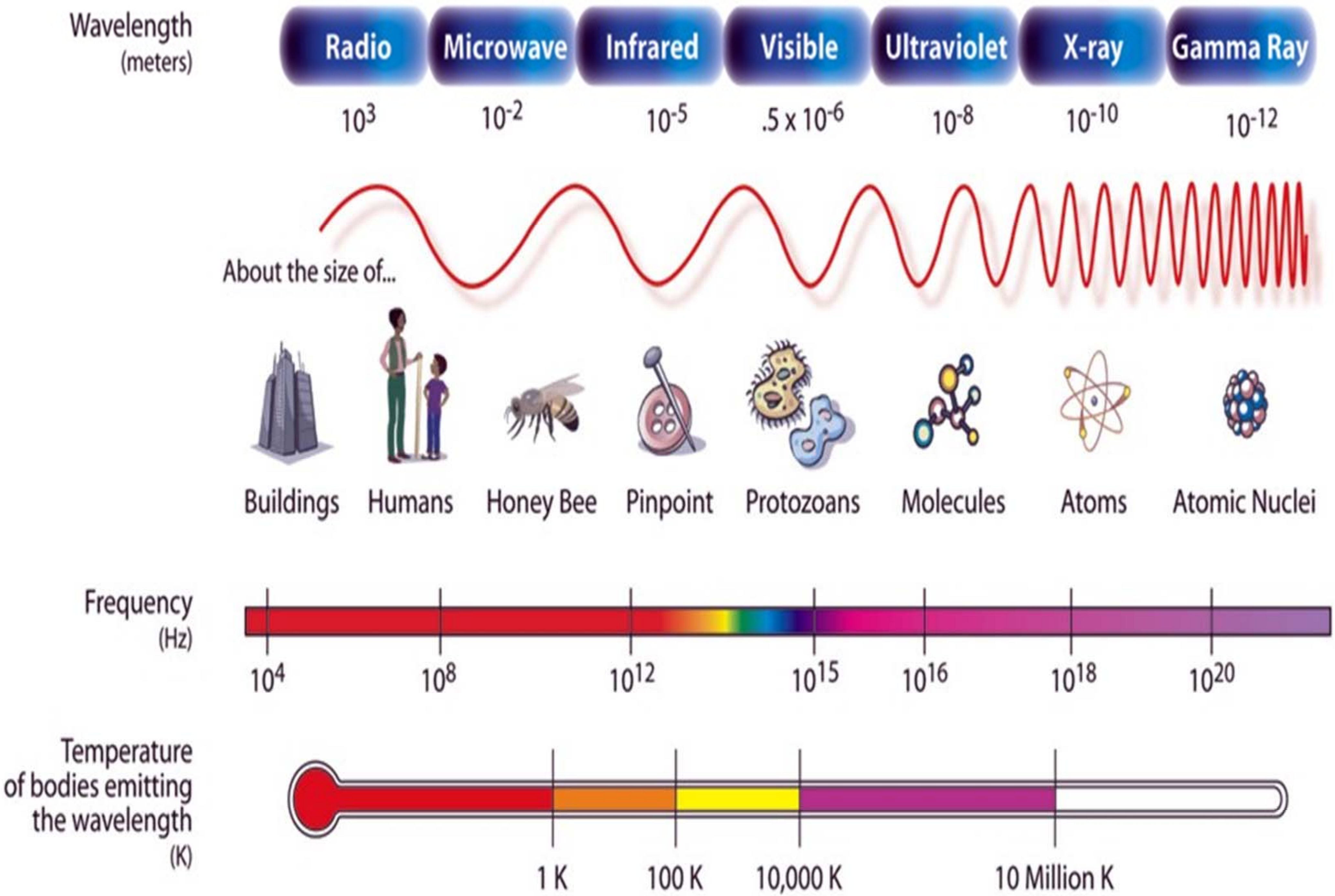
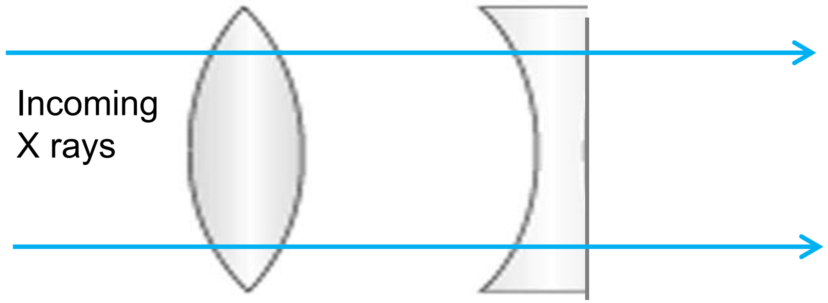
Background: Short story of X-ray space telescopes

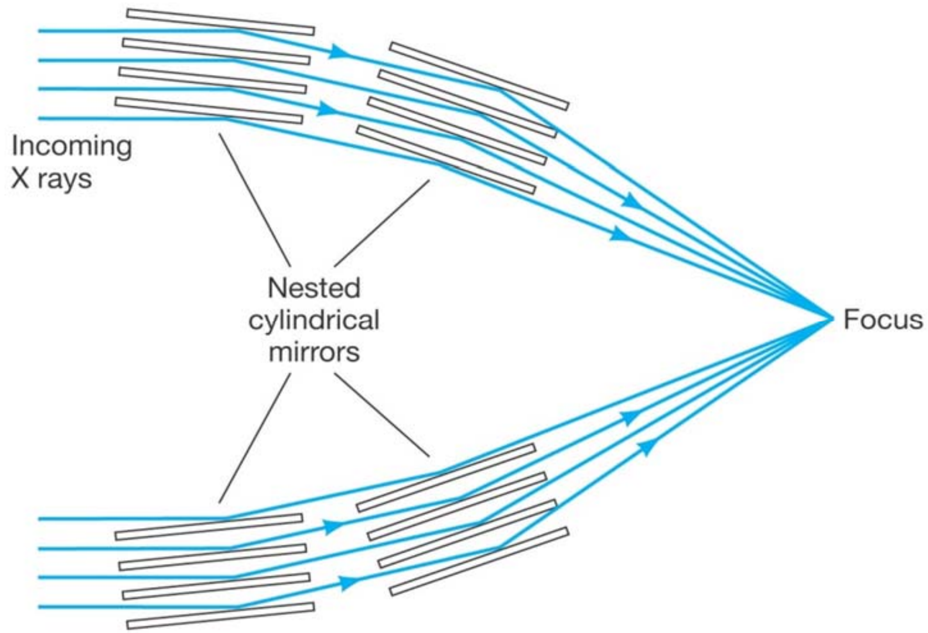


X-ray Astronomy: Making an X-ray Telescope.

- Standard lenses and mirrors cannot be used, because X-rays are not reflected/refracted!

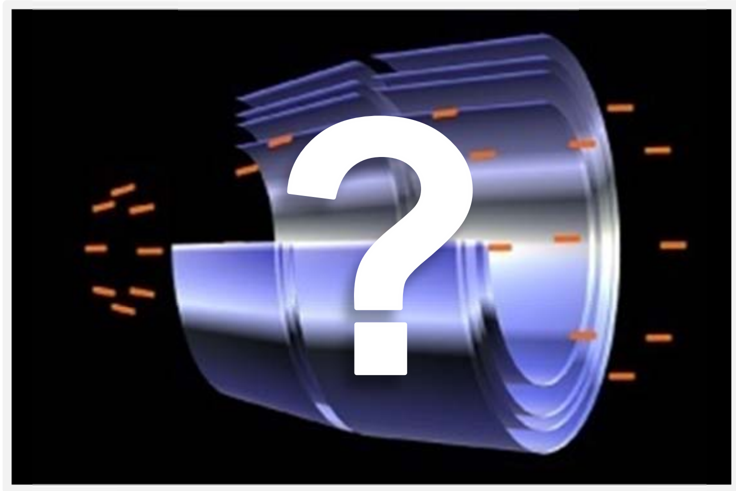


- But if the angle is very small, then X-rays can be reflected: it is called "Grazing Incidence".



Motivation for future "Aspheric" X-ray Telescopes

Goal: ~2020



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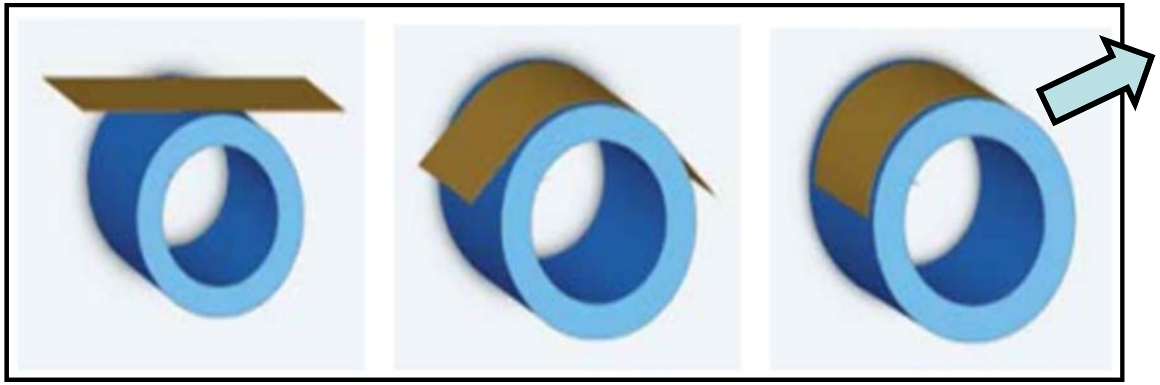
<u>Fabrication Method</u>

Slumping thin glass over molding dies



<u>Objectives</u>

- Obtain Molding Die Micro-Roughness **<0.2nm rms**.
- Reduce manufacturing cost per mold!
  (modern telescope requires > 200 molds)

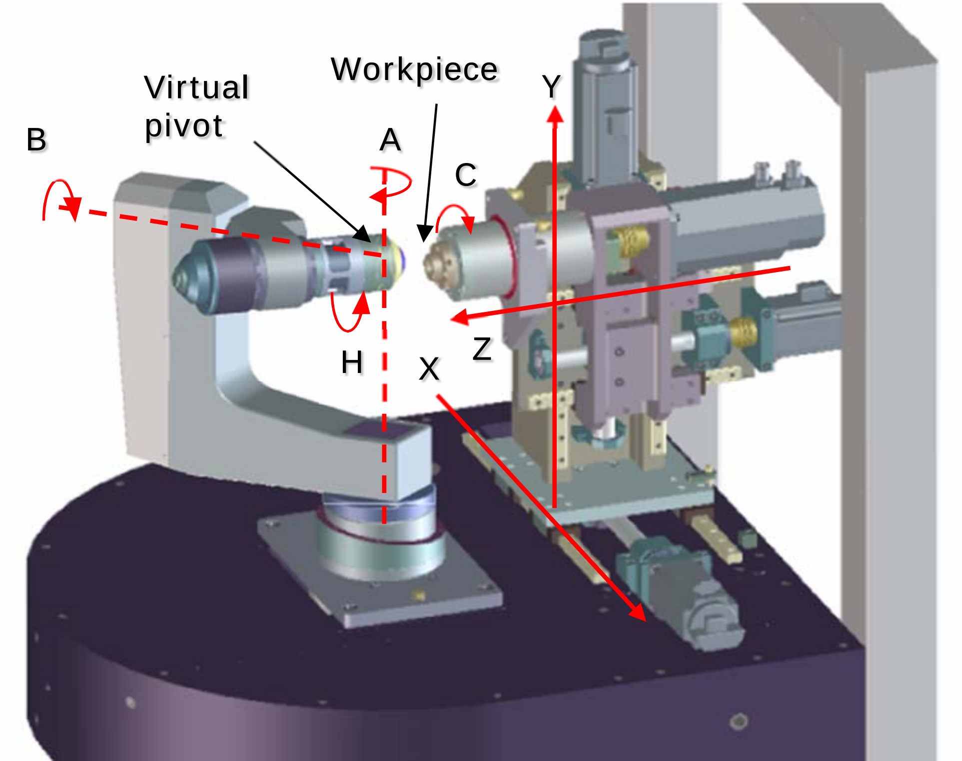
Background: Principle of Fluid Jet Polishing

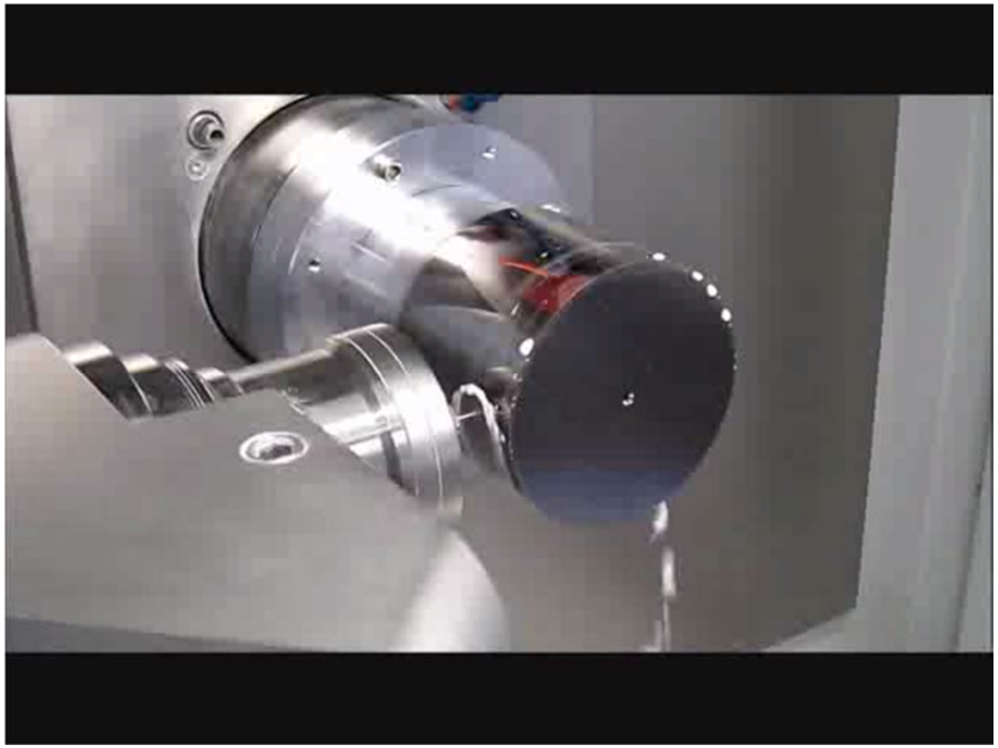
- A pumping system is used to deliver abrasive slurry to a nozzle pointing at the work-piece.
- The jet impinges the surface, generating a polishing spot where material removal occurs.
- This spot is moved along a spiral of raster path.

Typical Parameters:

Pressure at nozzle: 4 ~ 20 Bar
Abrasives type: CeO_2, Al_2O_3, SiC

Nozzle diameter: 0.1 ~ 2.0 mm
Abrasives grit: 0.2 ~ 50 μm





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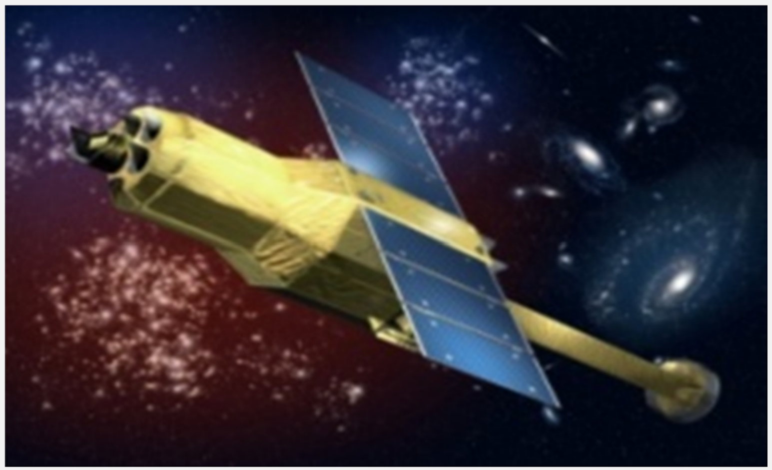

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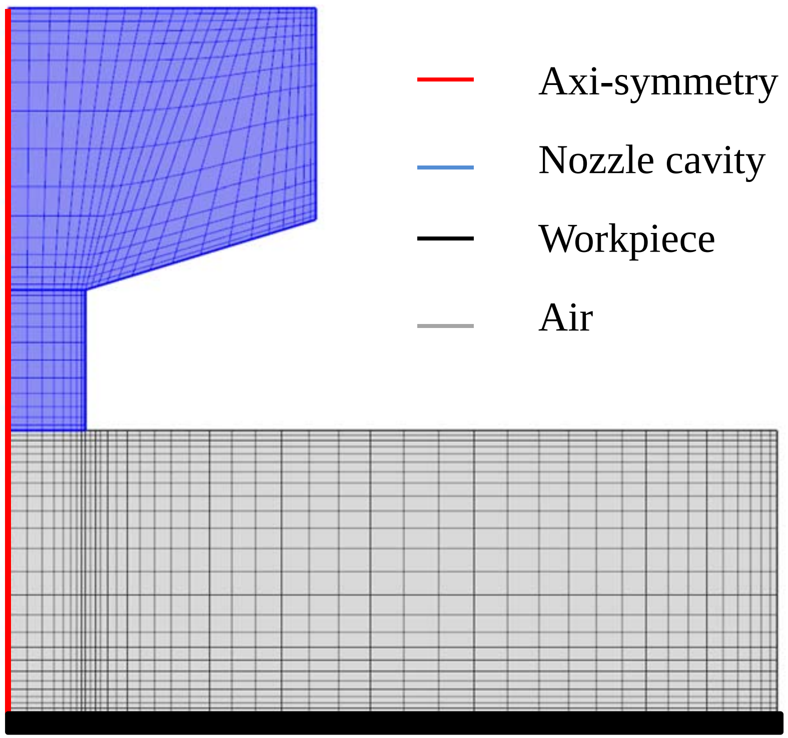
2. Modeling of Process: Computational Fluid Dynamics

The simulation consists of a jet steam impinging a flat surface along the local normal:

- Features axial-symmetry, offering the possibility to simplify to a 2D problem.
- Experimental conditions can be easily reproduced in laboratory (bottom-right).



2. Modeling of Process: Multi-Phase Flow Equations

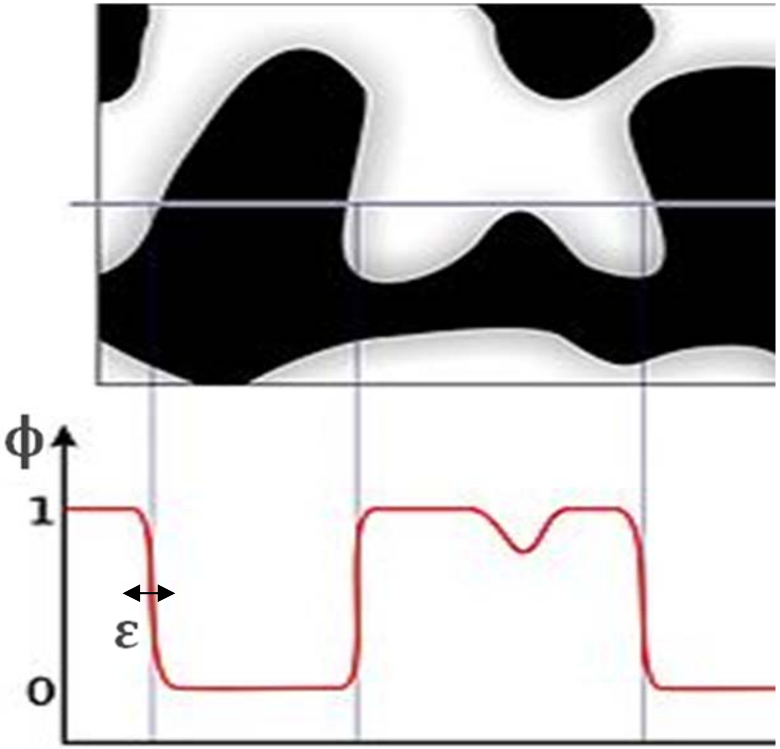
(1) Incompressible Navier-Stokes equation (low pressure, stable temperature):

$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{Unsteady acceleration}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\text{Convective acceleration}}\Big)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\text{Pressure gradient}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\text{Other body forces}}.$$

v (m/s) the fluid velocity field
μ (Pa.s) the fluid viscosity
p (Pa) the fluid pressure
F (N) are external forces
ρ (kg/m3) the fluid density

(2) Slurry/Air interface defined such that:

$$\rho = \rho_{air} + \phi\,(\rho_{slurry} - \rho_{air})$$
$$\mu = \mu_{air} + \phi\,(\mu_{slurry} - \mu_{air})$$



> Evolution of Φ governed by Cahn-Hilliard:

$$\frac{\partial \phi}{\partial t} + (\mathbf{v}.\nabla)\phi = \nabla.\gamma\nabla G$$

G (Pa) chemical potential of system
γ (-) mobility parameter (controls relaxation time)

> G is derived from Ginzburg-Landau equation:

$$G = \lambda\left[-\nabla^2\phi + \frac{\phi(\phi^2 - 1)}{\varepsilon^2}\right]$$

λ (N) is the mixing energy density ~ surface tension
ε (m) arbitrary capillary width

2. Modeling of Process: Turbulent Flow Model

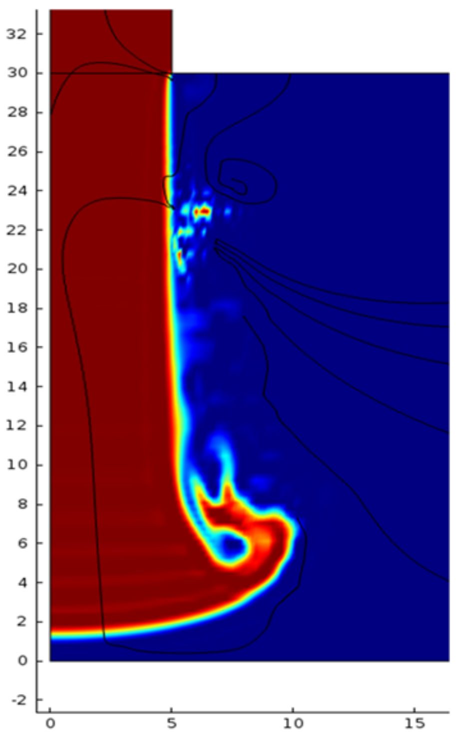
Model Name	***k-ε***	***k-ω***	**SST *k-ω***
(short) Description	2 transport equations • turbulent kinetic energy ***k*** • turbulent dissipation ***ε***	2 transport equations • turbulent kinetic energy ***k*** • turbulent frequency ***ω***	Combination of: • ***k-ω*** in near wall regions • ***k-ε*** in free stream regions
Pros / Cons	+ Numerically robust - Valid only if flow is fully turbulent - Poor results against severe pressure gradients	+ Superior treatment of near wall regions + Suitable against severe pressure gradients - Flow separation can occur excessively in free stream regions	+ Well suited for laminar to turbulent flow transitions - Less suitable for free shear flow regions

2. Modeling of Process: Numerical Stability

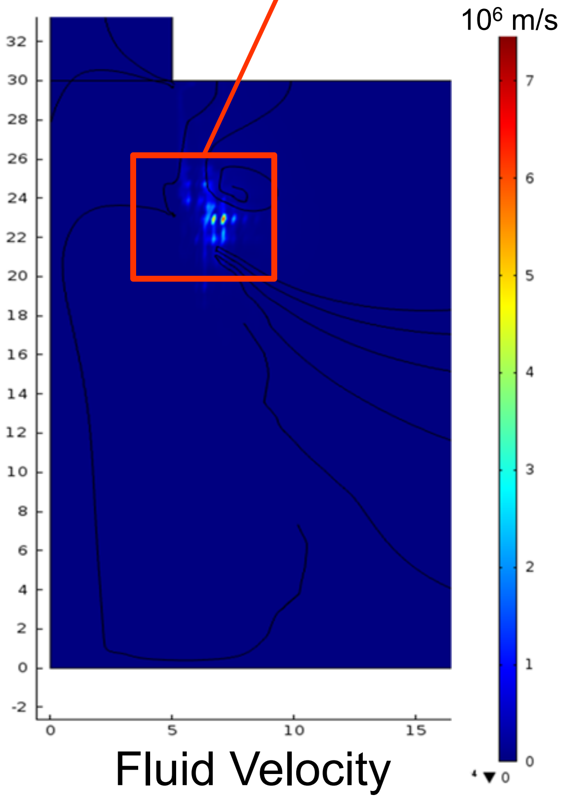
Balancing the “PDE terms” is sometimes necessary, to avoid numerical instability.

Example: “Run-away Vortices” may arise if viscosity and pressure gradient are not balanced within the stress divergence term. Defining a “transient” viscosity can solve such problem.

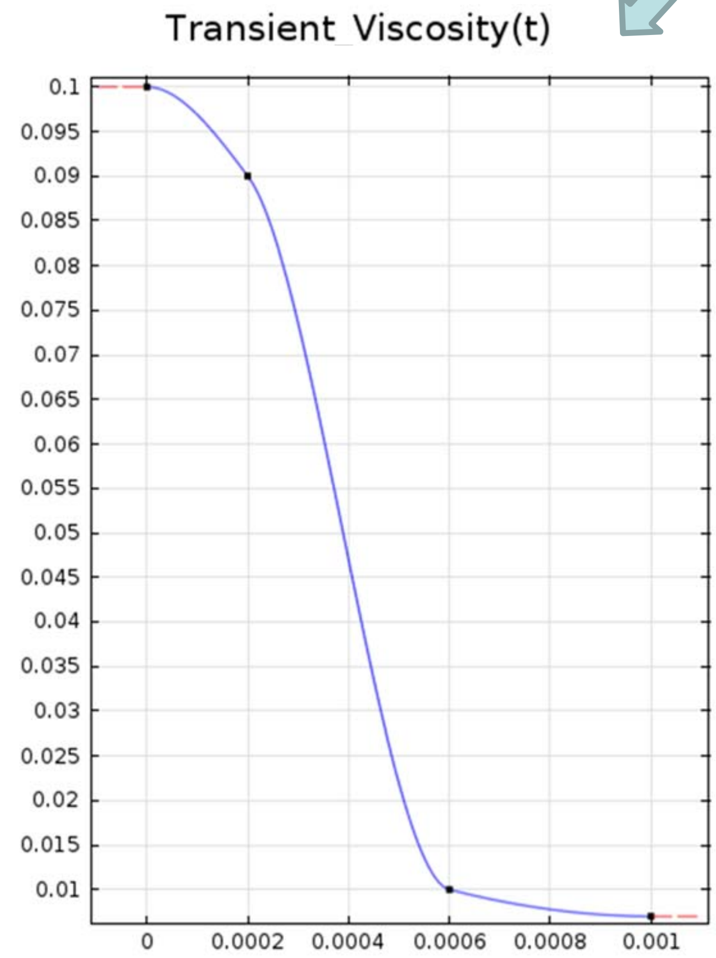
$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\substack{\text{Unsteady}\\ \text{acceleration}}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\substack{\text{Convective}\\ \text{acceleration}}}\Big)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\substack{\text{Pressure}\\ \text{gradient}}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\substack{\text{Other}\\ \text{body}\\ \text{forces}}}.$$



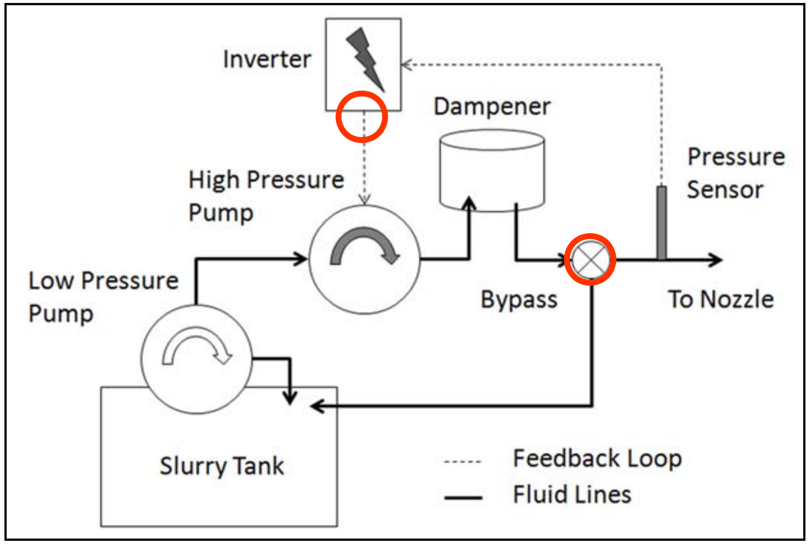
Volume Fraction (slurry)



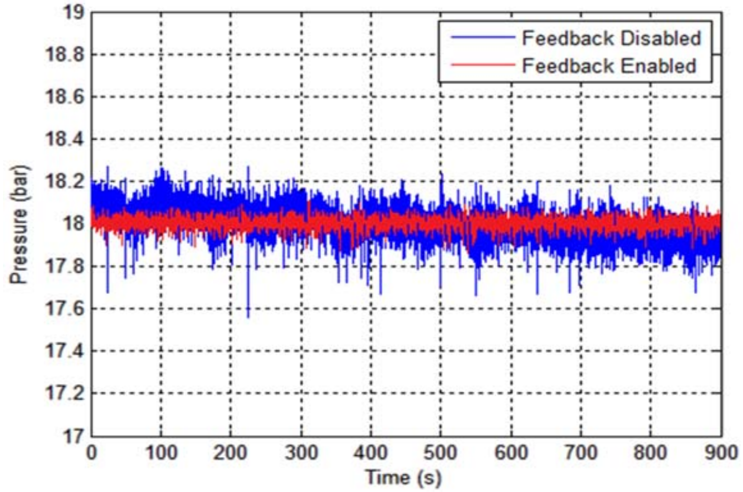
Fluid Velocity



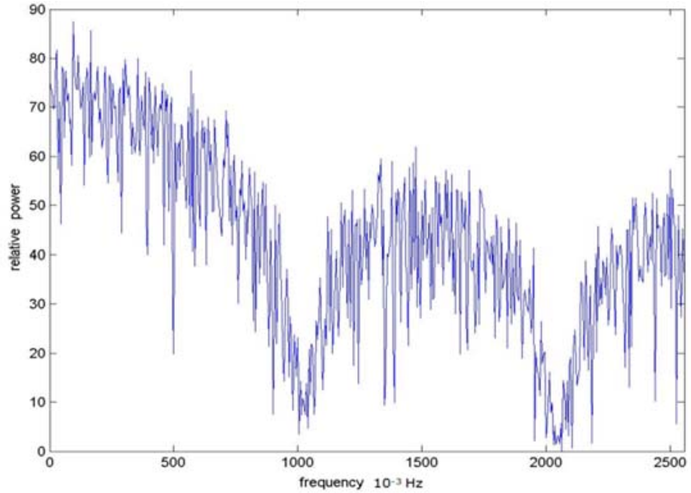
3. Optimization of Process: Slurry management system



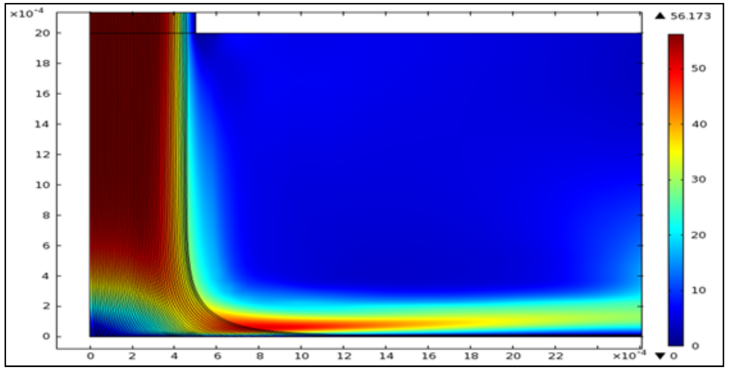
Live Pressure Logging



Fourier Analysis



Simulate Time Series



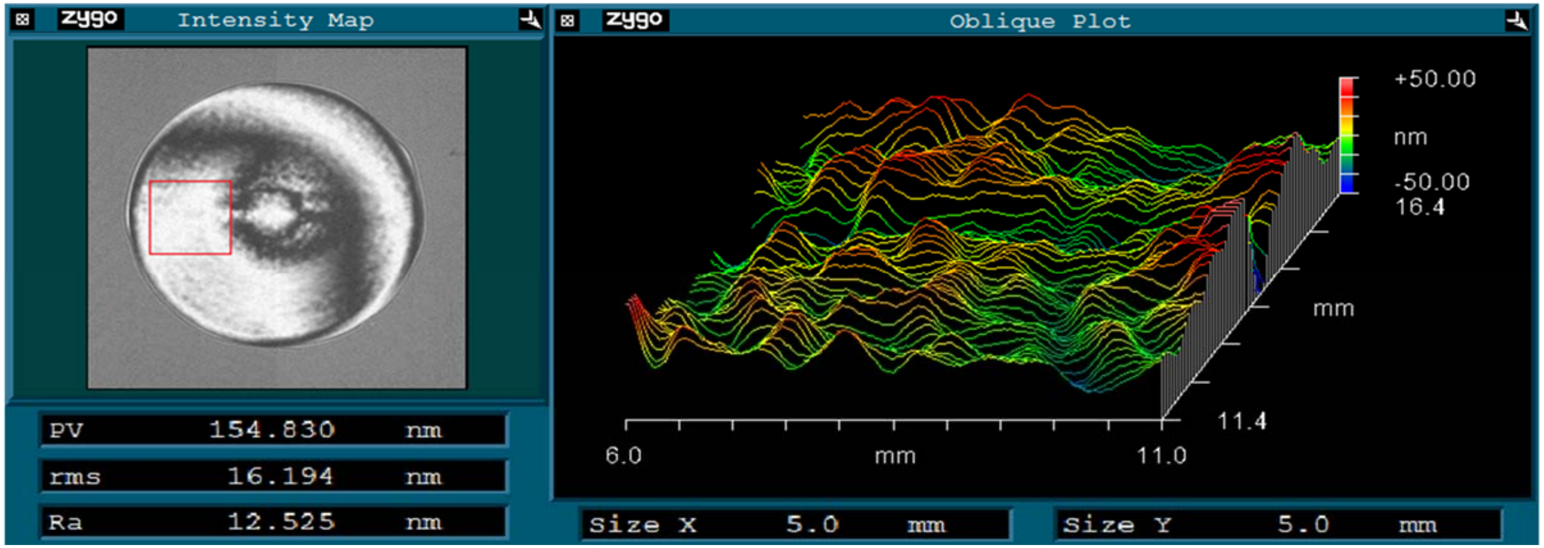
$$W(params\{u',v'\}) = \sqrt{\sum_{u}\sum_{v}\left(\sum_{\{u',v'\}} Influence(params\{u',v'\})\right)}$$

Adjust System Parameters

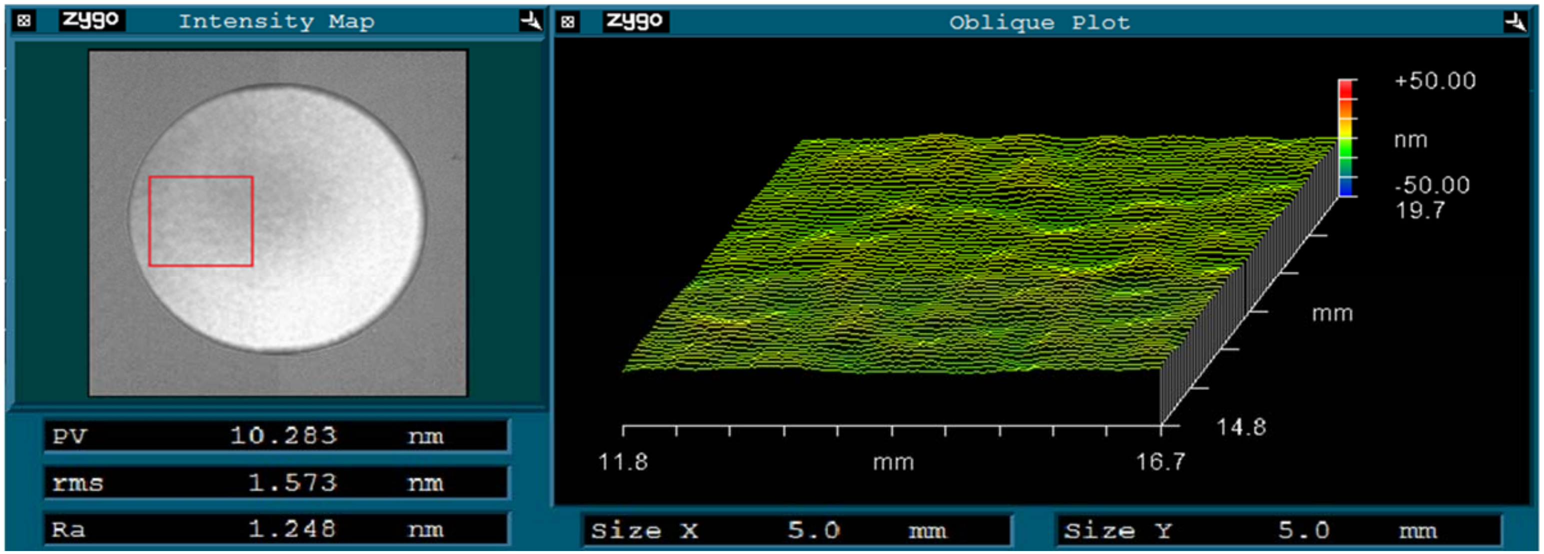
Fluid Jet Polishing: Waviness Improvement from Process Optimization

Post-polishing of “laser grade” fused silica windows, with 1.5um CeO_2 (1µm removal depth).

Before
Optimization
rms 16.1 nm



After
Optimization
rms 1.5 nm



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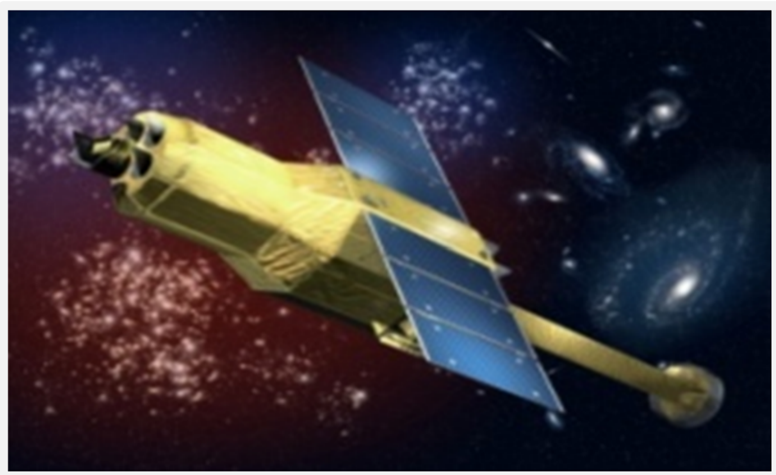

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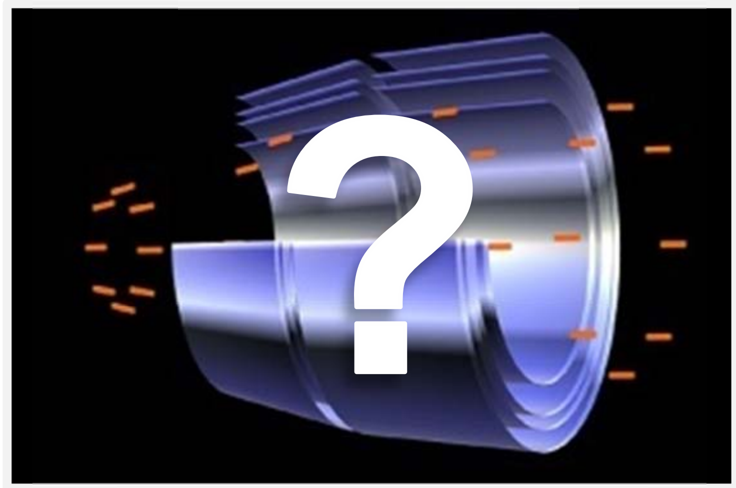
Motivation for future "Aspheric" X-ray Telescopes

Goal: ~2020



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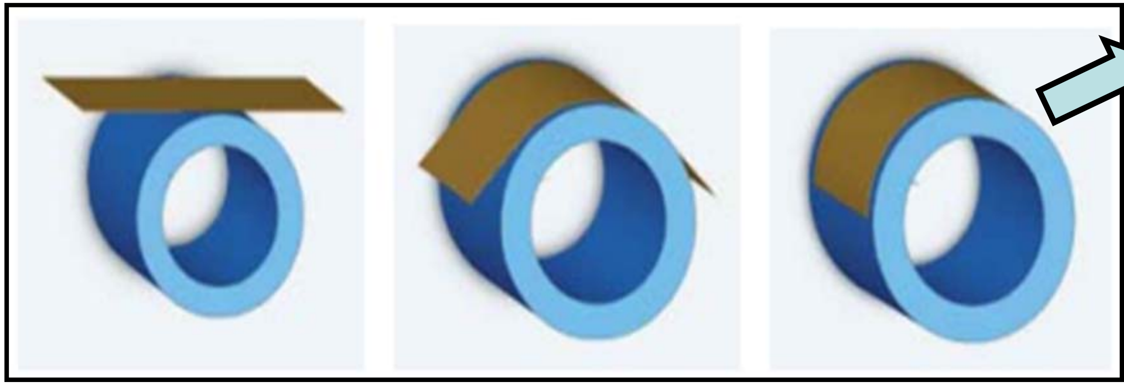

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- Reduce manufacturing cost per mold!

  (modern telescope requires > 200 molds)

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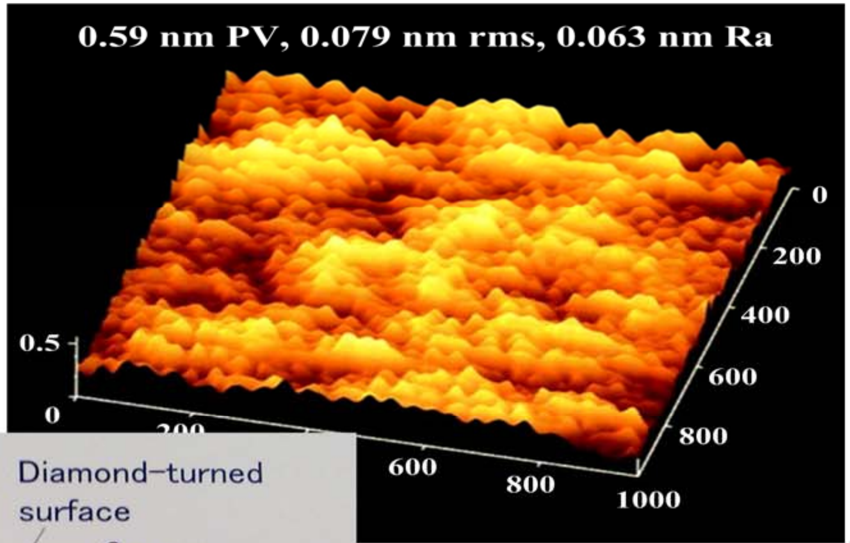
Hybrid Strategy: Float Polishing

Float polishing is a non-contact finishing method (like FJP!)

Roughness < 0.1nm rms routinely achieved (Fused Silica, Silicon, Elct. Nickel)

BUT, it is applicable only to Flat Surfaces.



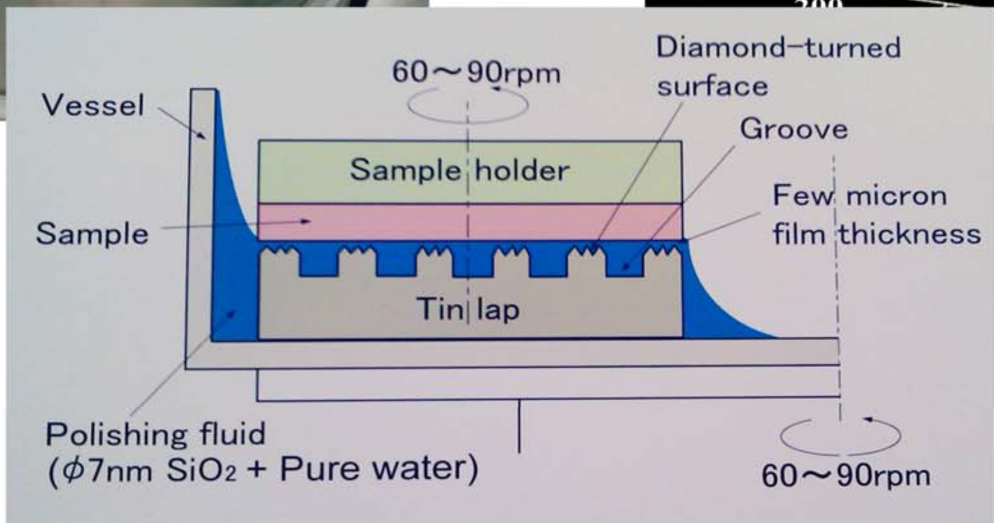


図 フロート・ポリシングの原理

Hybrid Strategy: Research Plan (2 year Post-Doc funded by JSPS)

Float Polishing

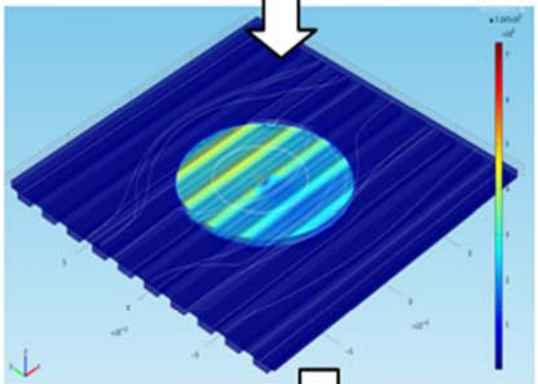
\+ Final roughness (0.1nm rms or less)

– Only flat surfaces

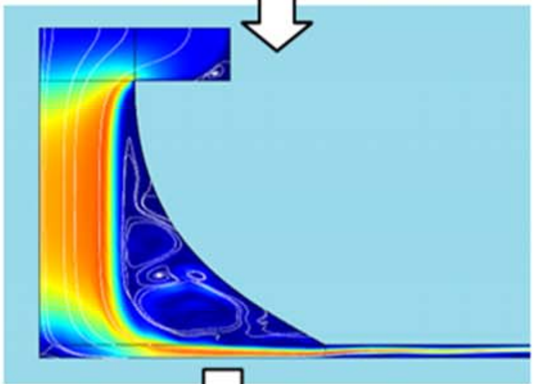
Fluid Jet Polishing

– Final roughness (1.0 nm rms or less)

\+ Any freeform shape



Computational Fluid Dynamics + Experimental Validation



New "Hybrid" Process

\+ Final roughness (0.1nm rms or less)

\+ Any freeform shape

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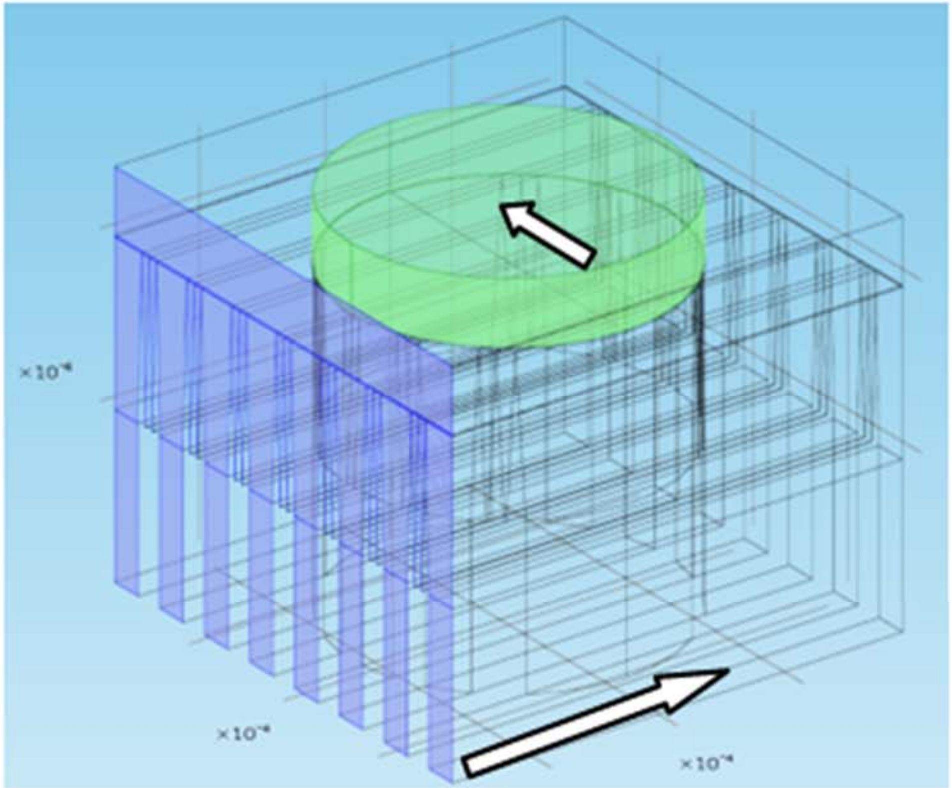
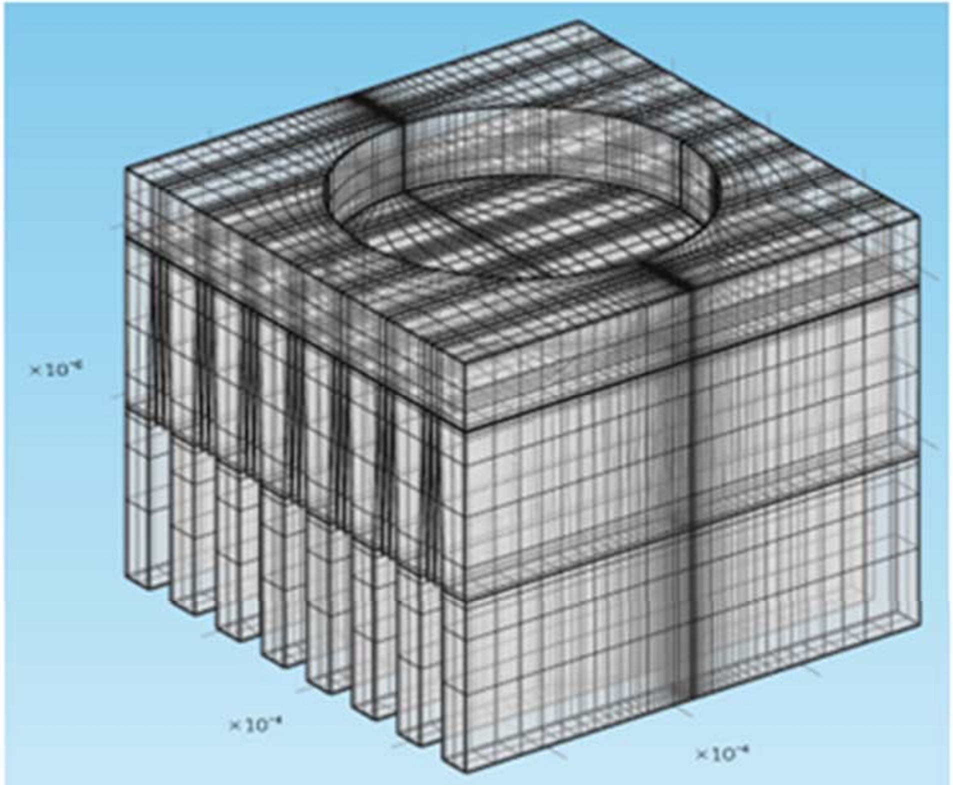
Modeling: Float Polishing Process

First, a 3D Computational Fluid Dynamics (CFD) model of float polishing was implemented.

The Navier-Stokes equation with Shear Stress Transport (SST) turbulence was used to compute fluid pressure/velocity.



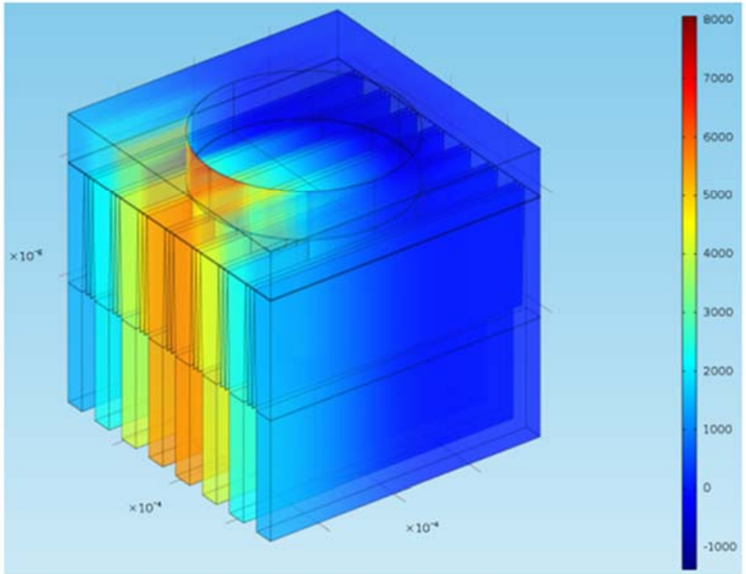
Fluid shown in Blue, Sample in Green



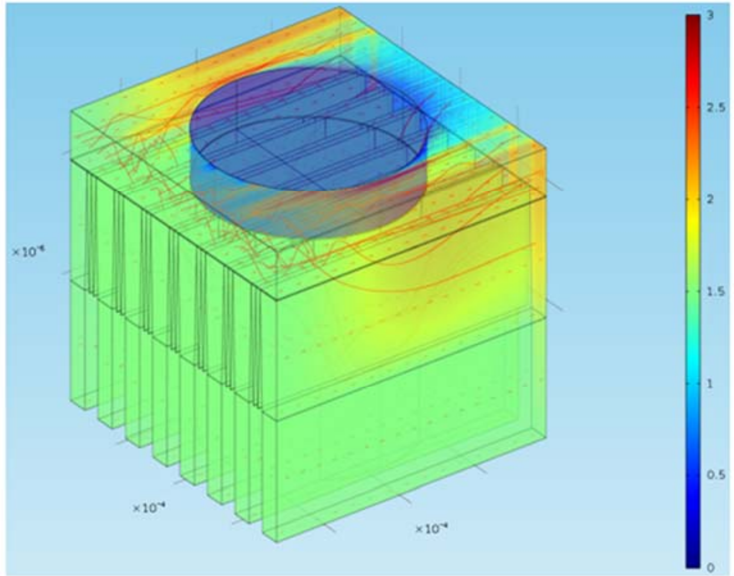
3D Finite Element Mesh

Modeling: Float Polishing Process

Actual abrasive particle trajectories (and impacts) were calculated by applying Newton's 2nd law.

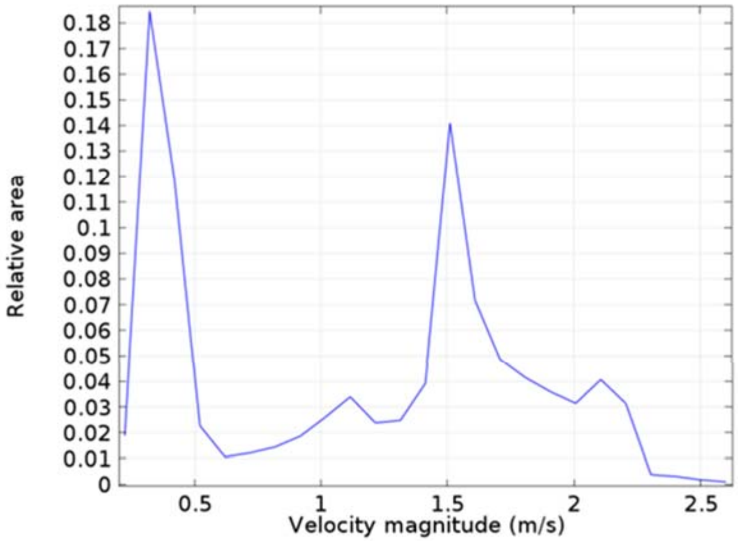


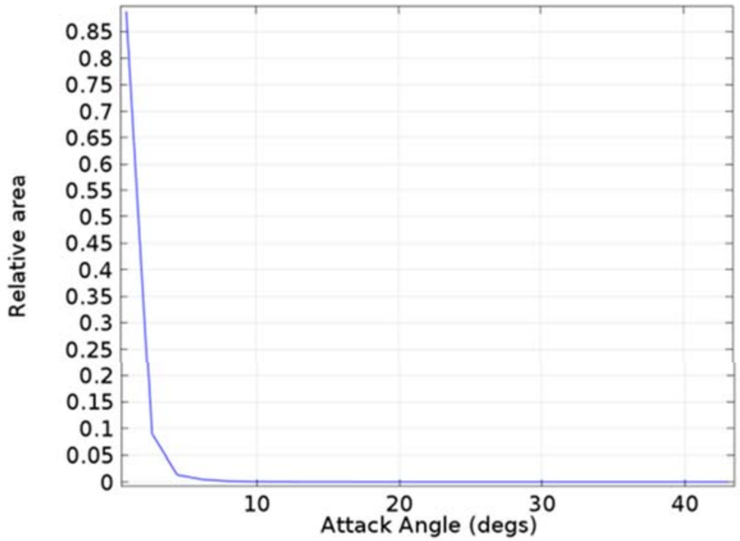
Fluid Pressure Map



Fluid Velocity Map & Particle Trajectories

Finally, distribution curves of <u>impact velocity</u> and <u>attack angle</u> were computed.

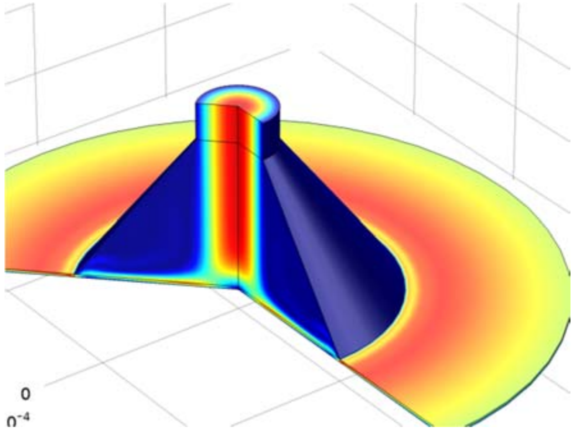




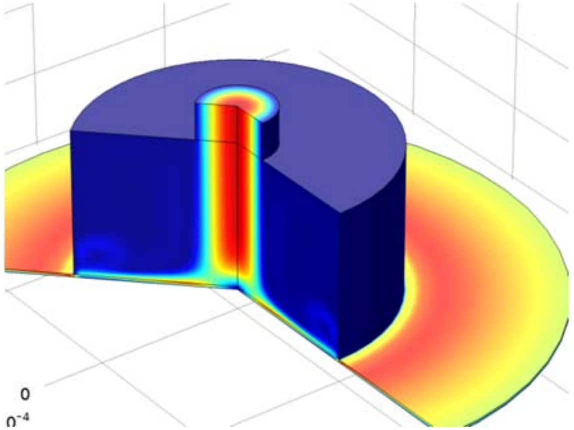
Target For Hybrid

Modeling: Fluid Jet Cavity Simulations

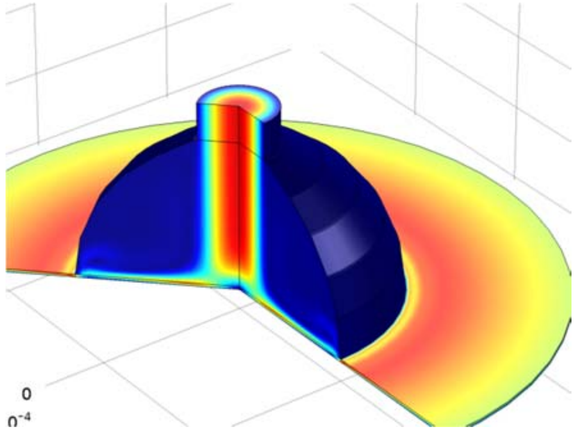
Different Nozzle Cavity Geometries were simulated, from simple geometries (cone, cylinder, sphere) to more complex ones (horn, grooved).



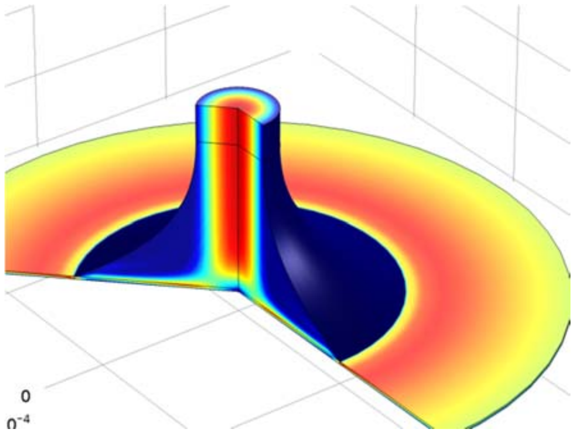
Cone Cavity



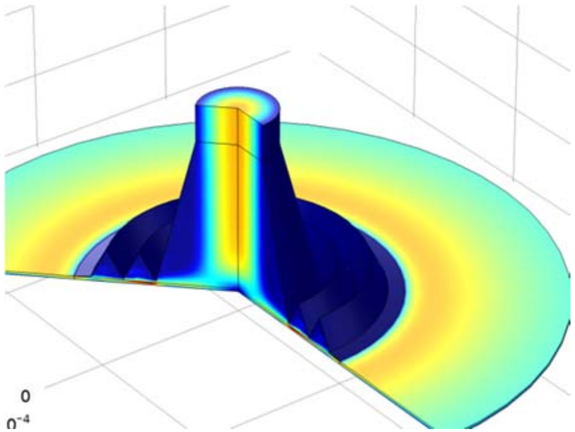
Cylinder Cavity



Sphere Cavity



Horn Cavity*



Grooved Cavity

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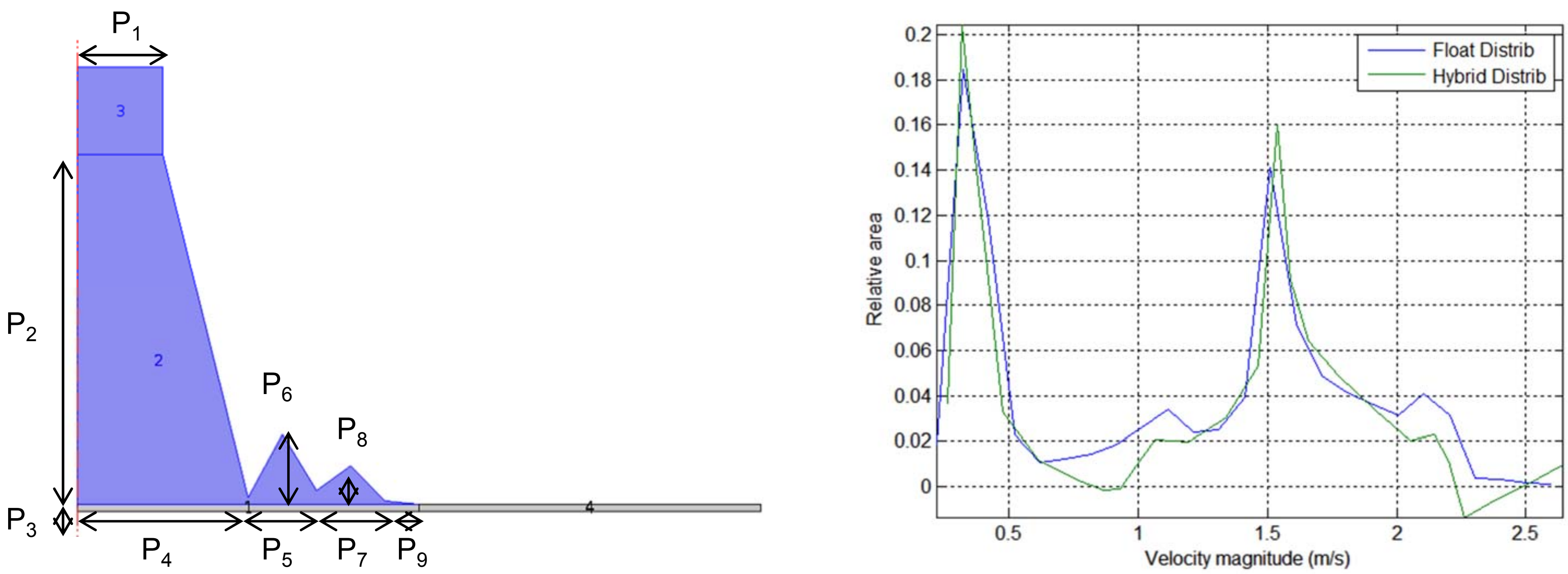
Modeling: Nozzle Cavity Optimization

For each cavity type, the geometry was parameterized such that CFD simulations and computation of Impact Distribution Curves could be automated.

Optimization consisted of parametric searches to find the best match between each cavity type and the float polishing process (comparison of Distribution curves).

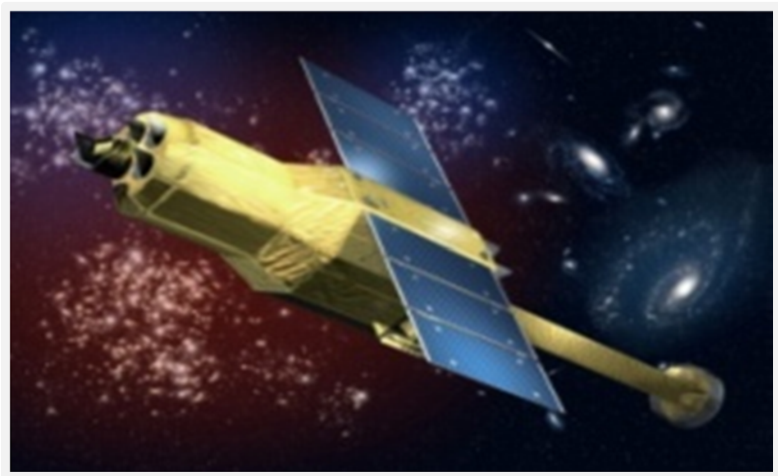
$$Cost(P_1, \ldots, P_n) = \sum_{Vel,Att} Distrib_{Float}(Vel, Att) - Distrib_{FJP(P_1,\ldots,P_n)}(Vel, Att)$$



Optimized design (Grooved cavity with variable pitch/depth)

Conclusions

- Our goal is to keep improving the roughness of Fluid Jet Polishing (currently 1.5nm rms, target < 0.2nm rms).
- A novel Hybrid “FJP/Float” process has been proposed to meet this requirement.
- Numerical simulations were used to derive a FJP cavity nozzle design that approaches removal conditions in Float polishing.
- **Future work**: Experimental validation of the optimized nozzle cavity design



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