

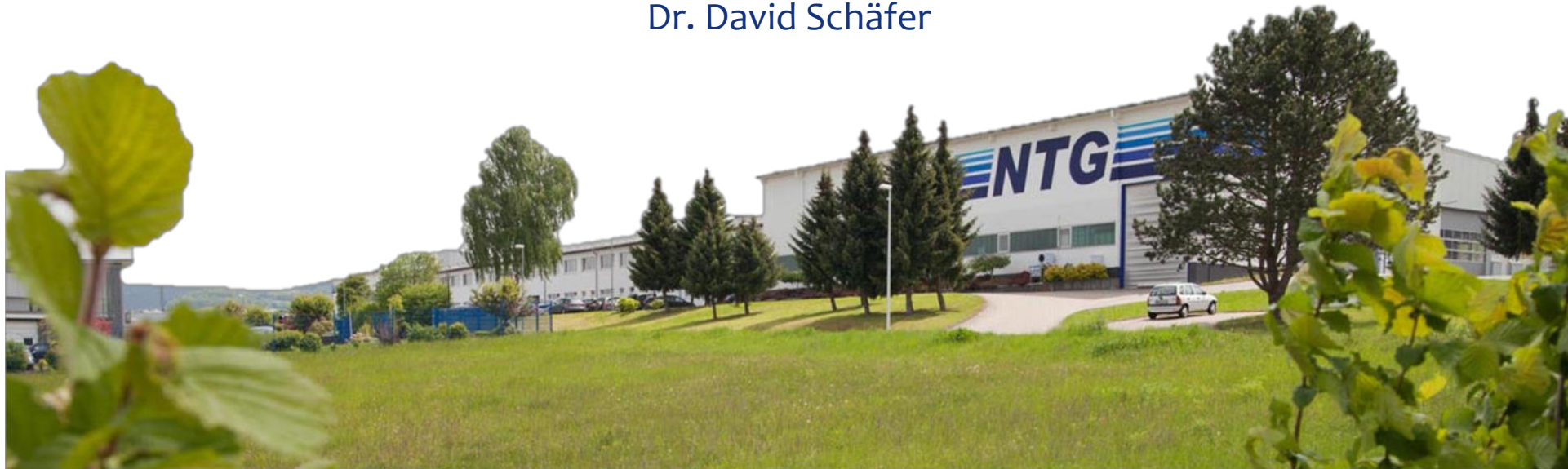


Since 1968

Pushing the limits: 40µm Ion Beam Processing

NTG Neue Technologien GmbH & Co. KG, Germany

Dr. David Schäfer





Content

NTG News

Ion Beam Figuring:
New Ion Beam Sources & Actual Developements

IBF 5: Machine Design

Processing Examples

Summary



Company

- **Founded 1968**
- **~ 100 employees**
- **~ 7500sqm. Production area**

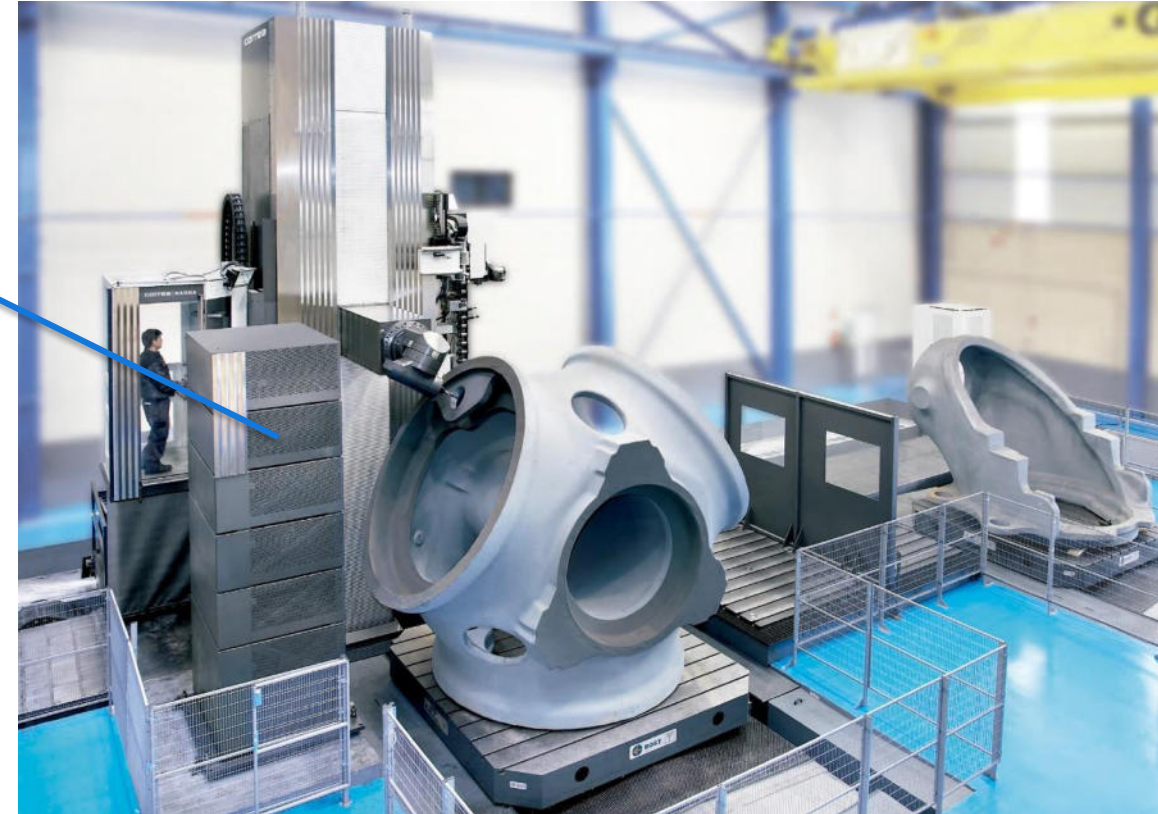
2021: 5th Extension

- 12 x 24 m
- ~ 865 sqm Prod.-area

02/2019:

MAGNA-75 Fahrständerfräsmaschine, 5 Axis
Travel Range: (x,y,z): 7.500 x 1.500 x 4.000 mm

2010 IBF-Lab





Ion Beam Machines

- ✓ >30 years IBF-experience
- ✓ Inhouse Lab (R&D, feasibility studies, job orders...)
- ✓ 100% inhouse competence
- ✓ Largest number of sold IBF-machines worldwide

IBF 700R IBF 1000 IBF 1000R IBF 1500 IBF F40 IBF 1500R IBF 2000

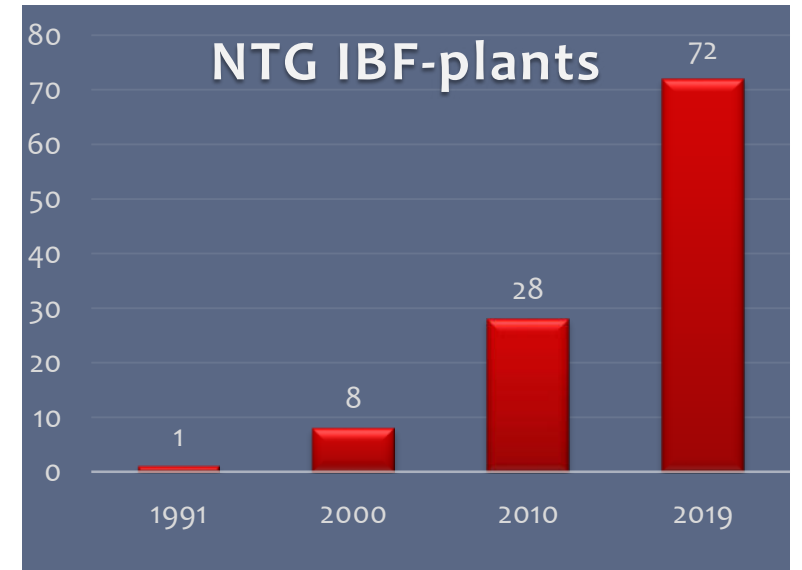
Large size - no load lock

IBF 5 IBF 100 IBF 200 IBF 200 SE

Small size - single load lock

IBF 300 IBF 350 RE IBF 450/IBF 500 IBF 700

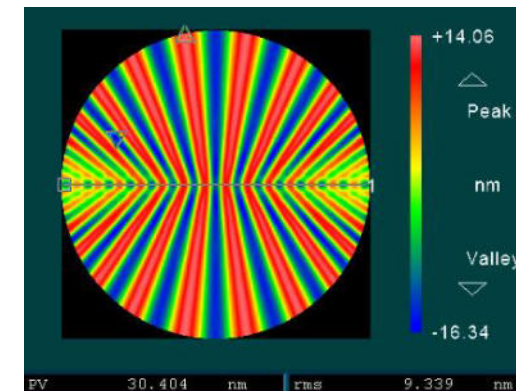
Medium size - double load lock



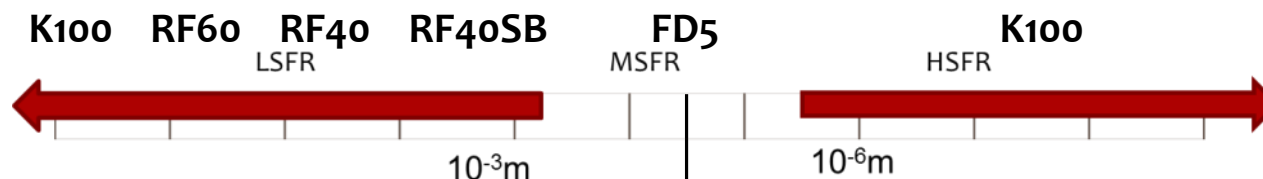


Ion Beam Figuring: New Ion Beam Sources

- Ion Beam Figuring – Mathematics
- Ion Beam Sources – Physics
- Ion Beam Sources – Overview
- Ion Beam Sources – Actual Developments

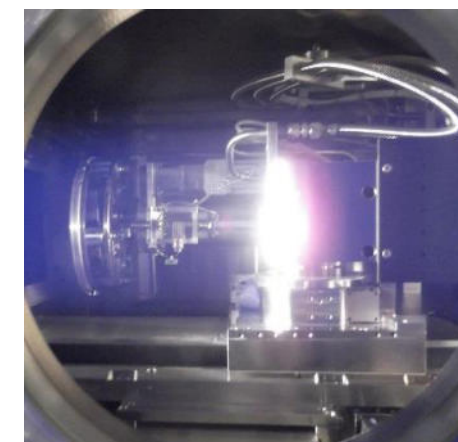
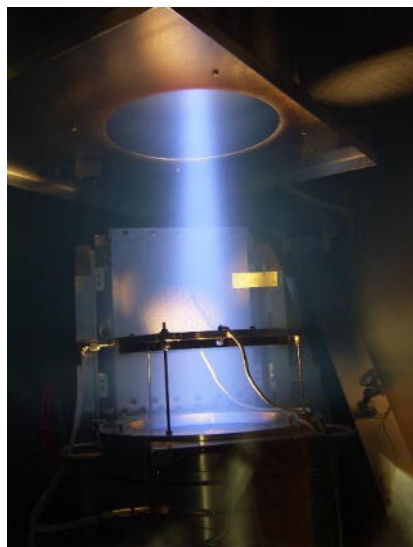
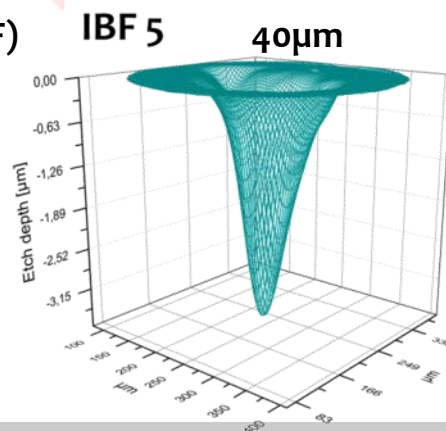


Ion Beam Guns / Feature Sizes



Deterministic
Ion Beam Figuring (IBF)

Statistical
Ion Beam Etching (IBE)





Ion Beam Figuring Mathematics

Dwelltime based Meander Processing

- Material removal: Relation to dwell time/speed and ion beam shape

$$\Delta h(x, y) = t(x, y) * r(x, y)$$

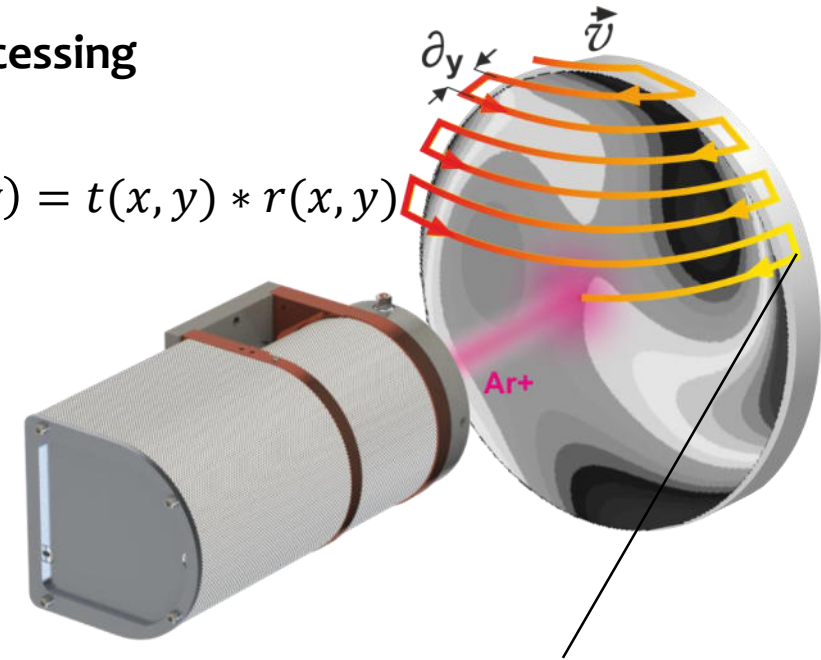
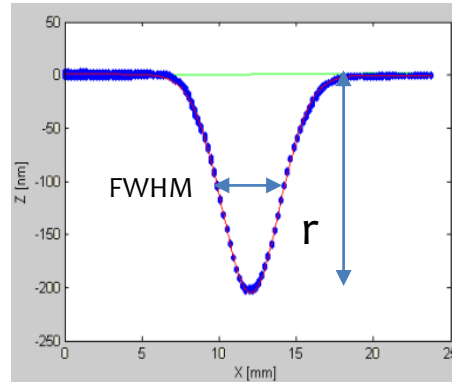
Removal height $H \cong \frac{\pi \cdot r \cdot \sigma^2}{\vec{v} \cdot \delta_y}$

Rate $FWHM = \sigma \cdot 2\sqrt{2\ln 2} \approx \sigma \cdot 2.35$

Ion Beam Size r

Speed \vec{v}

Row pitch (Resolution) δ_y



Edge Extension:
Every Pixel is treated by the whole beam

- Maximum speed of axis system defines „base removal“
- Smaller row pitch (higher resolution) \leftrightarrow higher base removal / longer treatment

$\delta_y \approx FWHM \times 1/5 \dots 1/20$

Coarse, fast low socket removal

Fine, accurate high socket removal

➔ Position accuracy of ion beam $< FWHM/20$

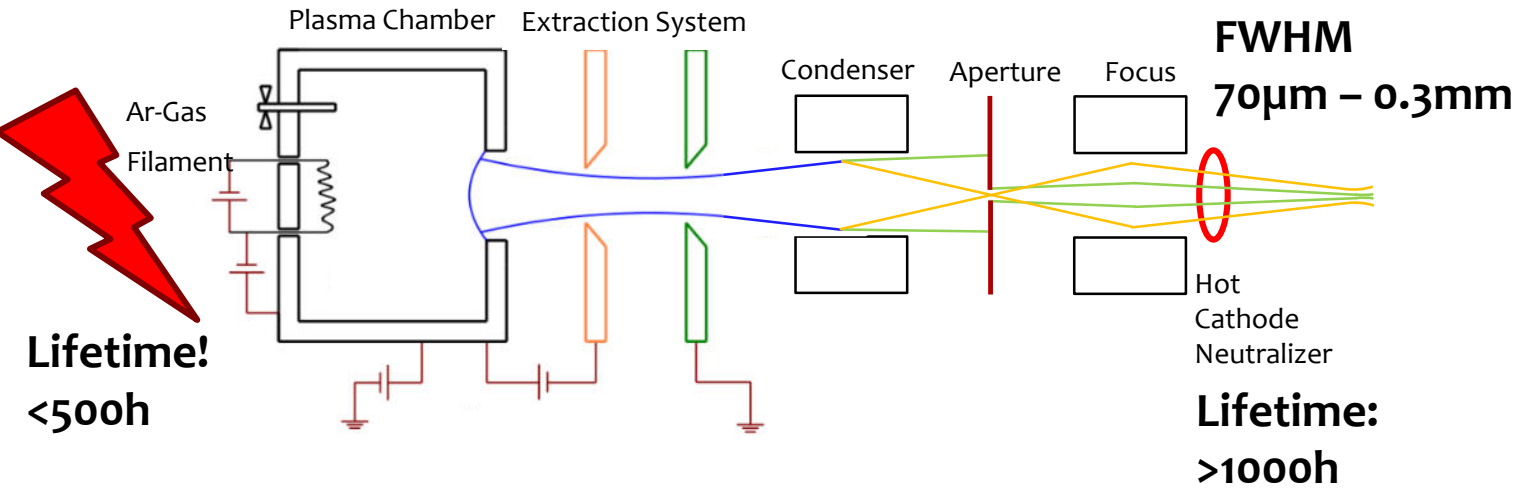
- ➔ 40µm FWHM: 2µm precision [machine]
- ➔ Long term stability of $r(x,y)$ [IBS]



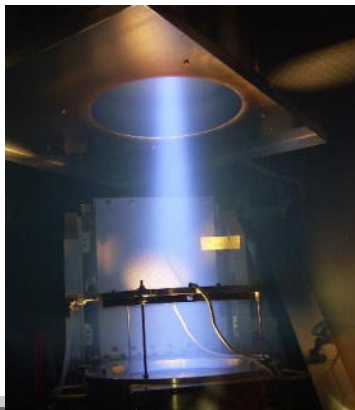
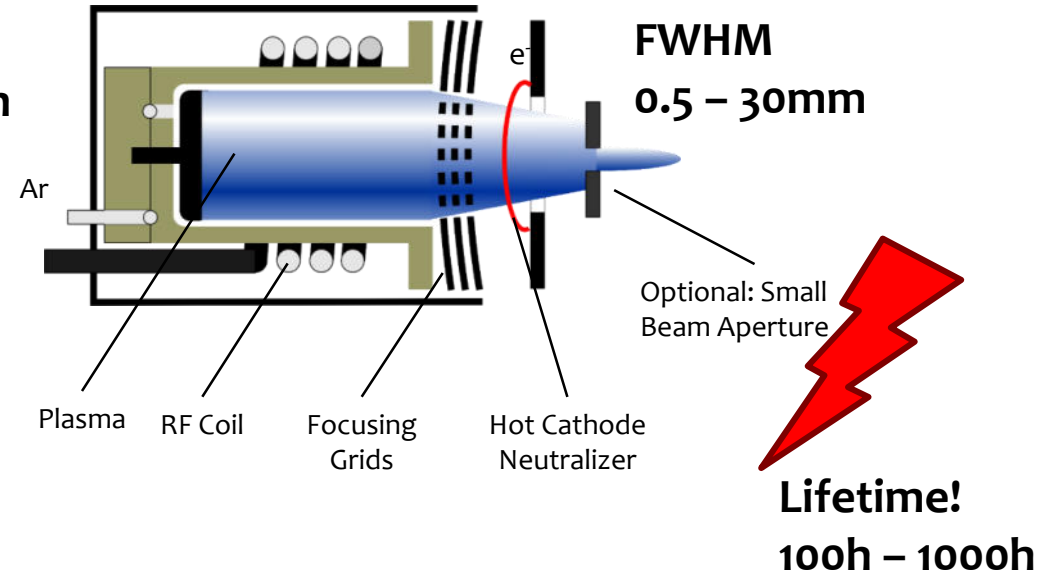


About maintenance intervals...

Filament Ion Beam Source (FD 5, single beam)



RF Ion Beam Source (RF40 & RF60, multiple beams)



Kaufman Ion Beam Source (K100, multiple beams)





Ion Beam Sources Overview

RF 5 micro Beam
Established 12/2019

RF 5 mini Beam
Prototype
08/2020

Name	Beam Size	Plasma	Beam Extraction	Neutralizer	Lifetime
FD 5	0.07 mm – 0.3 mm	Filament	Single Beam	Hot Cathode	Plasma 500h Neutr. >1000h
RF 5 (µB)	0.04 mm – 0.15 mm	RF	Single Beam	Hot Cathode	> 1000 h
RF 40	0.5 mm – 4 mm	RF	Multiple Beam + Aperture	Hot-Cathode	500 h – 1000 h
RF 40	5 mm – 20 mm	RF	Multiple Beam	Hot-Cathode	150 h – 500 h
RF 60	30 mm	RF	Multiple Beam	Hot-Cathode	100 h
K 100	60 mm (Gauss)	Filament	Multiple Beam	Hot-Cathode	<50 h (both)



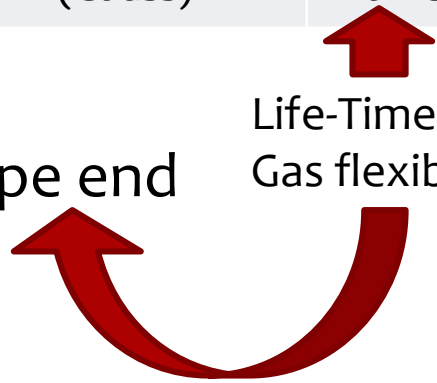
More Vol.-Rem.
More Flexibility
Less Contamination



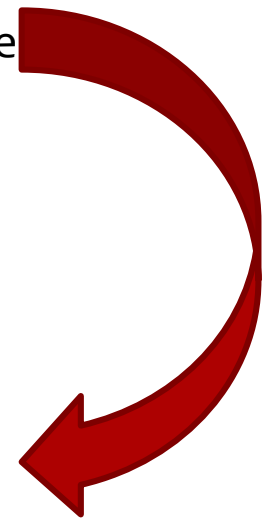
Life-Time

RF 200
Prototype end
of 2020

Life-Time,
Gas flexibility (RIBE)



RF Neutralizer
Prototype 04/2020





Actual Developements RF 200, RF Neutralizer

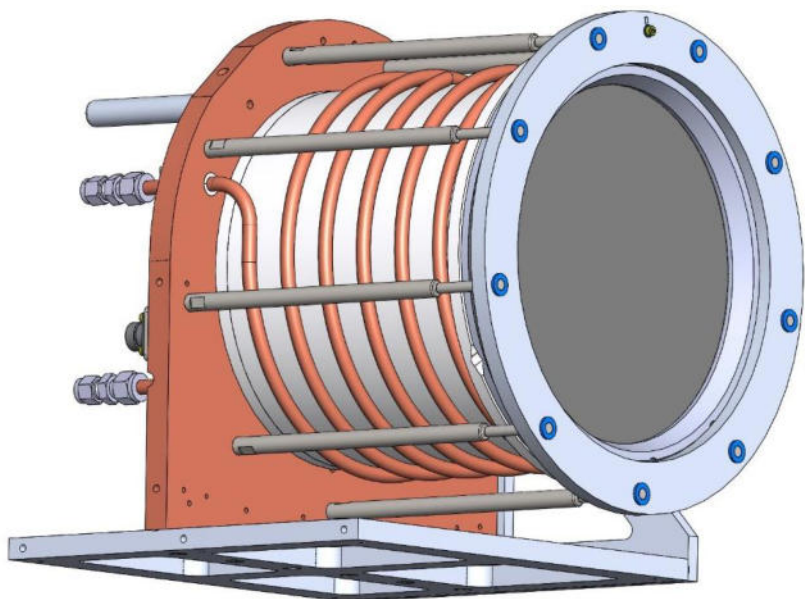
RF200 – under commisioning

Extraction energy: 0.6 kV – 1.5 kV

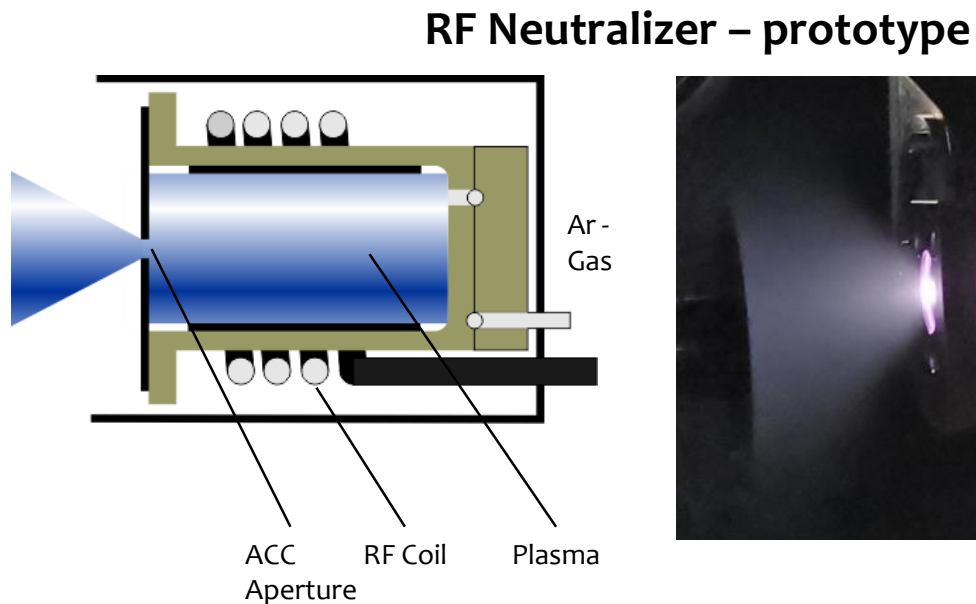
Beam shape: gauß + flat top

FWHM: 150 mm – 200 mm

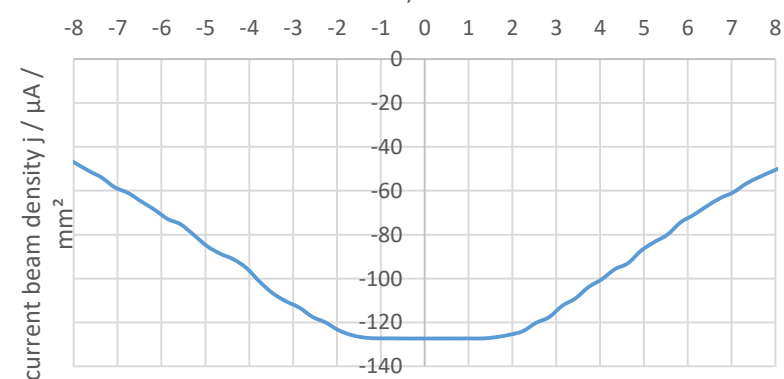
Gas: inert + reactive



RF 200

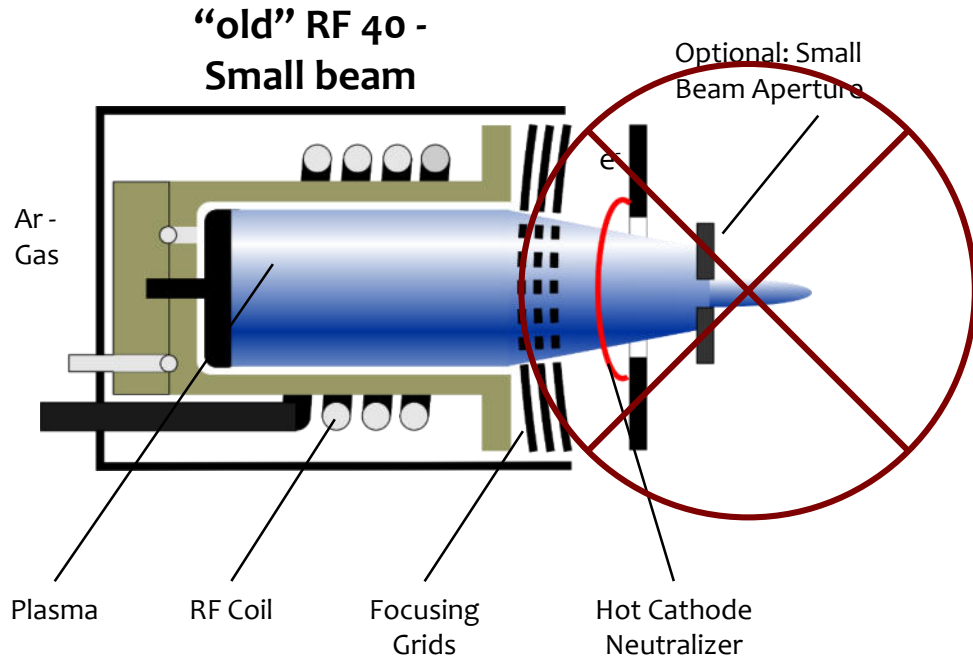


Plasma bridge e-Beam - current density



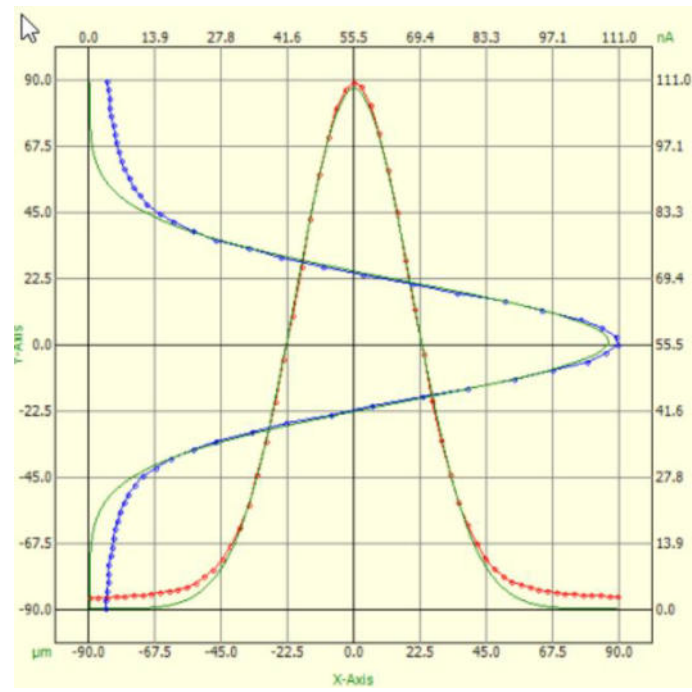
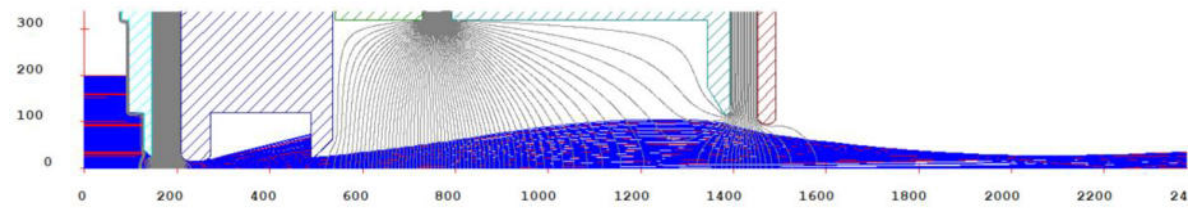


New Development RF 5 μ B & mB

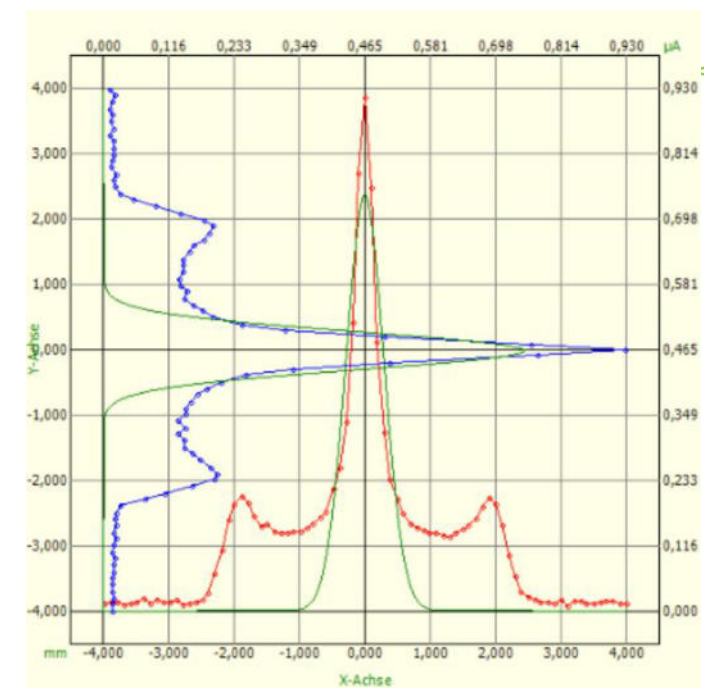


➔ No Neutralizer for conductive materials necessary

“new” single extraction system



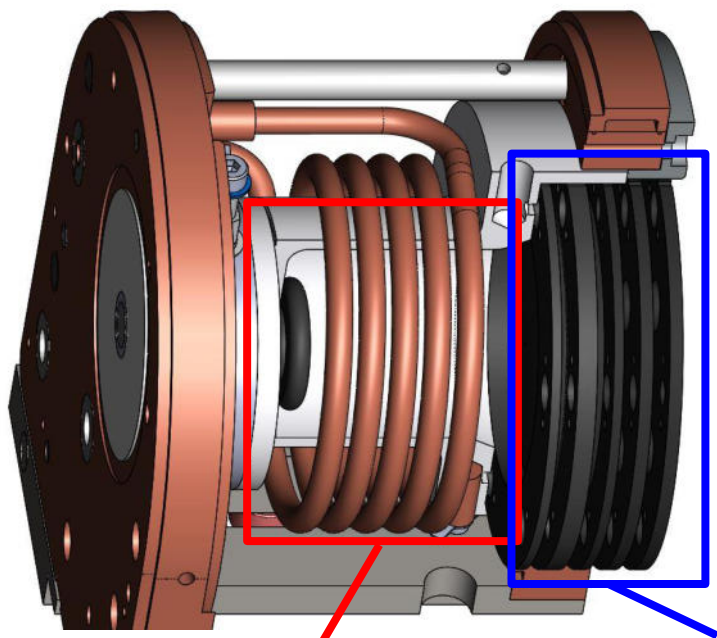
RF5 μ B \rightarrow 40-150 μ m



RF5 mB (under dev.) \rightarrow ~1mm



New Ion source RF 5 μ B

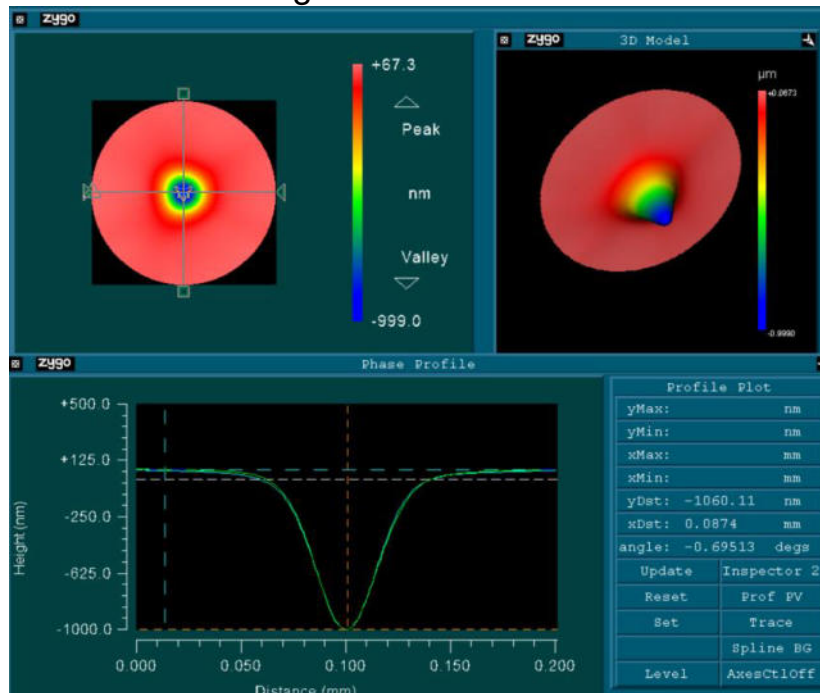


Plasma chamber

5-grid extraction system

Ion beam energy: <1 keV – 3 keV
Working distance: ~15 mm

Material: Si
Etching time: 40 s
Working distance: 15 mm



double Gauss fit		double Gauss fit error	
baseline :	0.416nm/s		
tilt X / Y :	0.182/s	0.362/s	
maximum 1 :	17.385nm/s		
FHWM X / Y :	0.041mm	0.041mm	
shift X / Y :	0.009mm	0.007mm	
maximum 2 :	8.112nm/s		
FHWM2 X / Y :	0.033mm	0.033mm	
rate :	25.497nm/s		
theoretical volumerate :	0.042657nm ³ /min		
chi-square :	115.824		
FHWM x / y :	0.038mm	0.038mm	

Beamparameter:
Beam energy: 2 keV
RF Power: 50W

Results:
Etch rate: ~25.5 nm/s
volume rate: ~0.043 nm³/min
FWHM: ~38 μ m

„Old“ IBF systems upgradeable!
IBF 100...200, F40



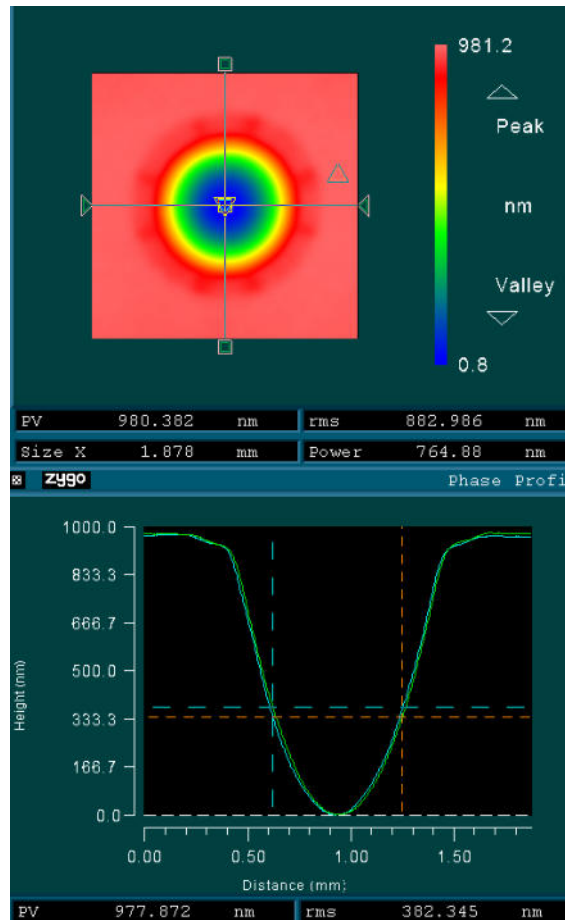
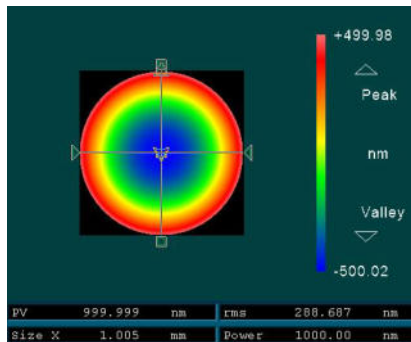
IBF 5 - Example Sphere on Plane

Ion Beam Parameter

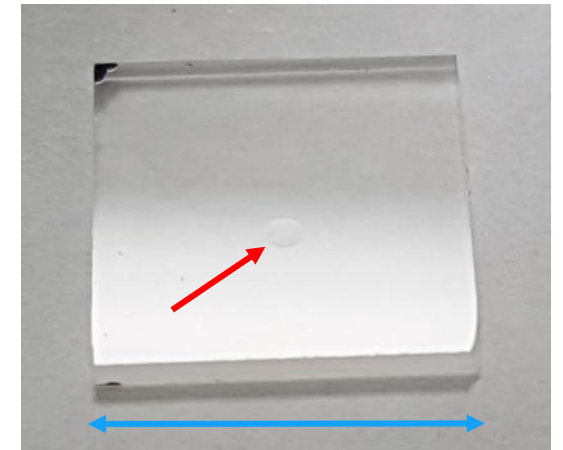
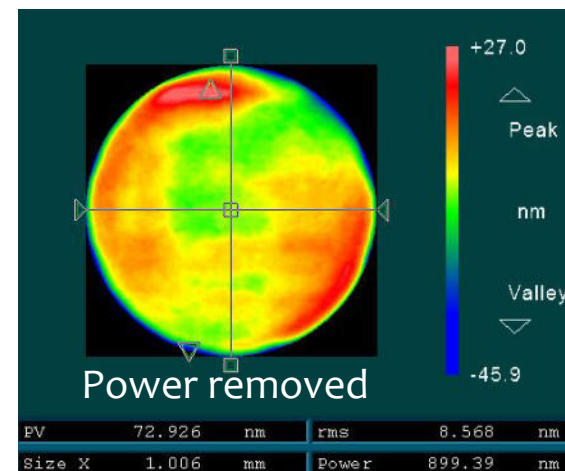
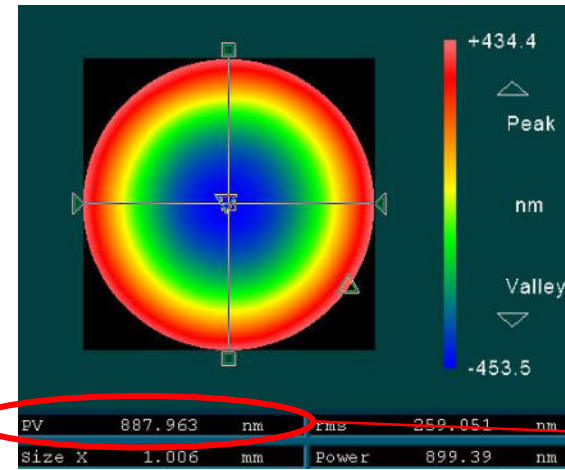
Ar+ Ion Energy: 3000 V
Beam Current: 0.7 μ A
FWHM: \sim 80 μ m

Sphere to generate

Diameter: 1 mm
Central removal: -1 μ m
 \rightarrow Radius: 125 mm

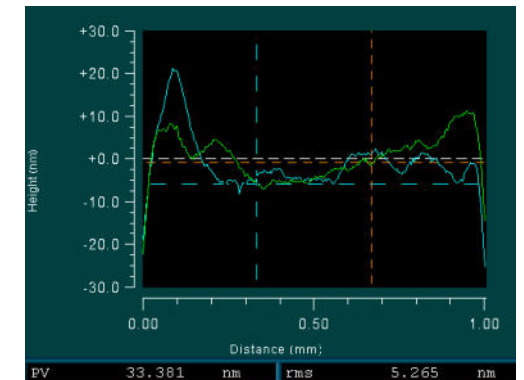


Spherization



10 mm

\sim 900 nm of
1 μ m Power
 \rightarrow R=139mm



Application: Mirrors, Laser Optics,
Wavefront manipulators

Any shape possible

Residual error \emptyset 100% \sim $\lambda/10$

\emptyset 95% \sim $\lambda/20$



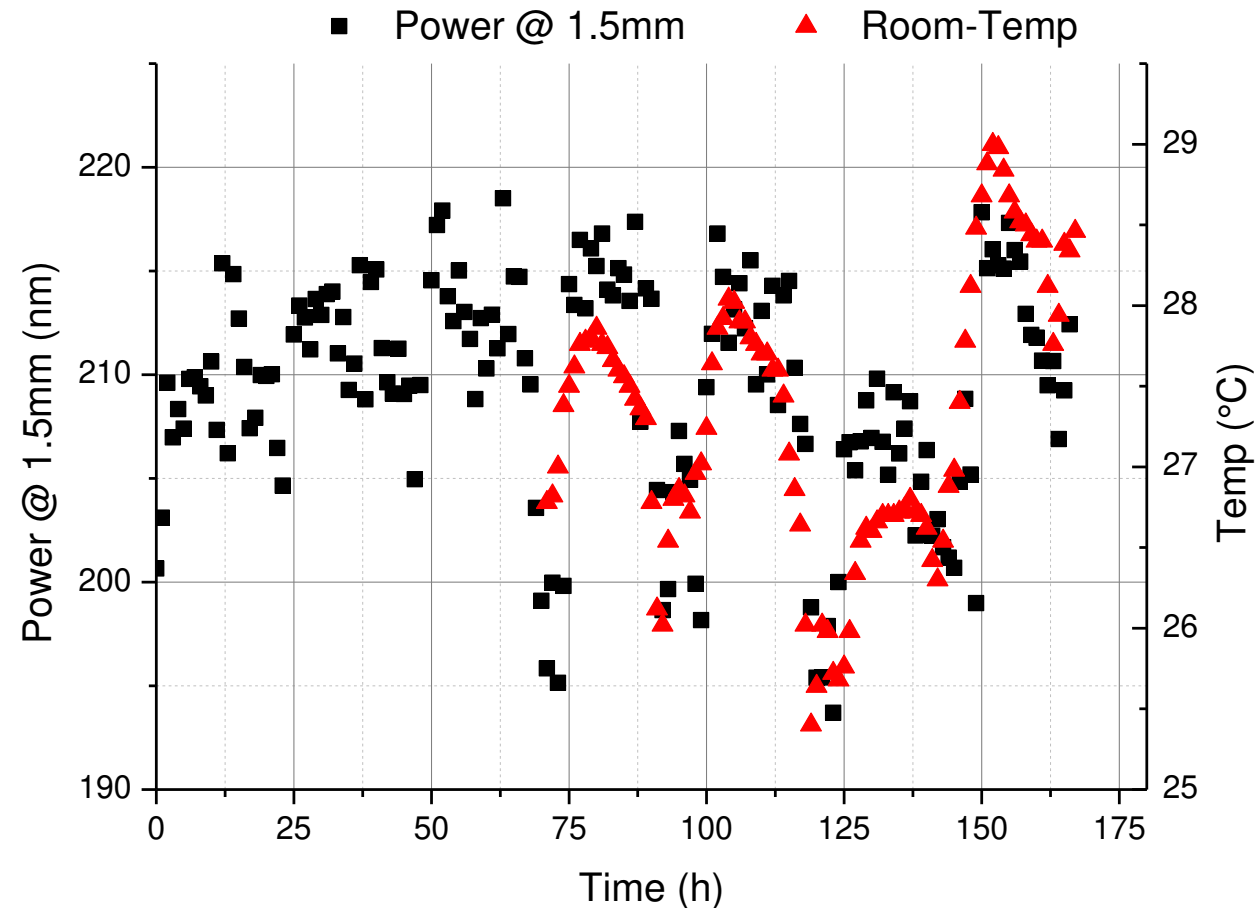
Long term Sphere etching test

Multiple Spheres: 6.5 rows, 25 each → 166 spheres
Material: Si-Wafer, 14mm working distance
Shape: D = 1.5mm, Power = 200nm → 24min
Process: 1 sphere in 1 hour
total ~166hours (7days)
Evaluation: Power value of etched sphere

Result Power (d=1.5 mm):

Mean = 209.4 nm
PV = 24.8 nm (11.8%)
 σ = 5.4 nm (2.6%)

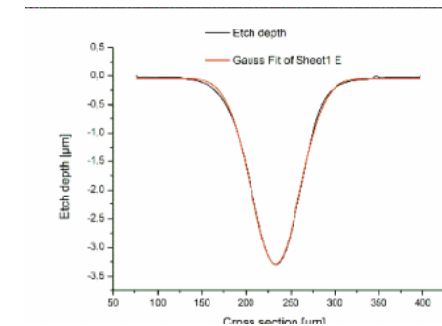
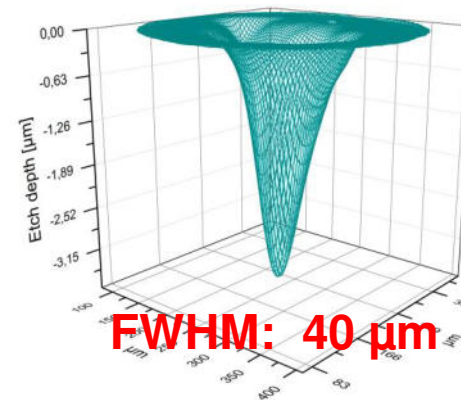
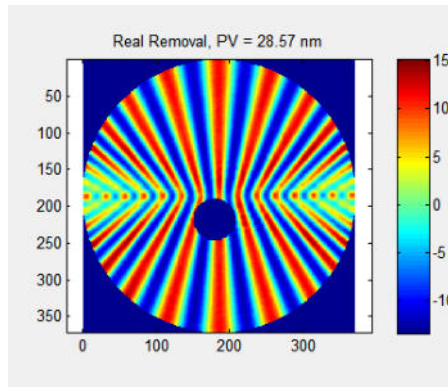
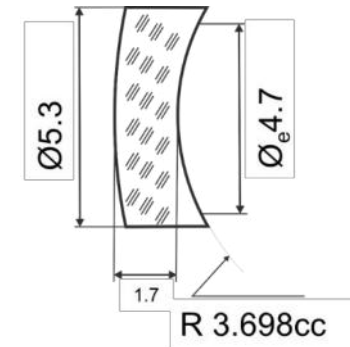
→ It seems roomtemperature mainly defines the error budget (NTG IBF 5 lab machine)





IBF 5 – New possibilities for smaller optics

- IBF 5 – IBF for Micro Optics
- Examples



IBF 5 Machine Design



Water cooled axis system + workpiece holder
 Position precision <math><2\mu\text{m}</math> @ 100 x 100mm²

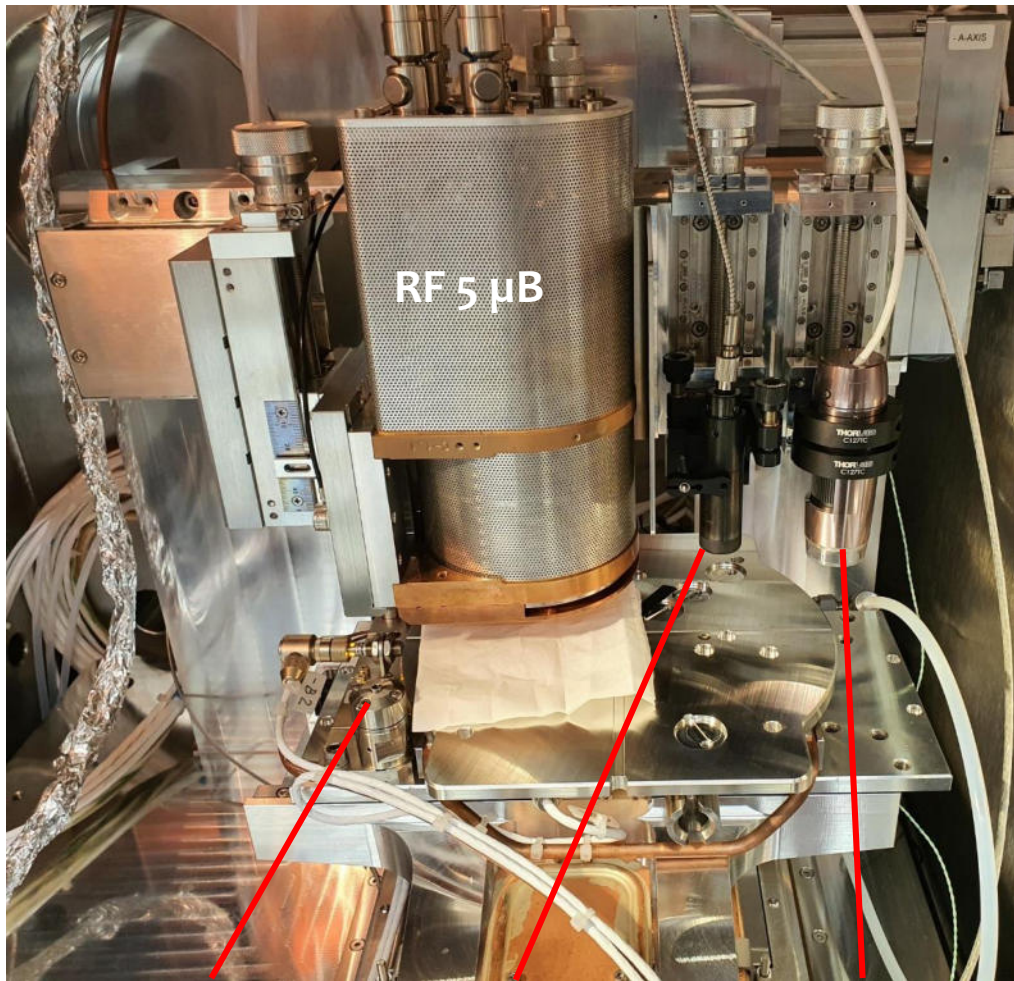


Technical data:

Optics Size:	<math><\varnothing 5\text{mm}</math> <math><\varnothing 0.2\text{ inches}</math>
Contact angle:	max. 72°
Shape:	freeform
Working Travel range:	100 x 100 mm ²
Thickness:	<math><50\text{mm}</math> (20 inches)
Weight:	max. 2kg (4.4 lb.)
Alignment system: (vacuum use)	μ -Faraday Cup Confocal Sensor Vision System
Load lock system:	no load lock, batch processing load lock optional available



IBF 5 Alignment System



μ Faraday Cup

Confocal

Camera

Camera System:

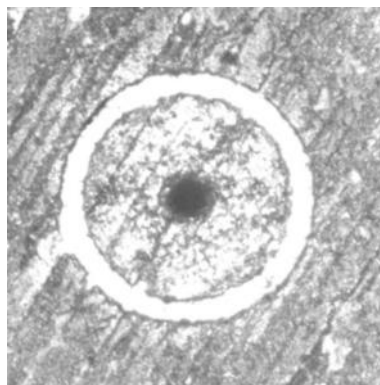
- Variable camera zoom (FoV ~1.5mm... >20mm)
- Confocal illumination visualize test etchings

Confocal System:

- Measurement range: 2.5mm
- Height measurement + ROC scan of sample

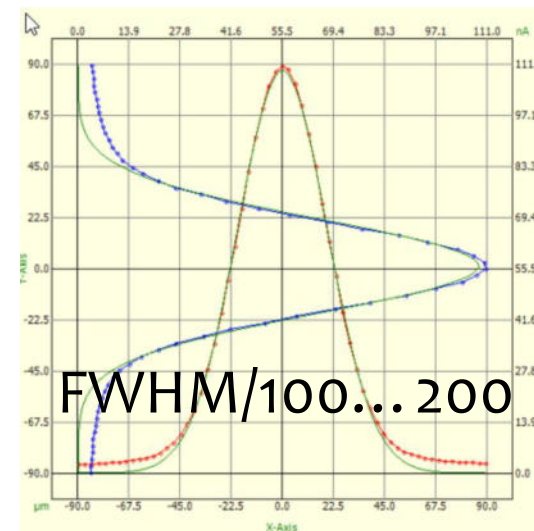
One Common reference:

- μ Faraday Cup



50μm aperture

500μm + Contrast groove



Ion Beam distribution Measurement (TCP)



IBF 5 Camera system

GUI for Camera Measurement

IBF 5 / Axis system - measuring

Enable	Home	Actual position
X		9.9986 mm
Y		-0.0041 mm
Z		81.9999 mm
XT		62.3000 mm

Axis system: Park position, Werkstück-Mitte, Faraday cup

Velocities: Linear axes: 0.0100 mm/s

Manual correction: Pos. - X: 0.0000 mm (19.266 mm X-Correction), Pos. - Y: 0.0000 mm (-23.148 mm Y-Correction)

Configuration: Source position (Z4): 28.8500 mm, Source distance: 14.0000 mm

Fixture Offset: Camera

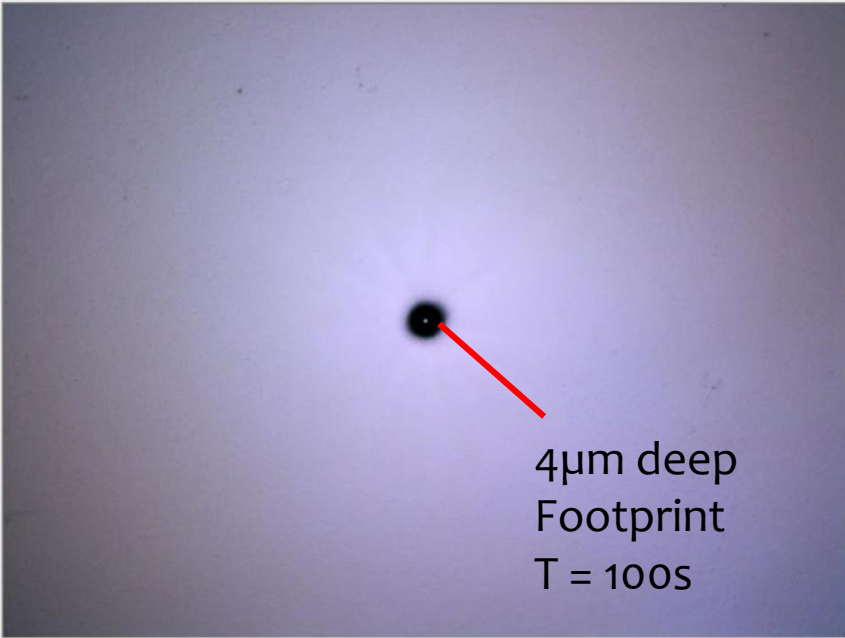
Faraday cup: X-Diff: 110.0277 mm, Y-Diff: -52.0846 mm

Circle Detection: Circle

Camera Exposure: 1 / 128 s

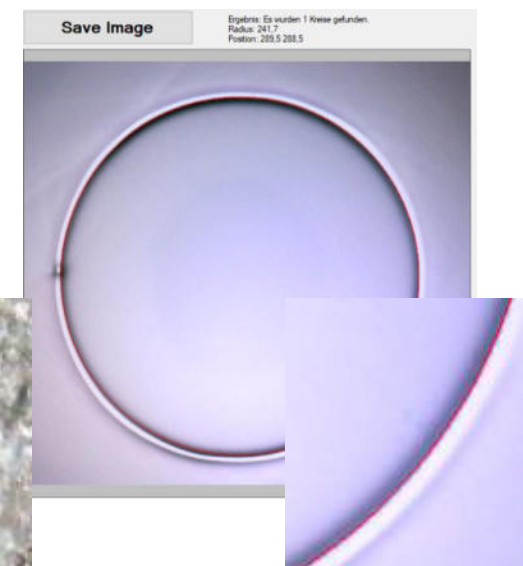
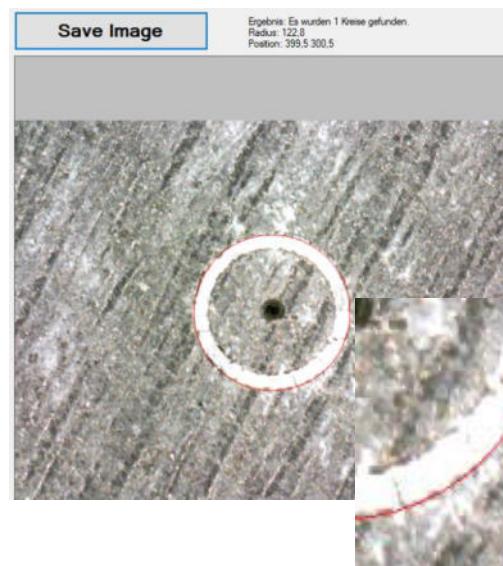
Settings: Circle detection - settings (r min: 145.000 μm, r max: 160.000 μm, Canny: 50, Circle Accumulation Threshold: 30, 633.1800 nm/pix), Transformation - parameters (Offset X: 0.00000 mm, Offset Y: 0.00000 mm, Angle: 0.00000 mrad, Zoom X: 1.0000000, Zoom Y: 1.0000000)

Buttons: Save picture, Open list, Read Next Position, Run Circle Detection, Load Trans para, Save Trans para, Loop, Fit, Circle on/off



4μm deep Footprint
T = 100S

- Circle Autodetection
- Automated Measurement loop for several fiducial measurement



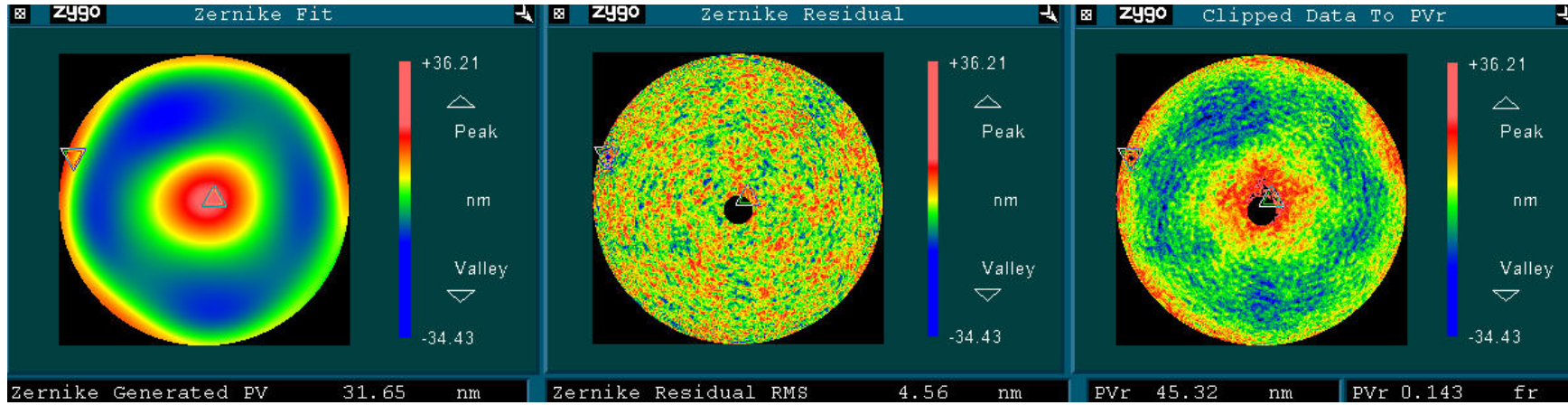
→ Finally evaluate sample position in relation to μ Fcup (Δx , Δy , Rot, Zoom)

IBF processed „ring“: 500μm groove, 1μm deep
T=60min



IBF 5 - Example
Tungsten Carbide Mold

Form Correction: Mold \varnothing 2.36mm



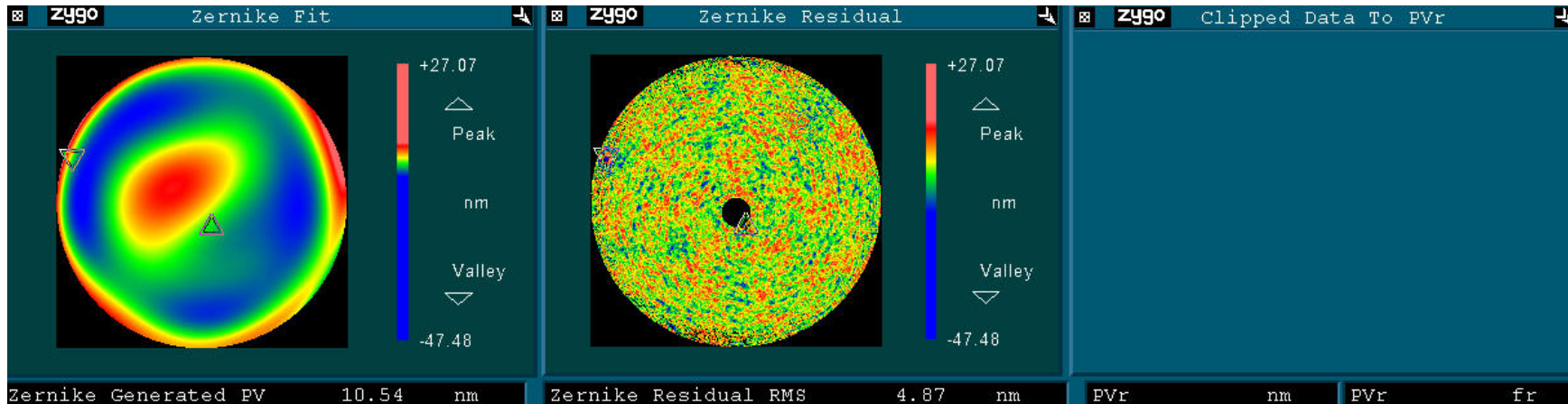
Sample

\varnothing 2.36 mm, R 1.35 mm (f/0.572)

Material: Tungsten Carbide

Treatment @90%:

Measurement using f0.75 (\varnothing 1.62mm)



Ion Beam Parameter

Ar+ Ion Energy: 3000 V

FWHM: 70 μ m

Vol.-Rate: 0.1 mm²nm/s

Processing Time: 0:06h

NTG lab machine



IBF – New State-of-the-art Resolution Limit

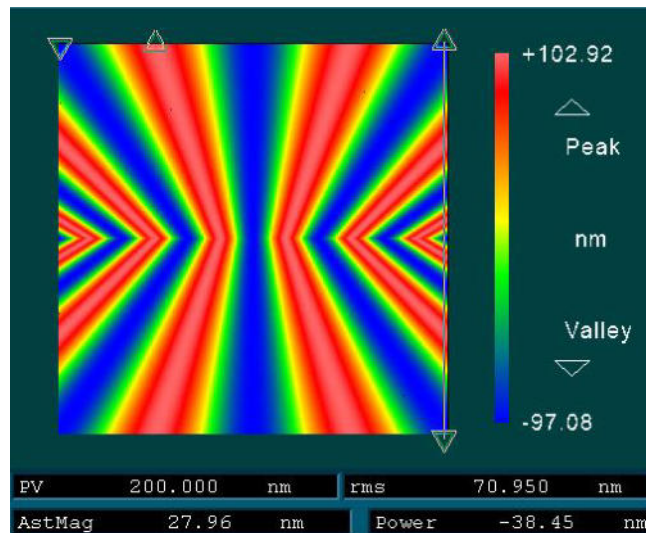
Ion Beam:
Energy [eV]: 2000

double Gauss fit

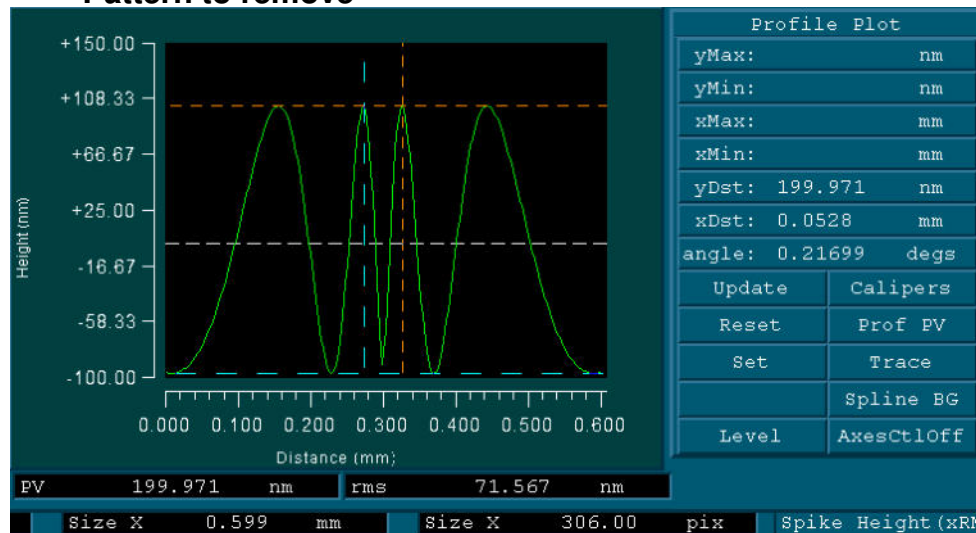
double Gauss fit error

baseline :	1.113nm/s	
tilt X / Y :	0.561/s	3.701/s
maximum 1 :	20.322nm/s	
FHWM X / Y :	0.049mm	0.050mm
shift X / Y :	0.001mm	0.006mm
maximum 2 :	14.589nm/s	
FHWM2 X / Y :	0.040mm	0.035mm
rate :	34.911nm/s	
theoretical	0.080156nm ² /mm ² /s	
volumerate :	0.000004809mm ³ /min	
chi-square :	198.732	
FHWM x / y :	0.045mm	0.043mm

base removal	18.85 nm/loop	PV
total time	0h 14min 33sec	RMS



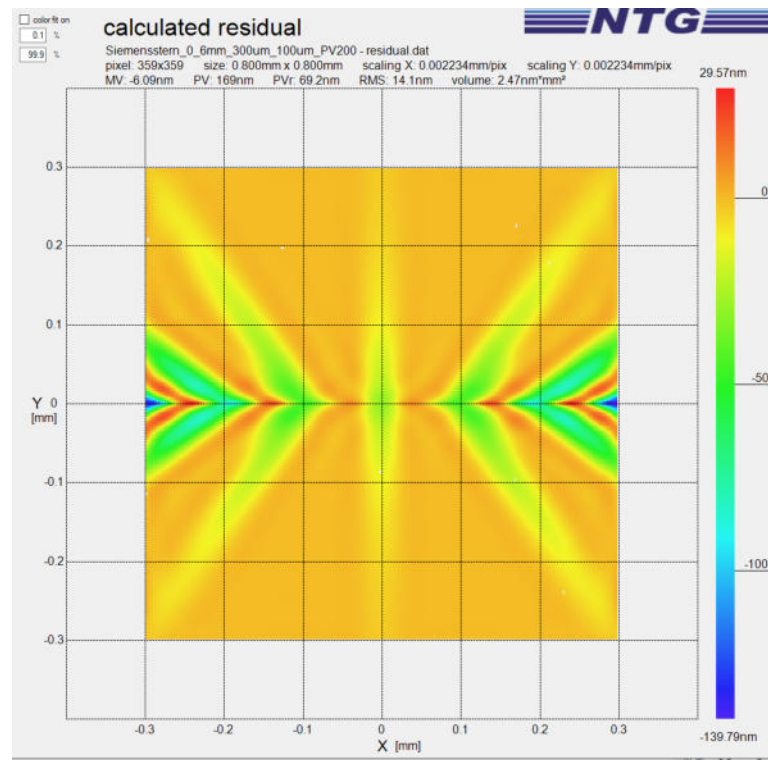
Pattern to remove



Simulation

Modified Siemensstar:

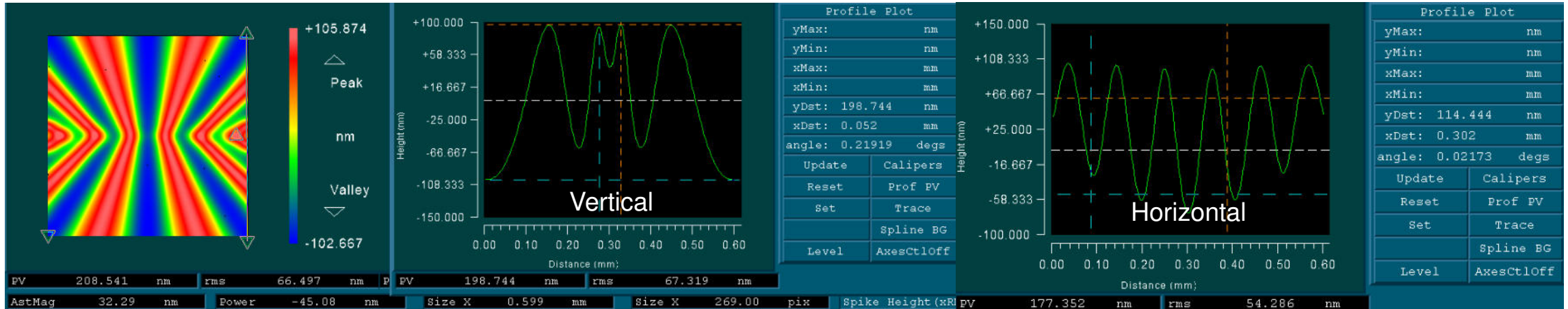
PV: 200nm
Spatial wavelengths
V: 300µm to 100µm
H: 50µm to inf.



Calculated residual

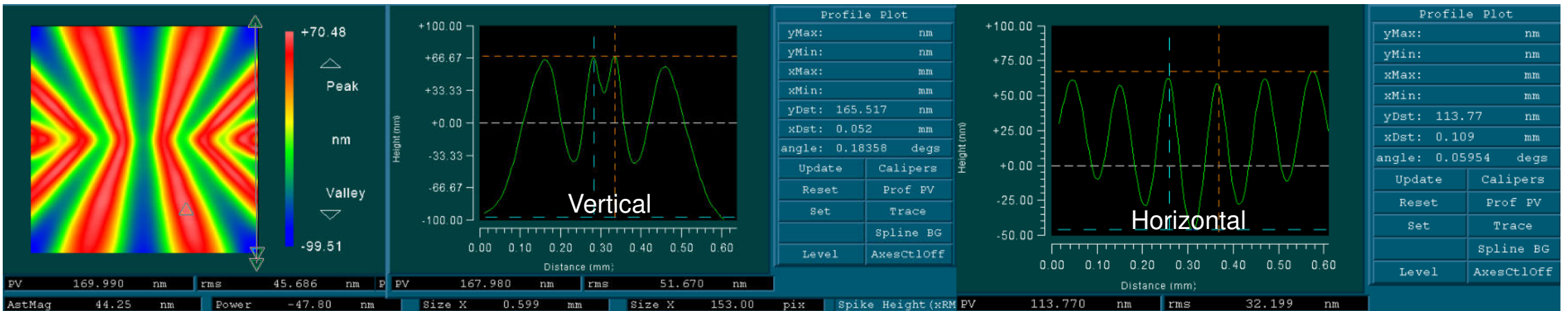


Simulated removal:



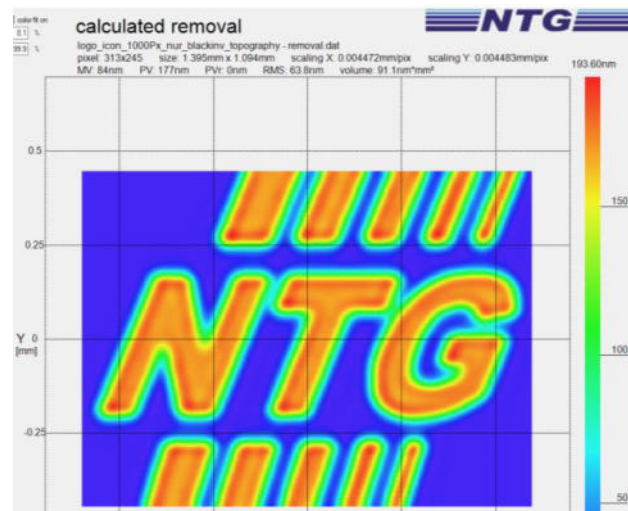
→ Full modulation @ l=100µm

Real removal:

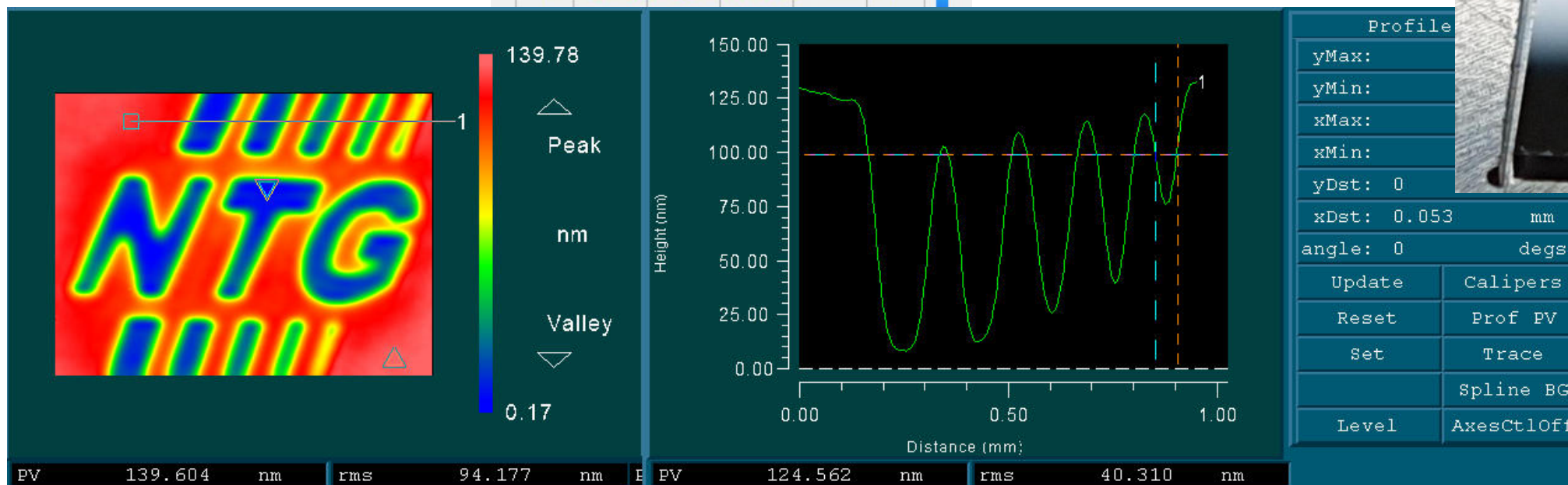
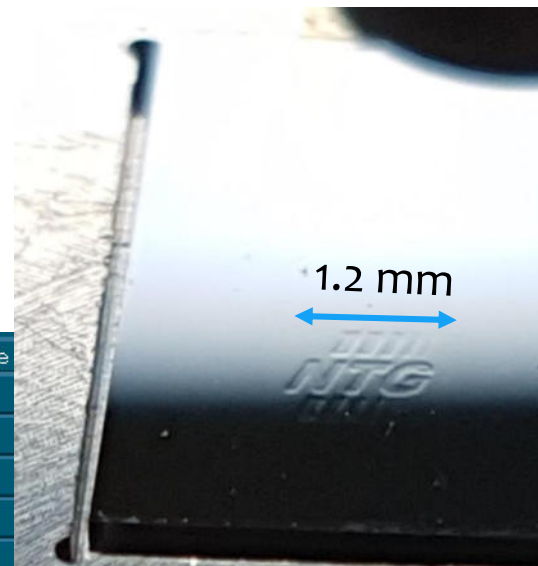




Name/Barcode Marker



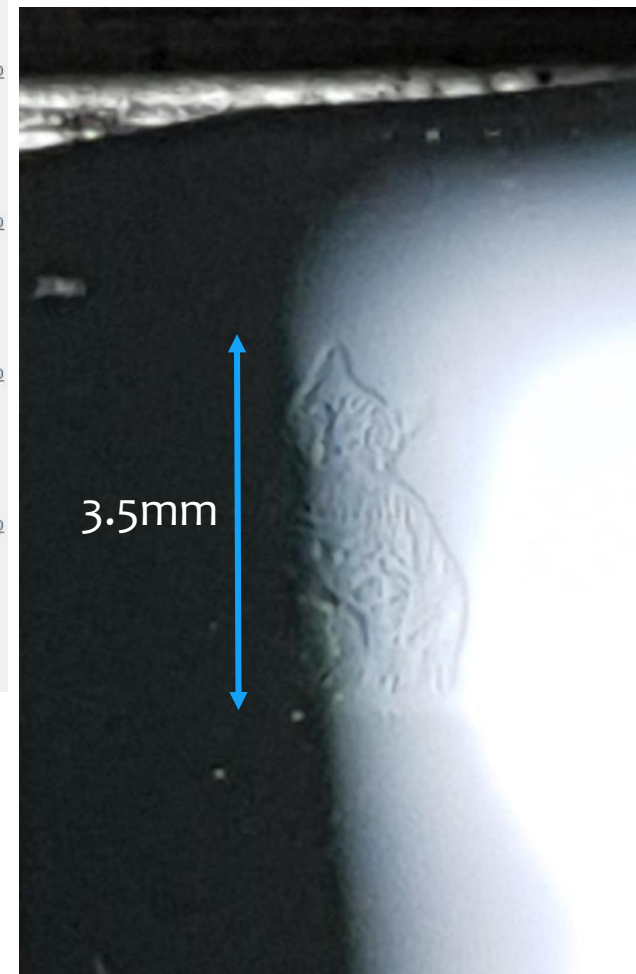
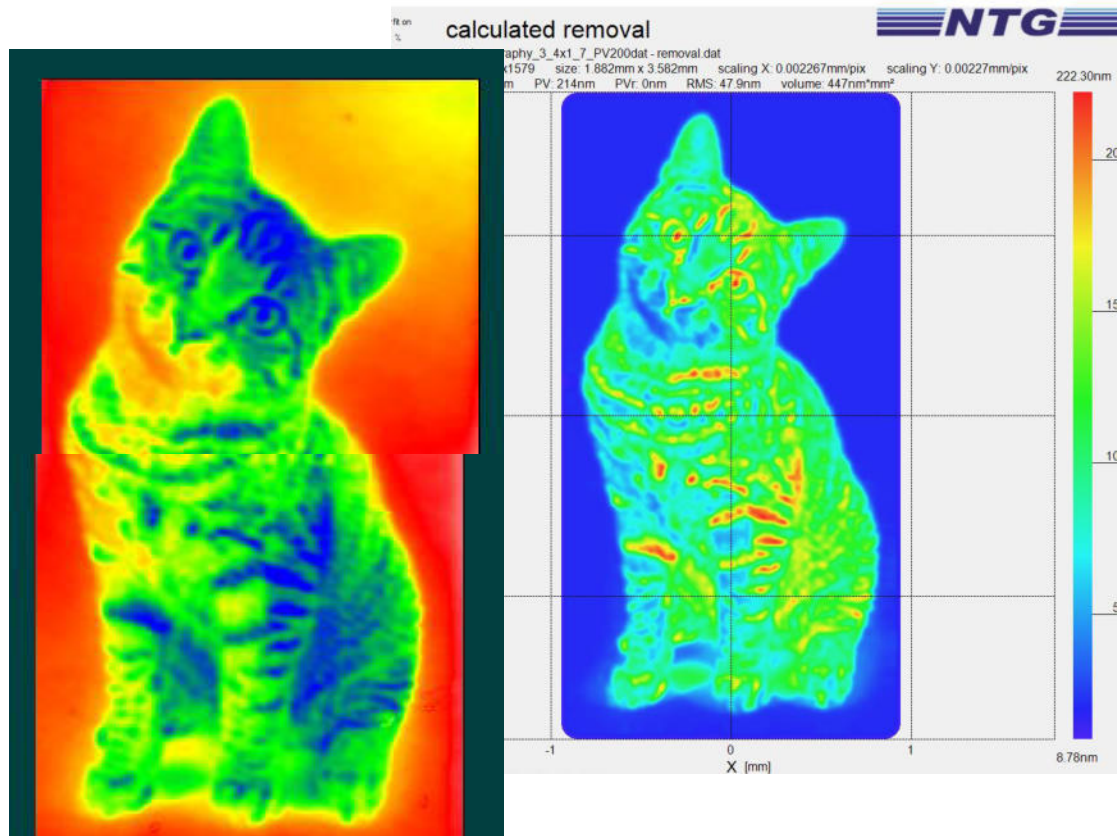
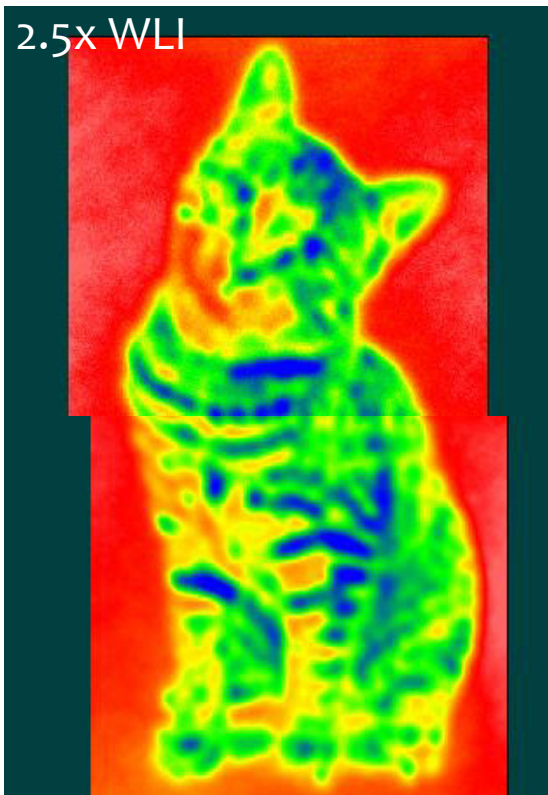
PV: 200nm
 Beam size: 50µm
 Processing Time: 0:24h





Comparison FD 5 / RF 5 μ B

Schrödinger's Cat found on Silicon Wafer!!!



FD 5 Ion Beam Source

PV: 100nm

Beamsize: 70... 90 μ m

Processing Time: 0:48h

RF 5 μ B Ion Beam Source

PV: 200nm

Beamsize: 45 μ m

Processing Time: 1:34h



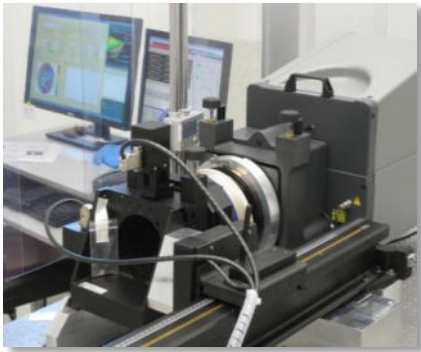
Summary

- IBS: Physics, mathematics, new gun developements
- IBF 5: Pushing the limits
- Examples: Form correction, spherization, markers

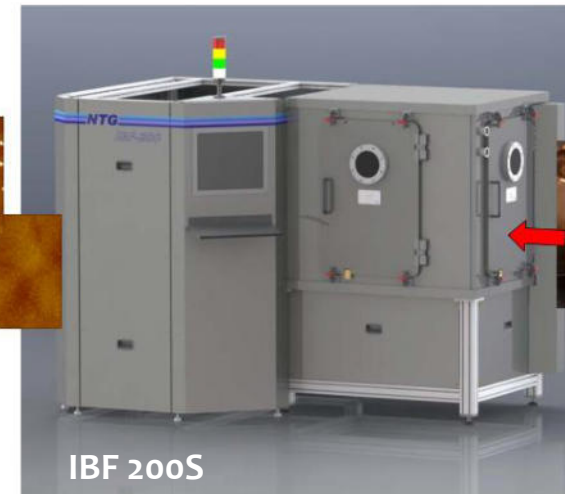


- ▣ NTG Laboratory
- Surface Measurements (Interferometer, WLI, AFM) → PSD
- Process Simulation, Process Development
- Feasibility Studies
- Reference-Optics (PtB certified)
- IBF / IBS / IBE
- IBF 5, IBF 200S
- Measurements internal/external

Thank you!



IBS



IBF 200S

IBF



- ▣ Materials
- Schott / Ohara,...
- WC, SiC, NiP...
- Zerodur, ULE,...
- Clearceram, TiN, AlN,...
- SiO₂, CaF₂,...
- Nd:YAG, KTP, BBO,...
- ... tbt