

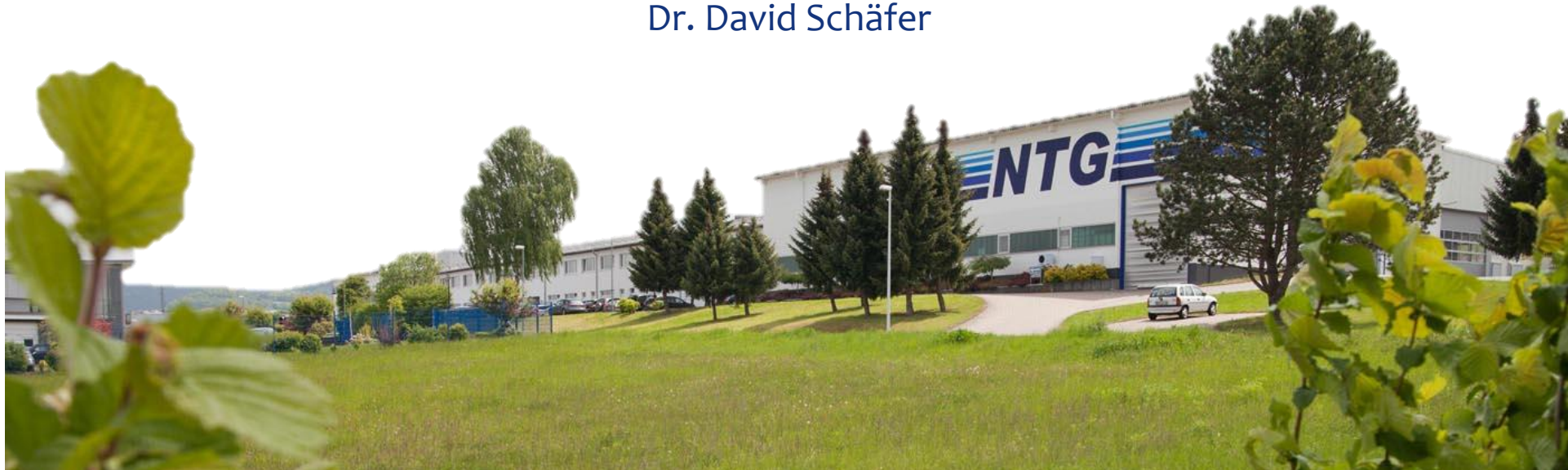


Since 1968

# 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: 5<sup>th</sup> Extension

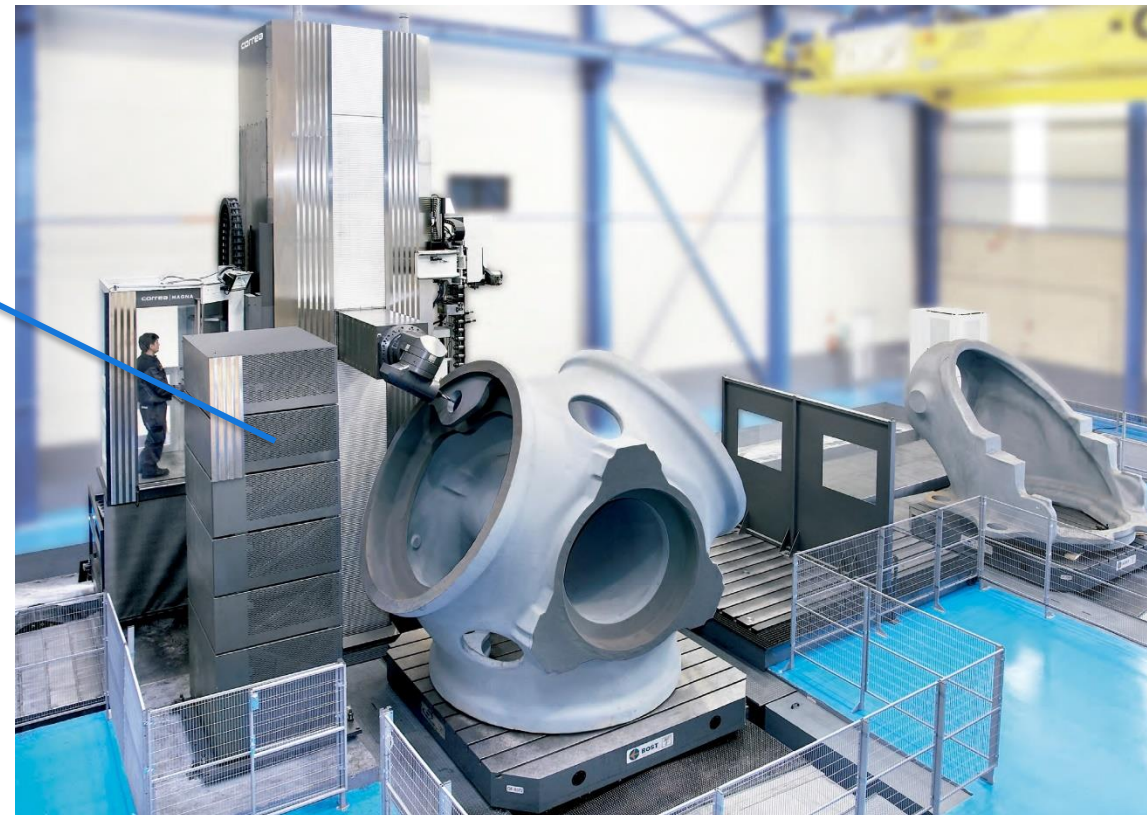
- 12 x 24 m
- ~ 865 sqm Prod.-area

### 2010 IBF-Lab



### 02/2019:

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





# 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 EUV    IBF 1500R    IBF 2000

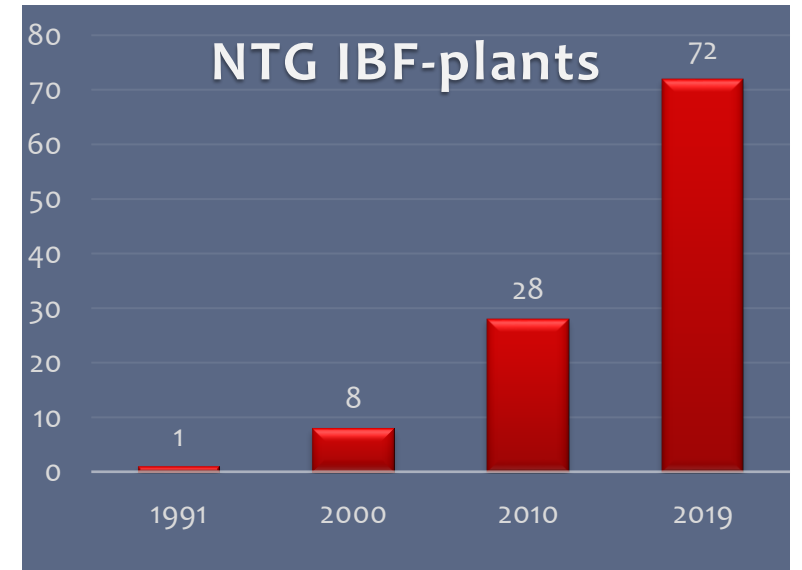
Large size - no load lock

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

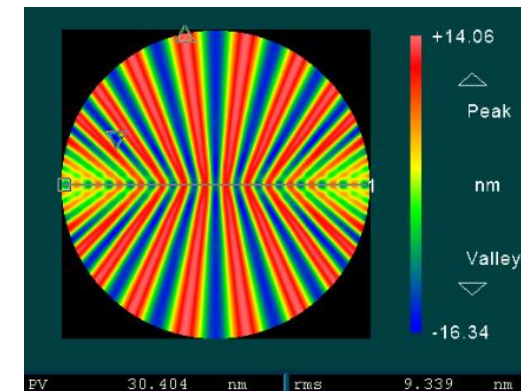




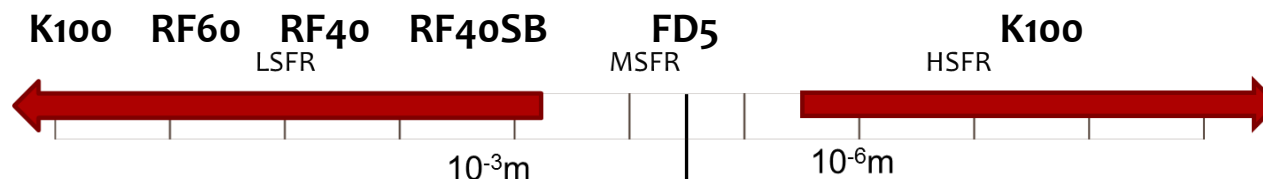


## Ion Beam Figuring: New Ion Beam Sources

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

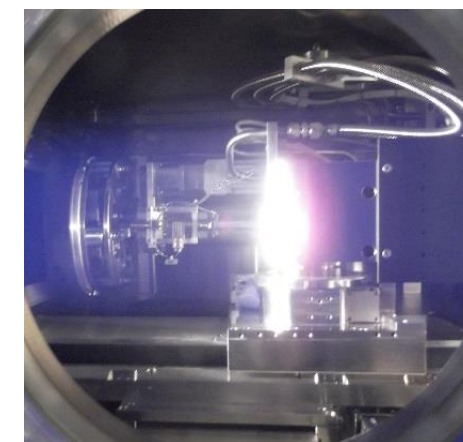
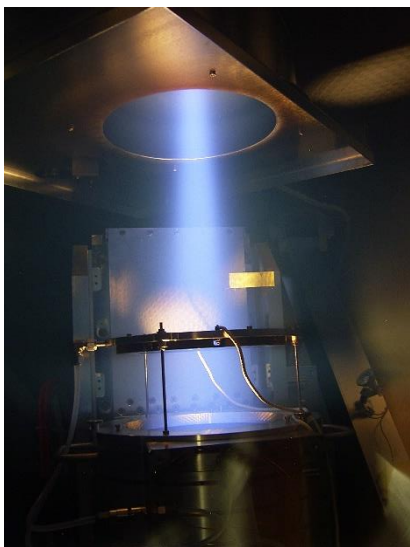
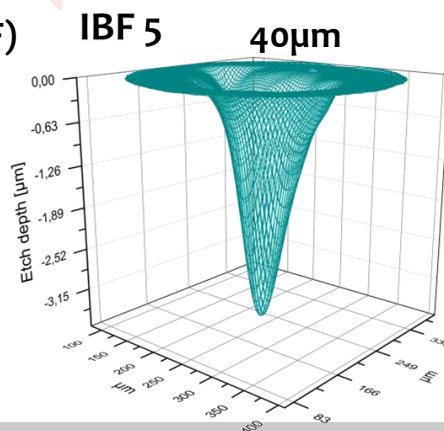


### Ion Beam Guns / Feature Sizes



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

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

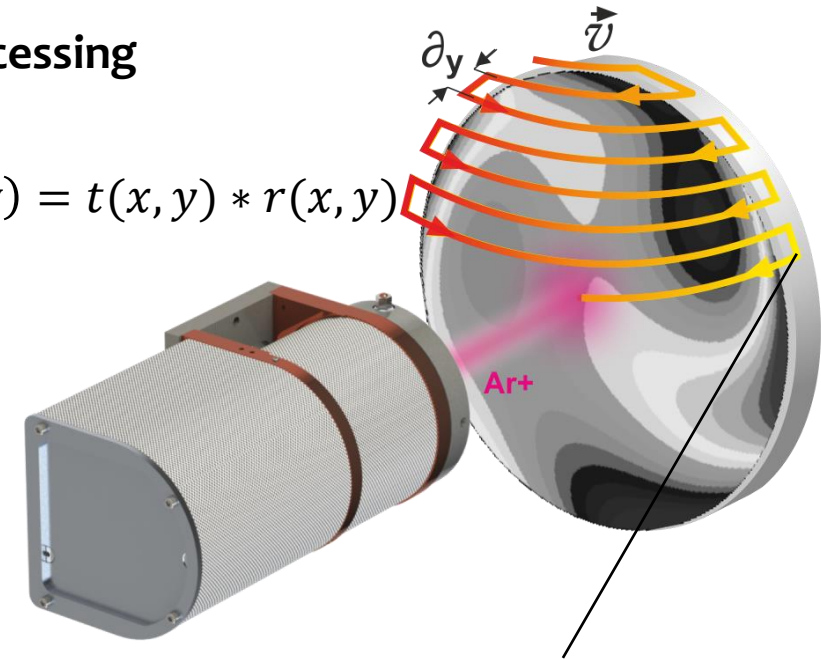
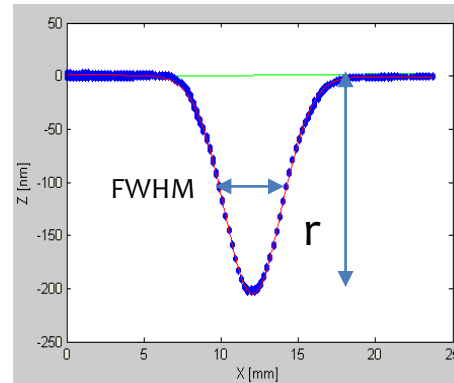
Removal height  $H \cong \frac{\pi \cdot r \cdot \sigma^2}{\vec{v} \cdot \delta_y}$

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

Ion Beam Size  $r$

Speed  $\vec{v}$

Row pitch (Resolution)  $\delta_y$



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  $\uparrow$

Fine, accurate high socket removal  $\uparrow$

$\rightarrow$  Position accuracy of ion beam  $< FWHM/20$

$\rightarrow$  40 $\mu$ m FWHM: 2 $\mu$ m precision [machine]

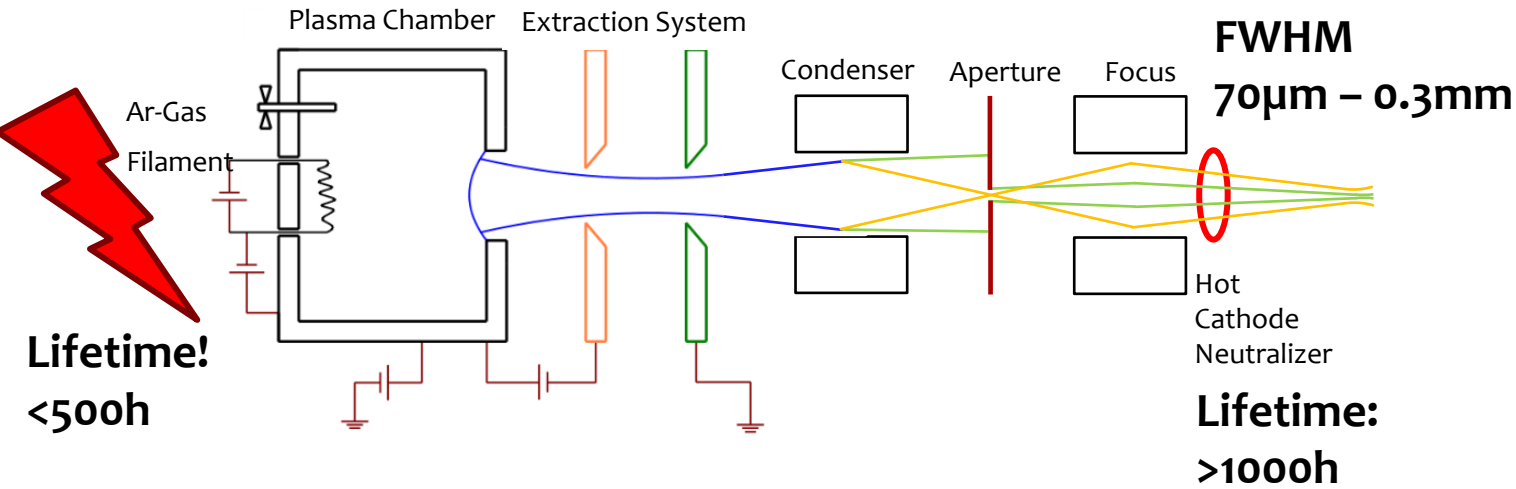
$\rightarrow$  Long term stability of  $r(x,y)$  [IBS]



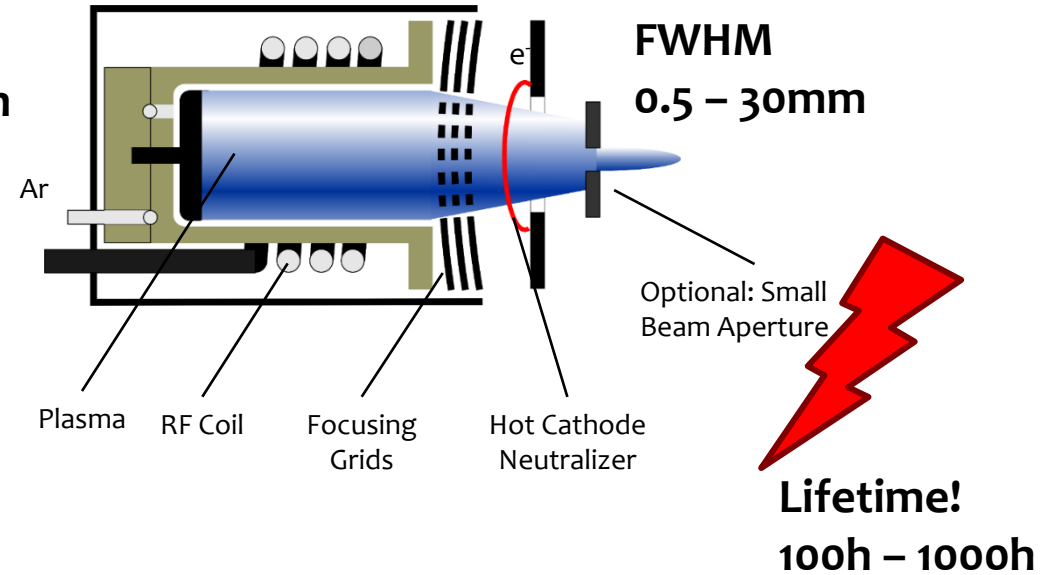


**About maintenance intervals...**

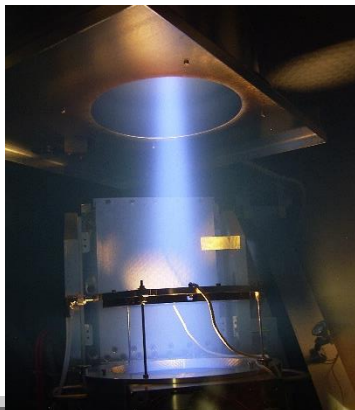
**Filament Ion Beam Source (FD 5, single beam)**



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



**Kaufman Ion Beam Source (K100, multiple beams)**



**FWHM >60mm**  
**Flat Top 100mm**



# 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 ( $\mu$ B)	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)



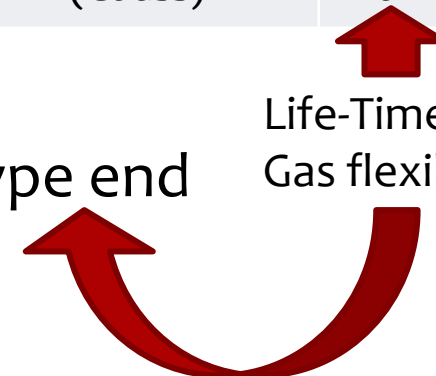
More Vol.-Rem.  
More Flexibility  
Less Contamination



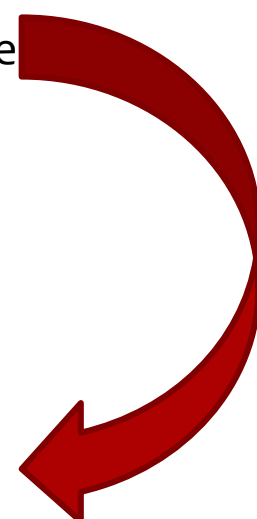
Life-Time

RF 200  
Prototype end  
of 2020

Life-Time,  
Gas flexibility (RIBE)



RF Neutralizer  
Prototype 04/2020







# Actual Developements RF 200, RF Neutralizer

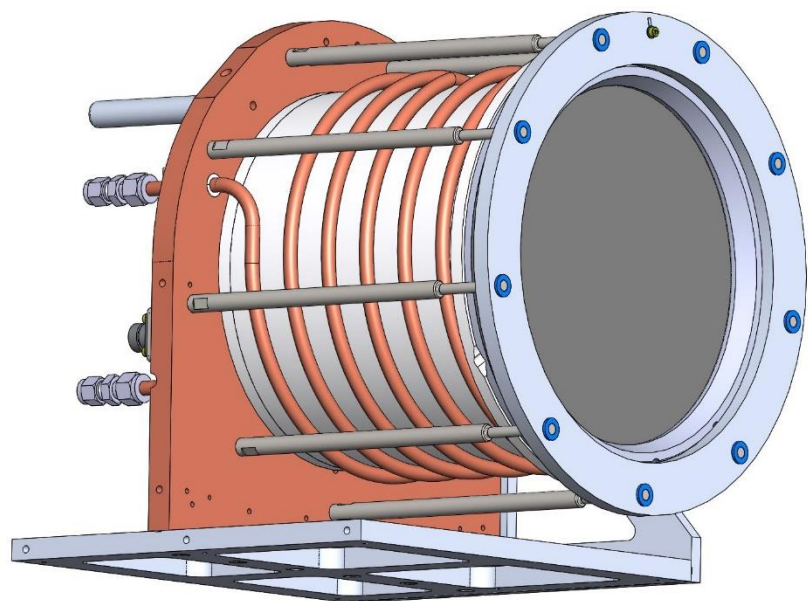
## RF200 – under commisioning

Extraction energy: 0.6 kV – 1.5 kV

Beam shape: gauß + flat top

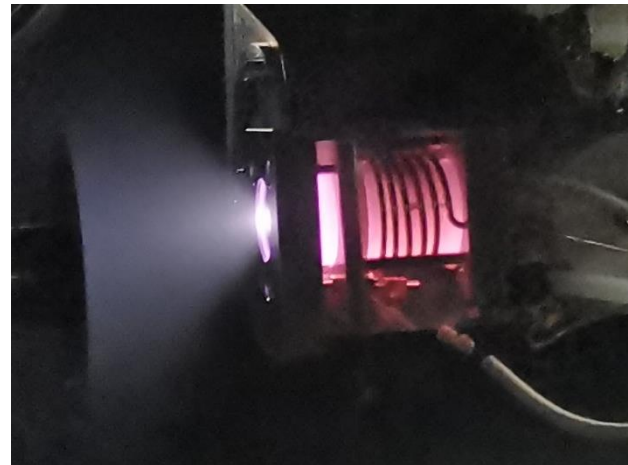
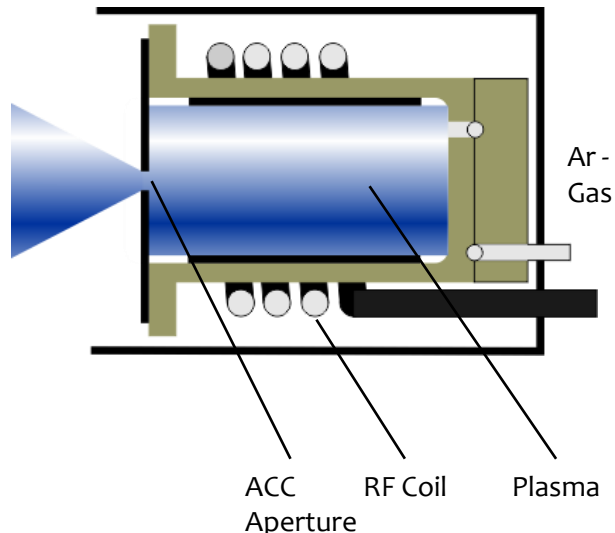
FWHM: 150 mm – 200 mm

Gas: inert + reactive

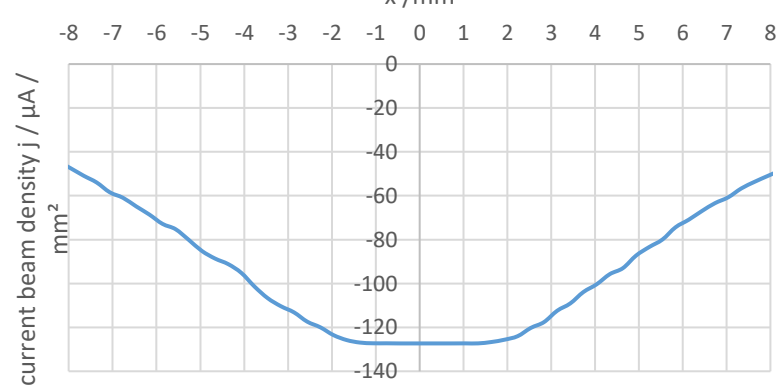


RF 200

## RF Neutralizer – prototype

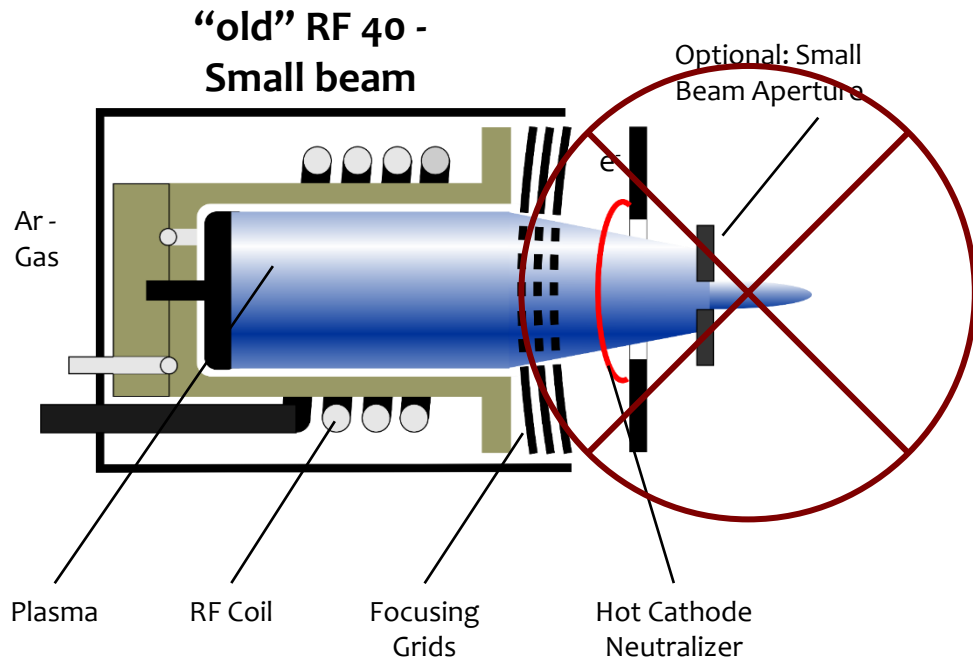


Plasma bridge e-Beam - current density



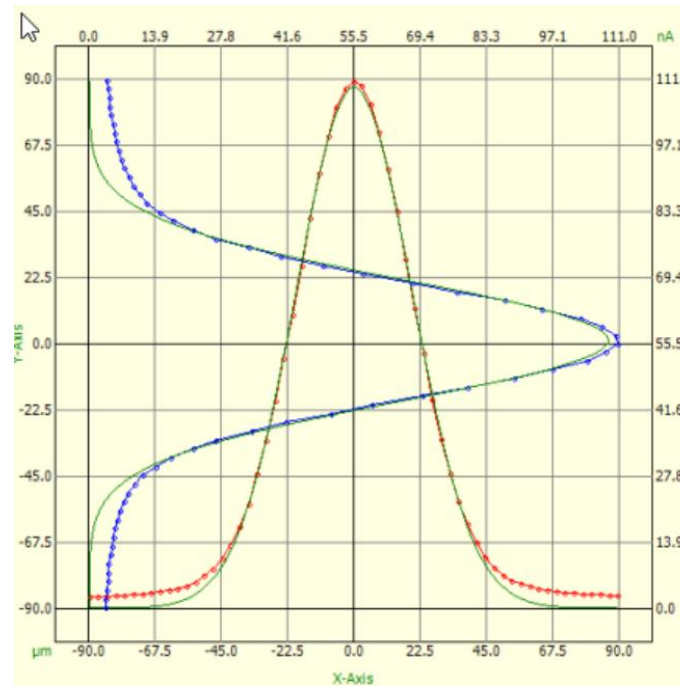
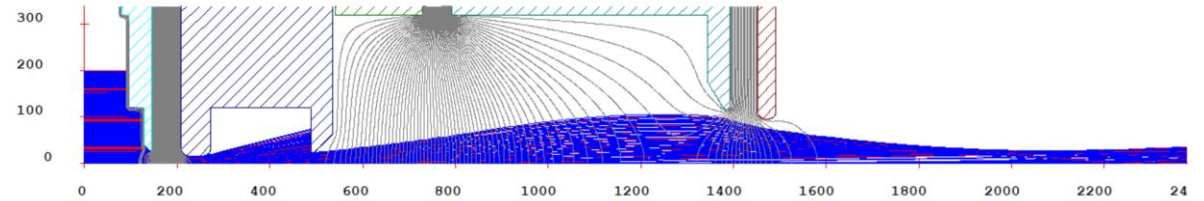


# New Development RF 5 $\mu$ B & mB

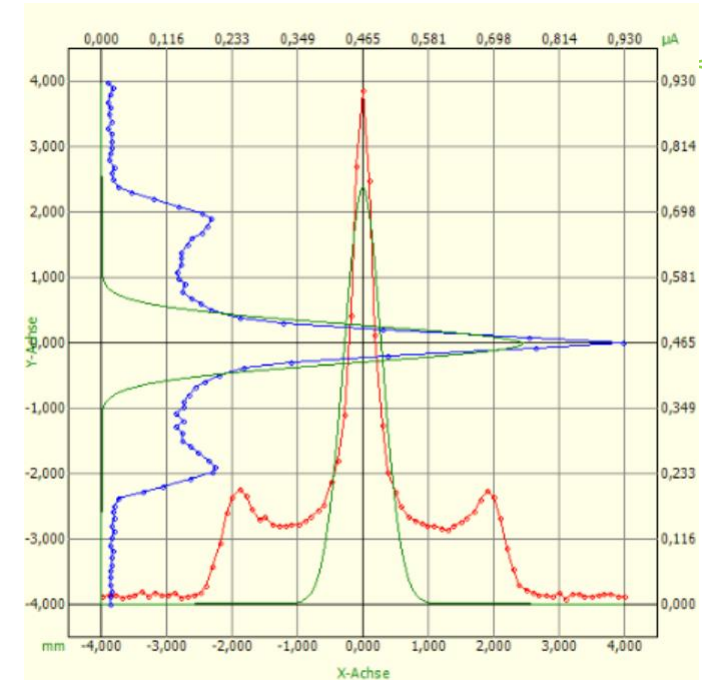


➔ No Neutralizer for conductive materials necessary

## “new” single extraction system



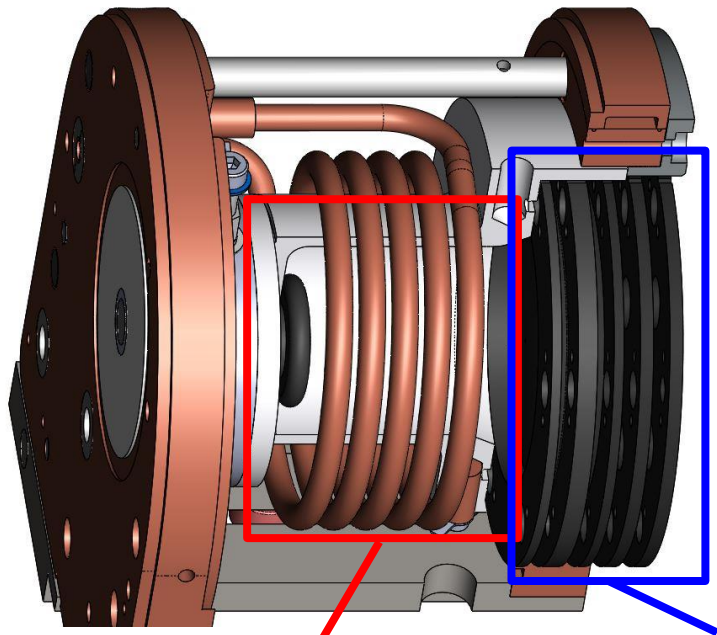
RF5  $\mu$ B  $\rightarrow$  40-150 $\mu$ m



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



# New Ion source RF 5 μB

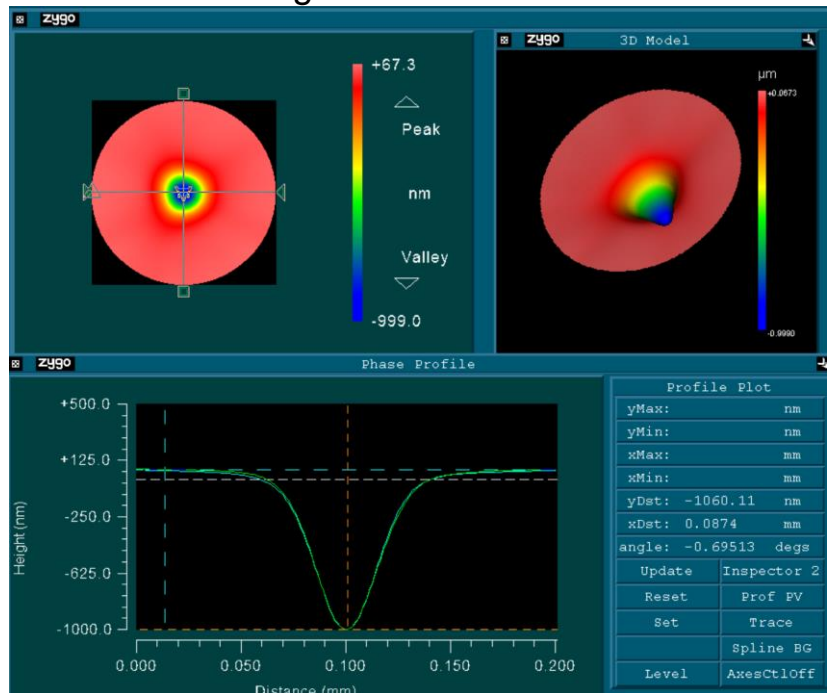


Plasma chamber

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 <sup>3</sup> /mm <sup>2</sup> /s		
chi-square :	115.824		
FHWM x / y :	0.038mm	0.038mm	

Beamparameter: Results:  
Beam energy: 2 keV Etch rate: ~25.5 nm/s  
RF Power: 50W volume rate: ~0.043 nm<sup>3</sup>/mm<sup>2</sup>/s  
FWHM: ~38 μm

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





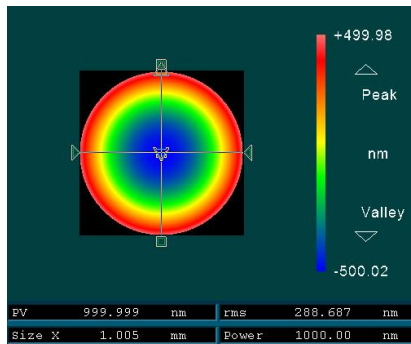
# IBF 5 - Example Sphere on Plane

## Ion Beam Parameter

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

## Sphere to generate

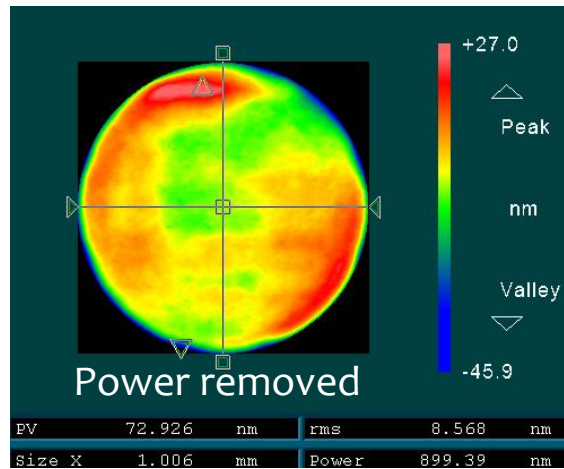
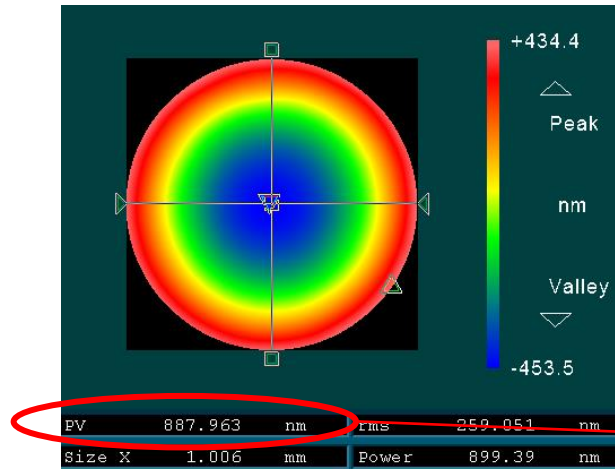
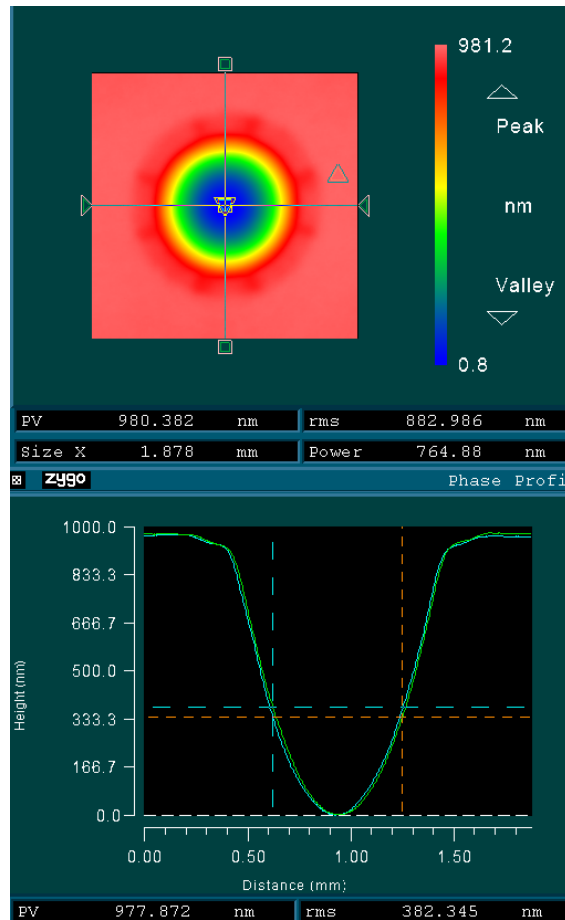
Diameter: 1 mm  
Central removal: -1  $\mu$ m  
 $\rightarrow$  Radius: 125 mm



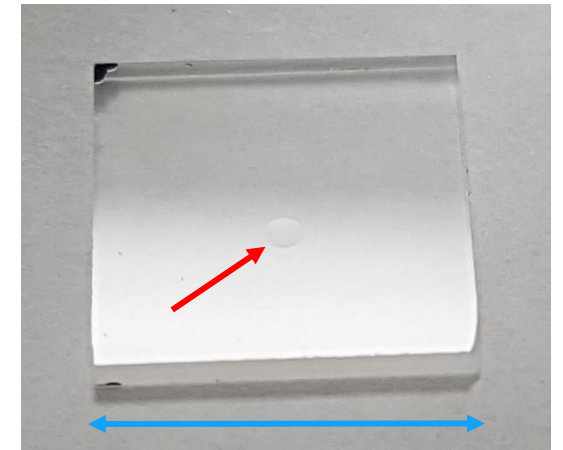
Application: Mirrors, Laser Optics,  
Wavefront manipulators

Any shape possible

# Spherization

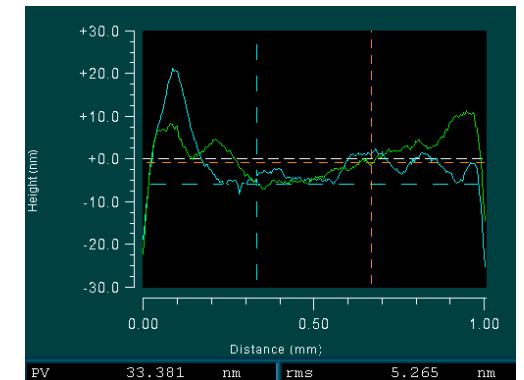


Residual error  $\emptyset$  100%  $\sim$   $\lambda/10$



10 mm

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



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



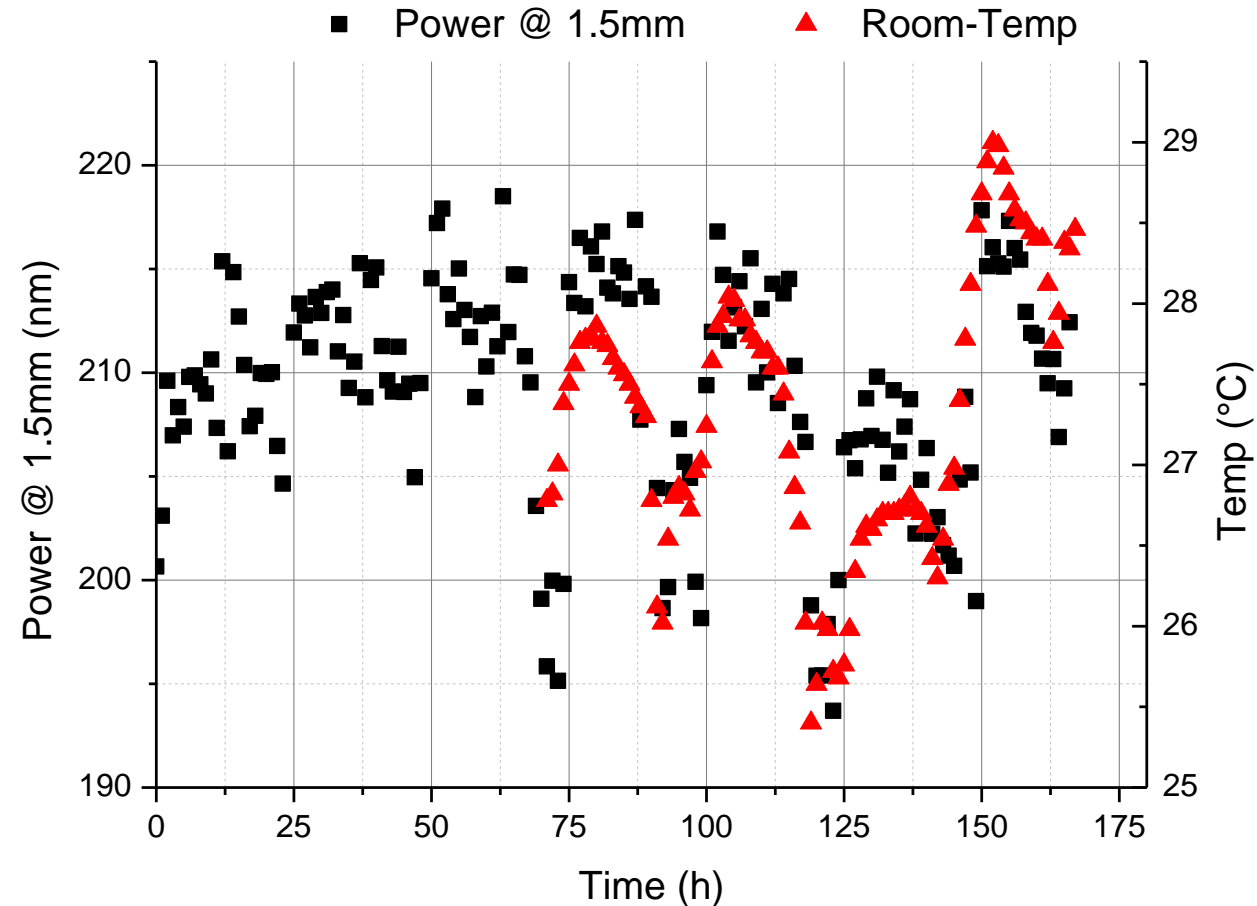
## Long term Sphere etching test

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%)  
 $\sigma$  = 5.4 nm (2.6%)

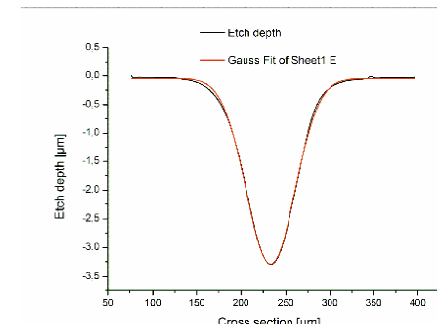
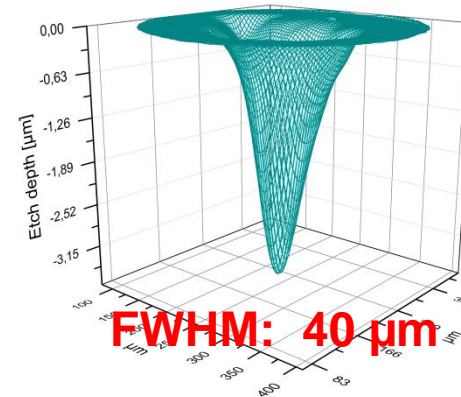
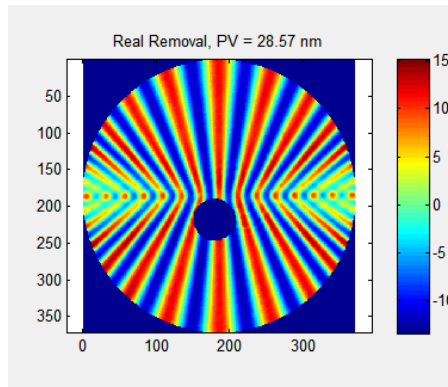
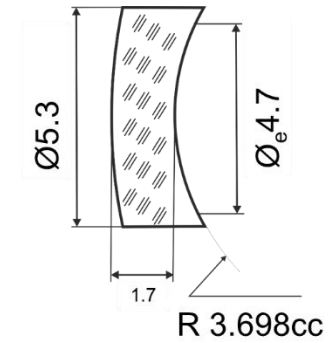
→ It seems roomtemperature mainly defines the error budget (NTG IBF 5 lab machine)





## IBF 5 – New possibilities for smaller optics

- IBF 5 – IBF for Micro Optics
- Examples





NEW 2020 !

## IBF 5 Machine Design



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

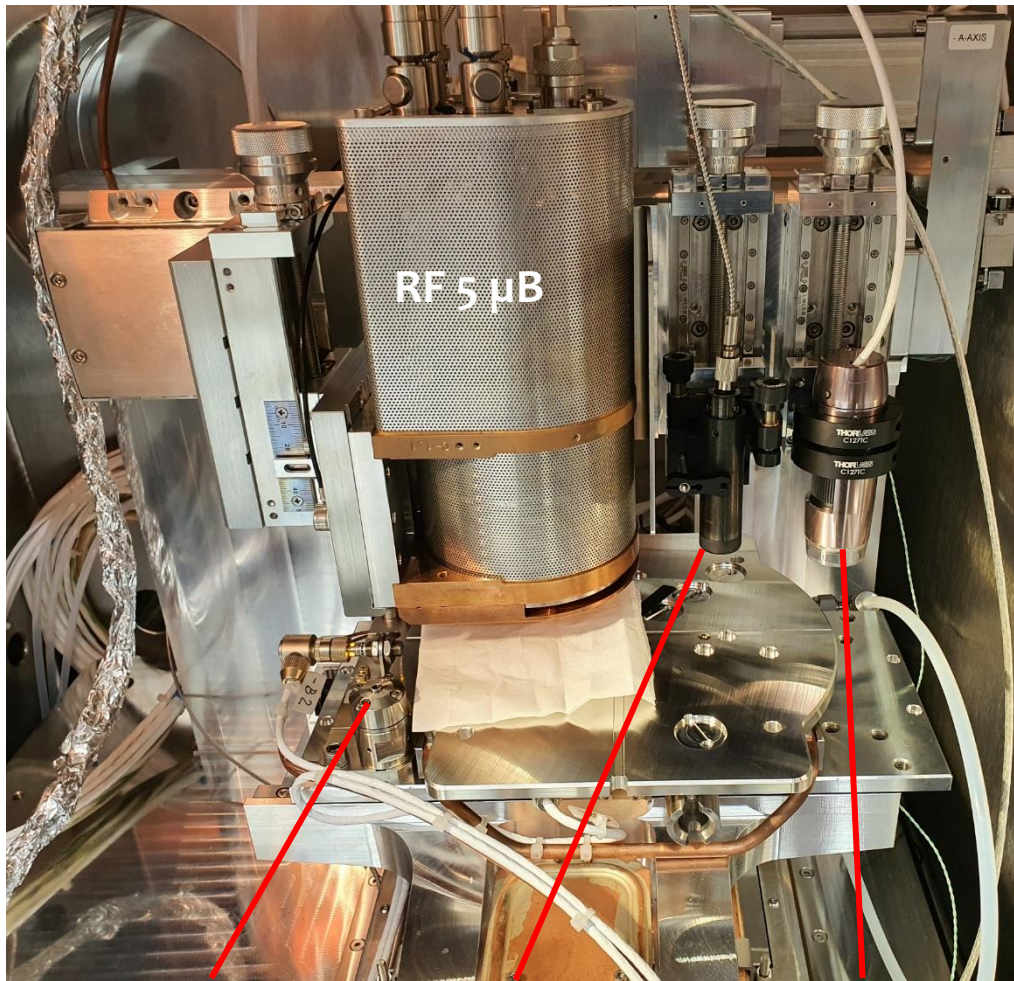


### Technical data:

Optics Size:	$<\varnothing 5\text{mm}$ $<\varnothing 0.2$ inches
Contact angle:	max. $72^\circ$
Shape:	freeform
Working Travel range:	100 x 100 mm <sup>2</sup>
Thickness:	$<50\text{mm}$ (20 inches)
Weight:	max. 2kg (4.4 lb.)
Alignment system: (vacuum use)	$\mu$ -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:

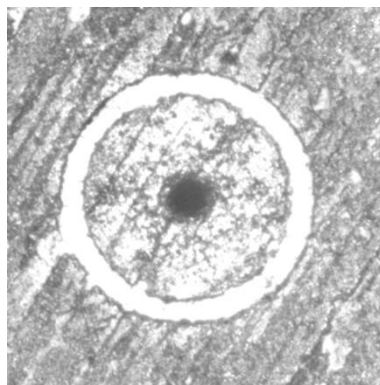
- Variable camera zoom ( FoV ~1.5mm... >20mm)
- Confocal illumination visualize test etchings

## Confocal System:

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

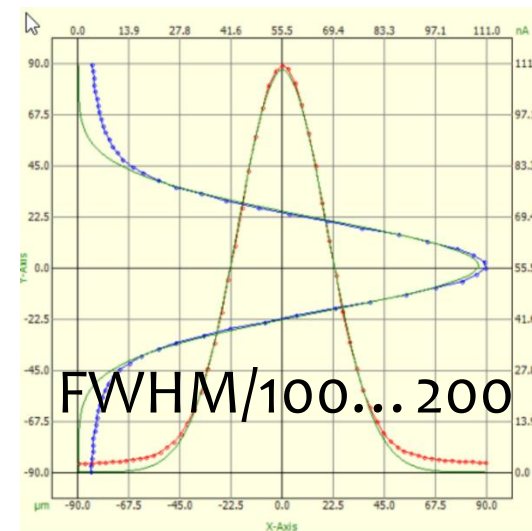
## One Common reference:

- 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

Cam: Cam connect: Dino-Lite Edg, Cam disconnect, Settings

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: Ion Source, Camera, Confocal Sensor

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

Circle Detection:

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

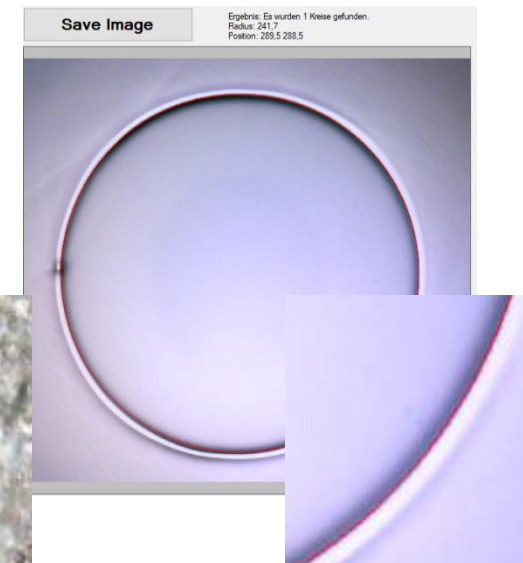
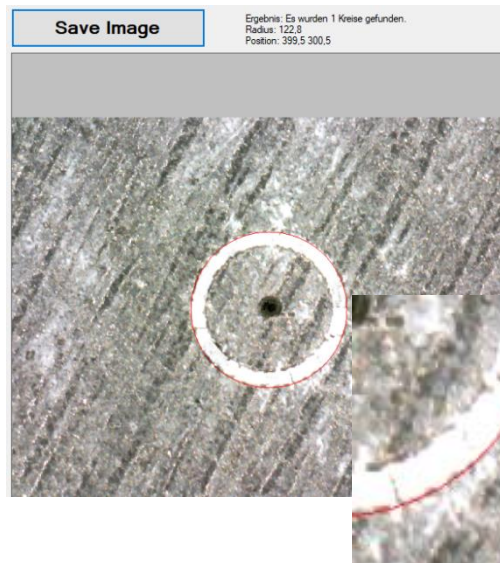
Save picture, Open list, Read Next Position, Run Circle Detection: 1, Load Trans para, Loop, Save Trans para, Fit

Circle on/off:

26

4μm deep Footprint  
T = 100S

- Circle Autodetection
- Automated Measurement loop for several fiducial measurement



→ Finally evaluate sample position in relation to μ Fcup ( $\Delta x$ ,  $\Delta y$ , Rot, Zoom)

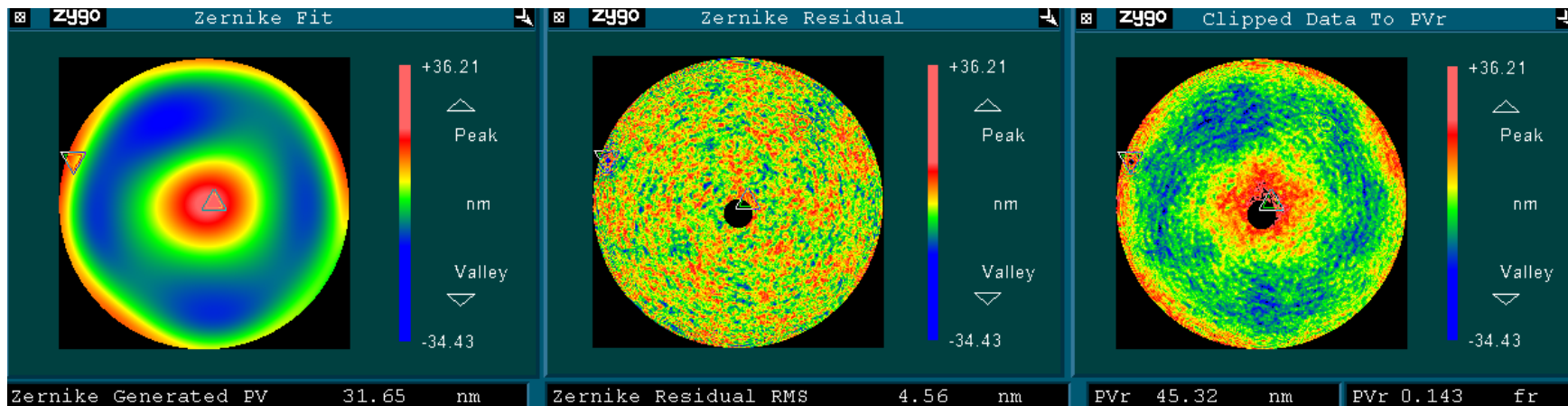
IBF processed „ring“: 500μm groove, 1μm deep T=60min





IBF 5 - Example  
Tungsten Carbide Mold

## Form Correction: Mold Ø 2.36mm



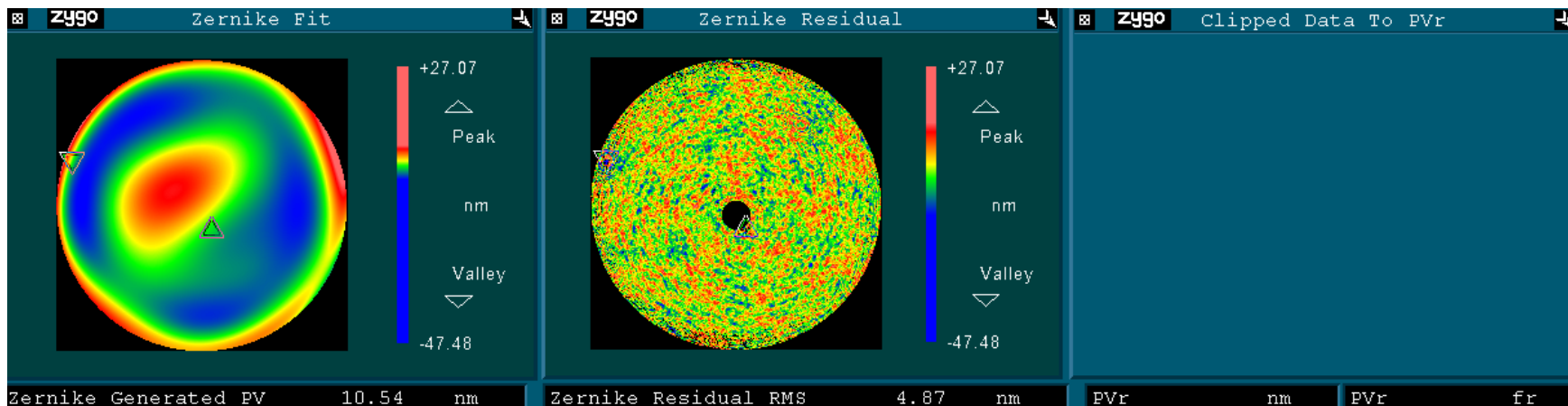
### Sample

Ø 2.36 mm, R 1.35 mm (f/0.572)

Material: Tungsten Carbide

Treatment @90%:

Measurement using f0.75 (Ø1.62mm)



### Ion Beam Parameter

Ar+ Ion Energy: 3000 V

FWHM: 70 µm

Vol.-Rate: 0.1 mm<sup>2</sup>/nm/s

Processing Time: 0:06h

NTG lab machine



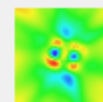
# IBF – New State-of-the-art Resolution Limit

**Ion Beam:**  
**Energy [eV]:** 2000

double Gauss fit

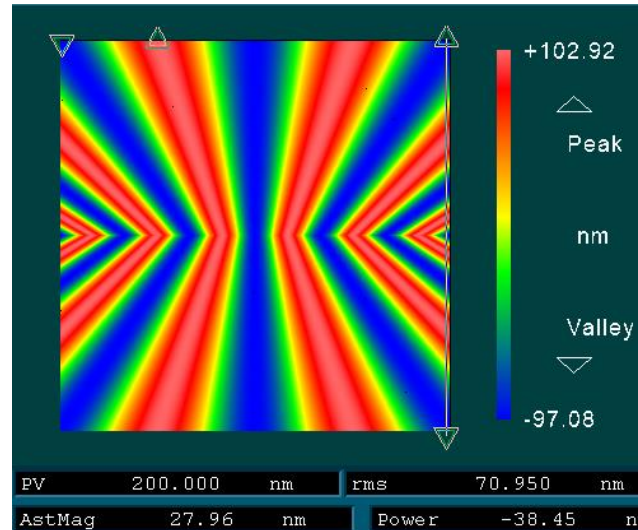


double Gauss fit error

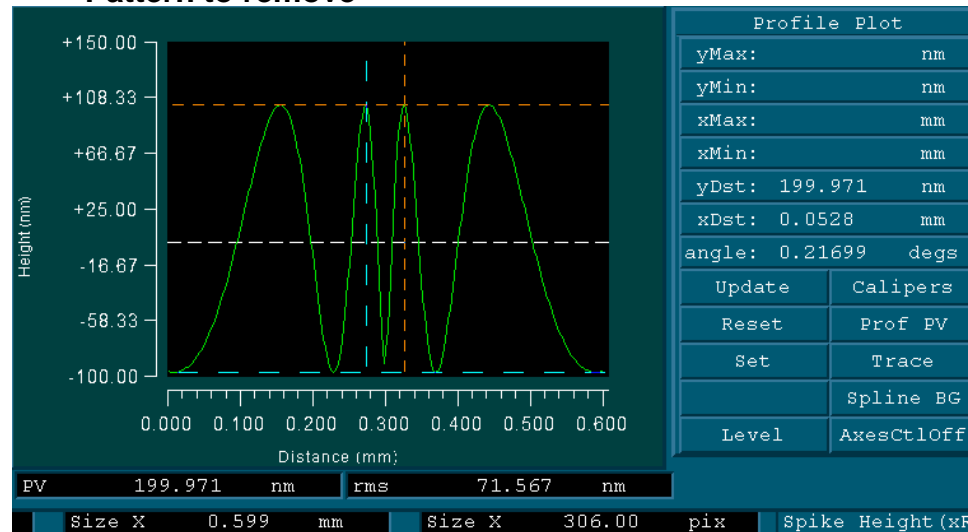


baseline :	1.113nm/s	
tilt X / Y :	0.561/s	3.701/s
maximum 1 :	20.322nm/s	
FHWM X / Y :	0.049mm	0.050mm
shift X / Y :	0.001mm	0.006mm
maximum 2 :	14.589nm/s	
FHWM2 X / Y :	0.040mm	0.035mm
rate :	34.911nm/s	
theoretical	0.080156nm <sup>2</sup> /mm <sup>2</sup> /s	
volumerate :	0.000004809mm <sup>3</sup> /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



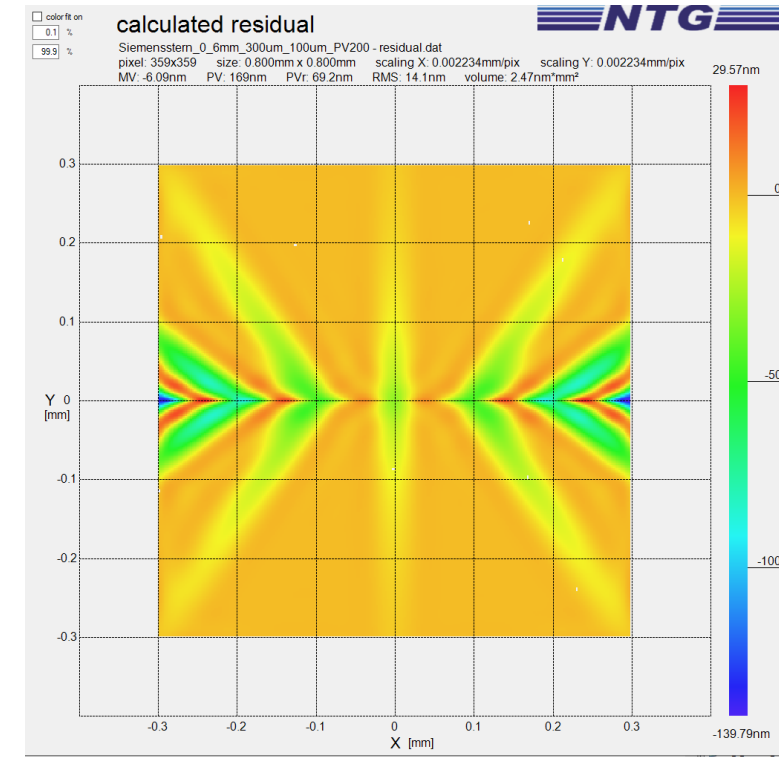
### Pattern to remove



## Simulation

### Modified Siemensstar:

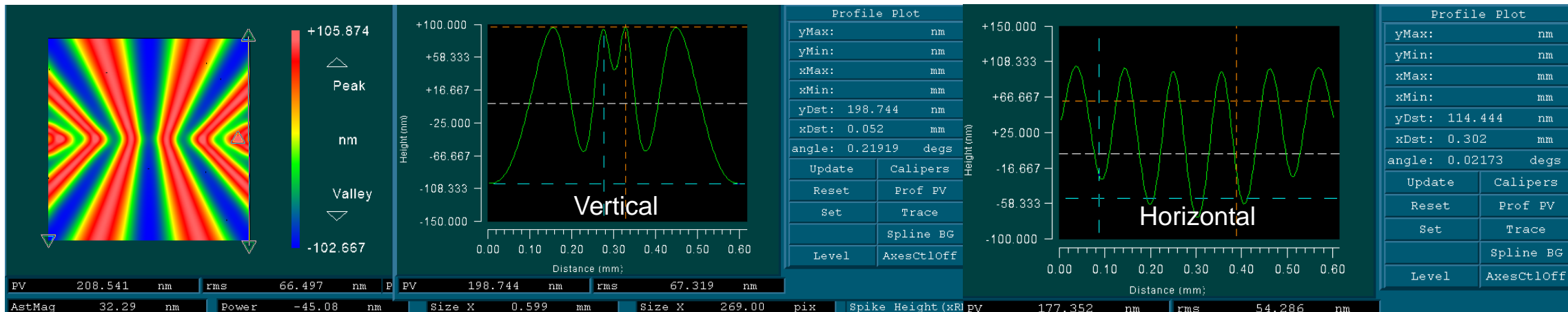
PV: 200nm  
 Spatial wavelengths  
 V: 300µm to 100µm  
 H: 50µm to inf.



### Calculated residual

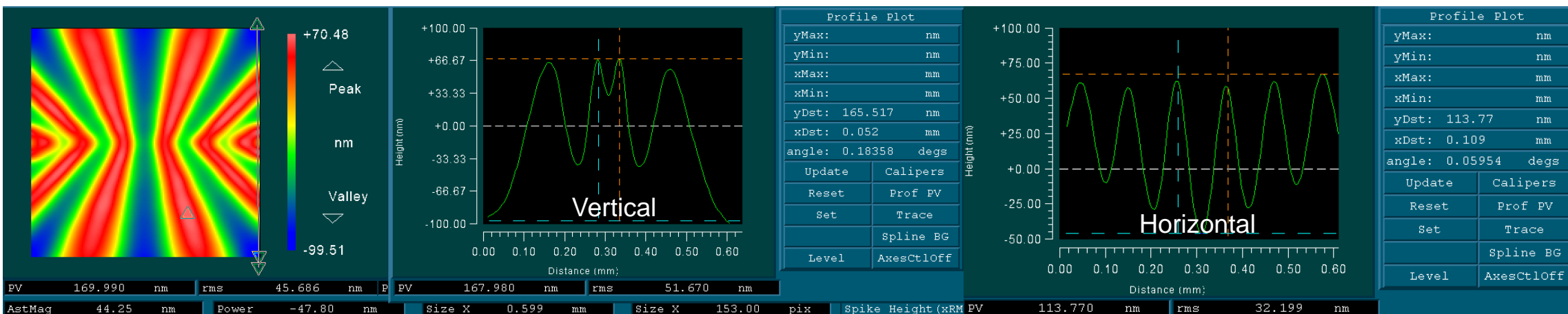


Simulated removal:



→ Full modulation @ l=100µm

Real removal:

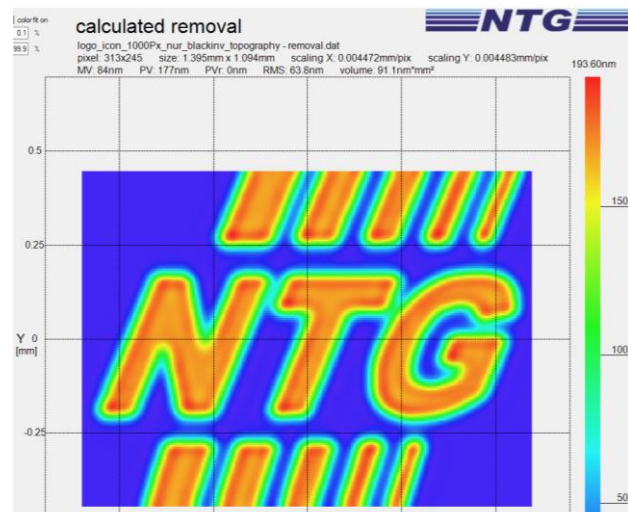




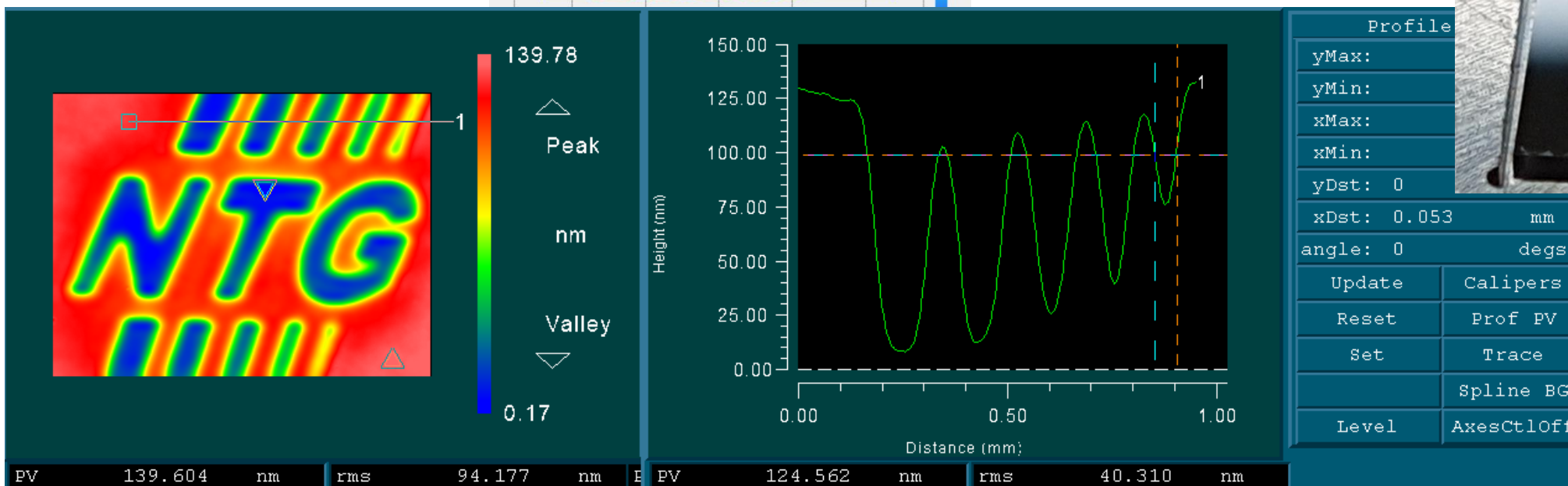
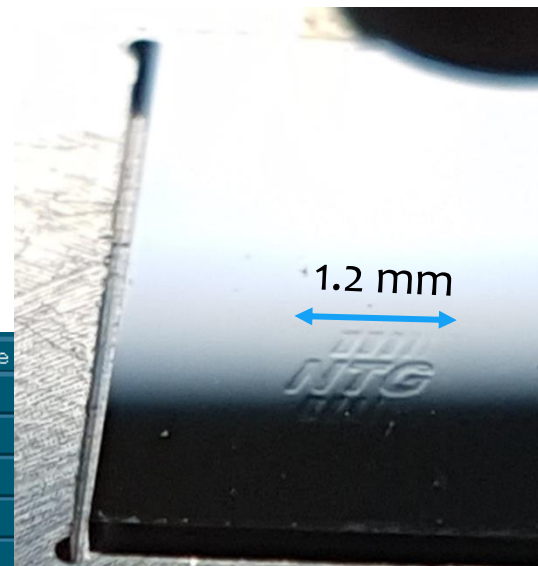


Name/Barcode Marker

# NTG



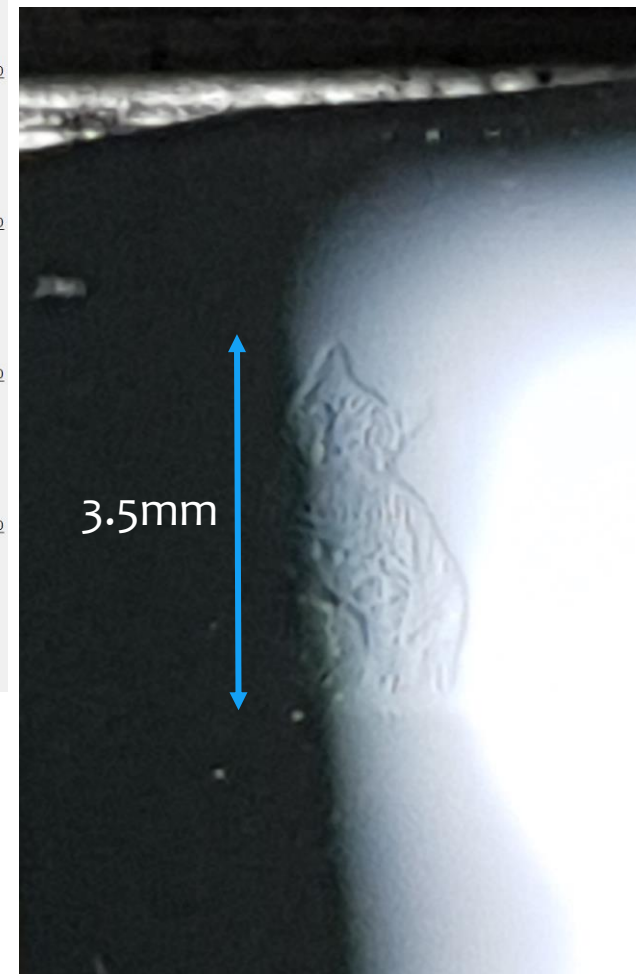
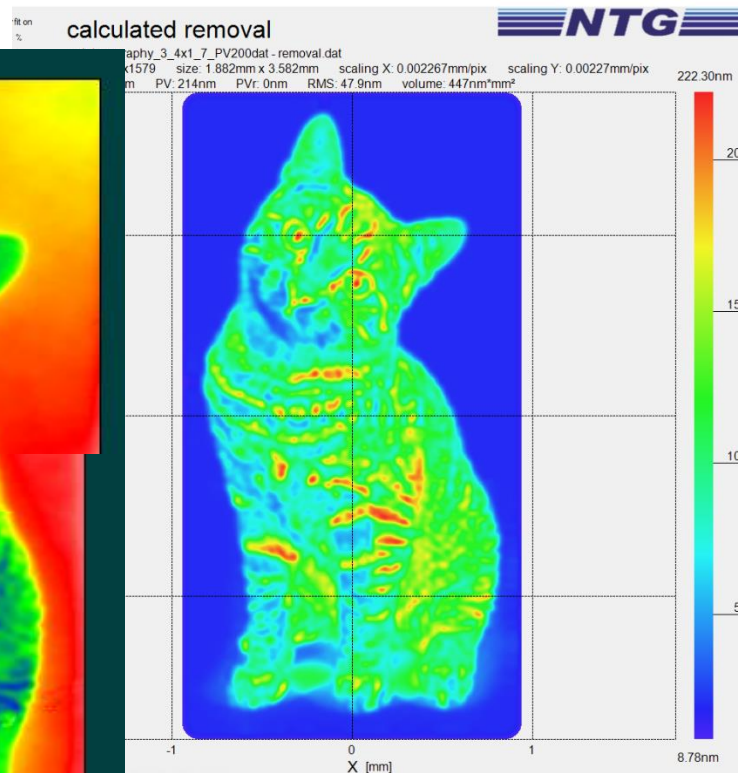
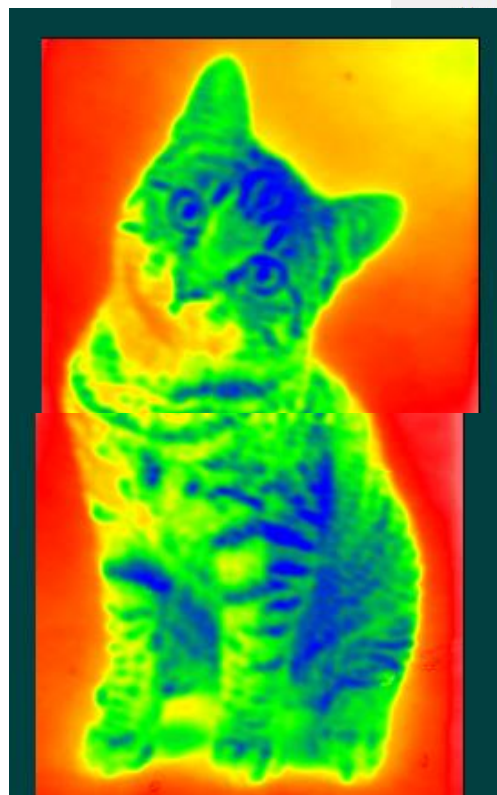
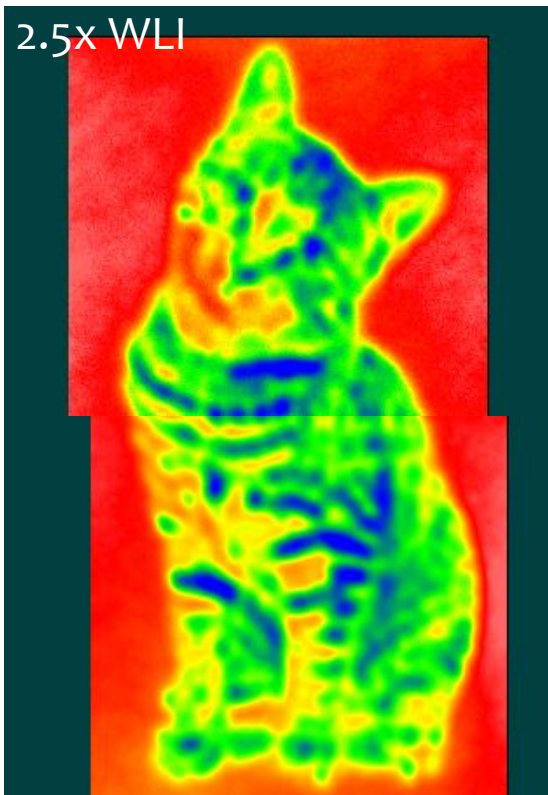
PV: 200nm  
 Beam size: 50µm  
 Processing Time: 0:24h





Comparison FD 5 / RF 5  $\mu$ B

# Schrödinger's Cat found on Silicon Wafer!!!



FD 5 Ion Beam Source

PV: 100nm

Beamsize: 70... 90 $\mu$ m

Processing Time: 0:48h

RF 5  $\mu$ B Ion Beam Source

PV: 200nm

Beamsize: 45 $\mu$ m

Processing Time: 1:34h



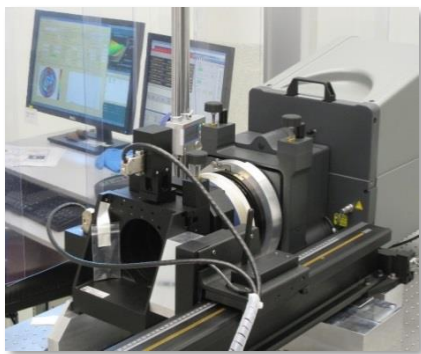
## Summary

- 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



- ▣ Materials
- Schott / Ohara,...
- WC, SiC, NiP...
- Zerodur, ULE,...
- Clearceram, TiN, AlN,...
- SiO<sub>2</sub>, CaF<sub>2</sub>,...
- Nd:YAG, KTP, BBO,...
- ... tbt