High-Gradient Test of a 3 GHz Single-Cell Cavity

4th Annual X-band Structure Collaboration Meeting

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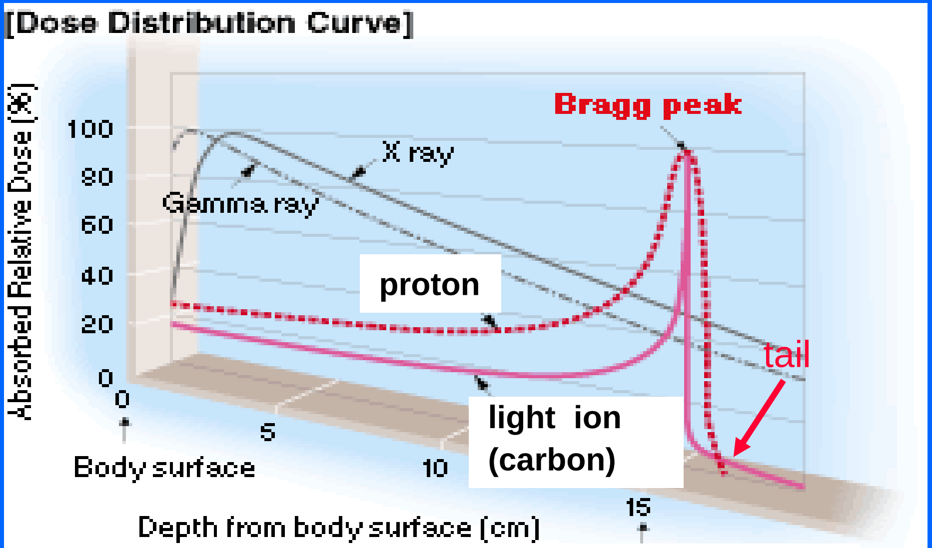
03.05.2010

Hadron therapy: *the basics*



httt://global.mitsubishielectric.com/bu/particlebeam/index_b.html

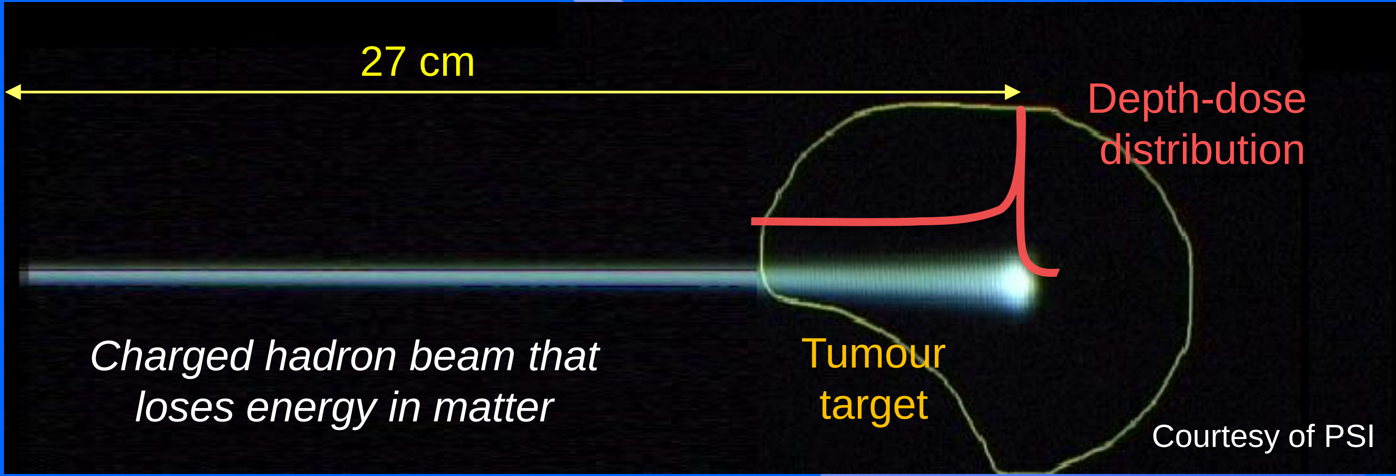
200 MeV - 1 nA

protons

4800 MeV – 0.1 nA

carbon ions

(radioresistant tumours)



Courtesy of PSI

Treating moving organs requires...

- **Fast Active Energy Modulation**

(a couple of ms)

↓

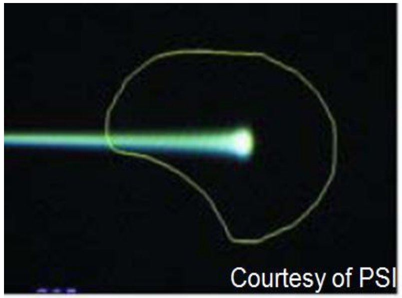
Fast 3D correction of
beam spot position in depth

- **Fast Cycling machine**

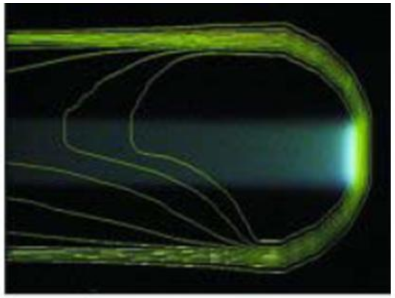
(high repetition rate ~ 200-300 Hz)

↓

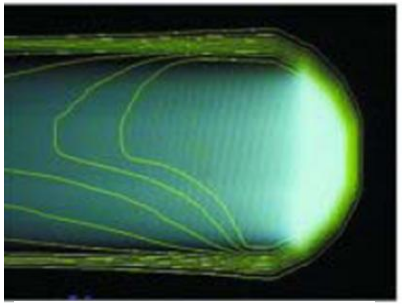
Tumour
MULTIPAINTING



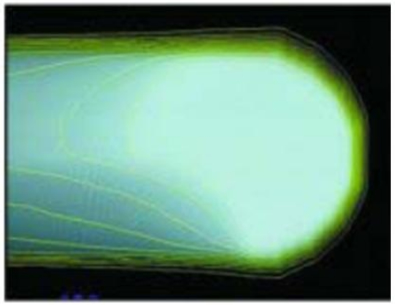
Single 'spot' pencil beam



Lateral scanning with magnets: 2 ms/step

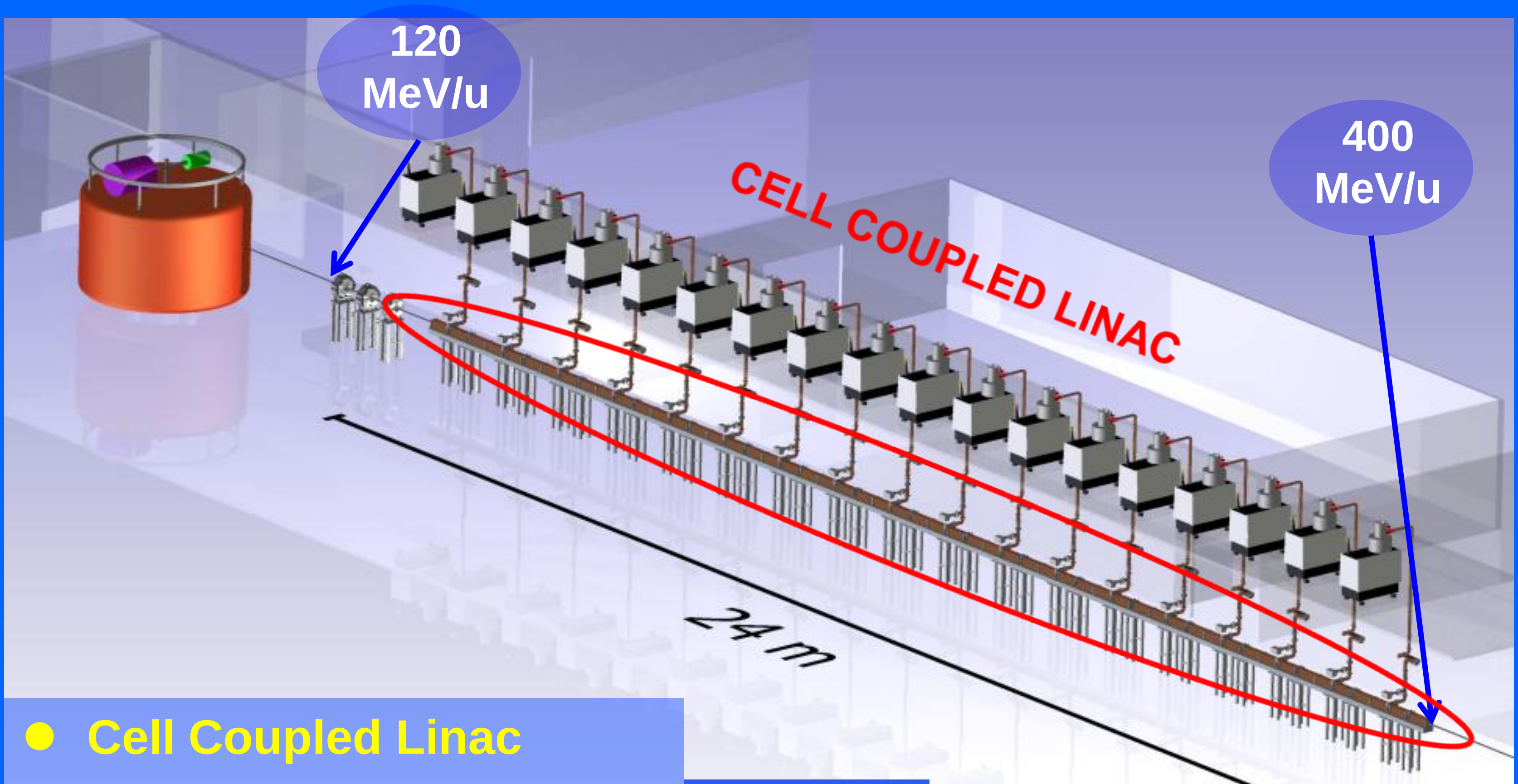


Depth scanning: ACTIVE ENERGY MODULATION



3D conformal treatment

TERA's proposal:
cyclotron + high-freq. linac = cyclinac

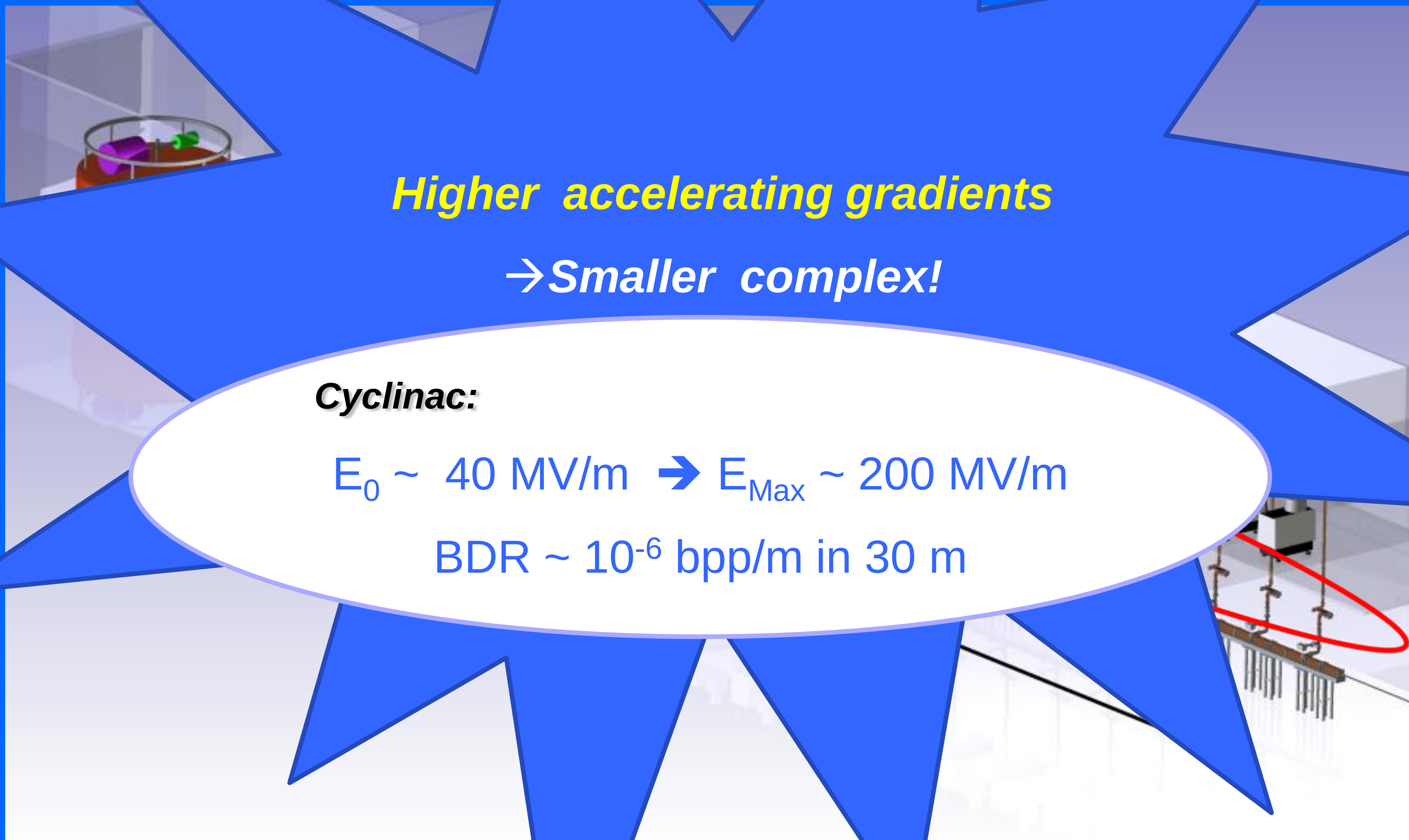


- **Cell Coupled Linac**
- **Standing-wave structure**
- RF frequency: **5.7 GHz**

CABOTO

(CArbon BOoster for Therapy in Oncology)

TER s proposal:
cyclotron high-fr nac = <u>cyclinac</u>



Higher accelerating gradients

→Smaller complex!

Cyclinac:

E_0 ~ 40 MV/m → E_{Max} ~ 200 MV/m

BDR ~ 10^{-6} bpp/m in 30 m

3 GHz high-gradient test:
motivation and objectives

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- **<u>Operation limit</u> for S-band cavities** → Break Down Rate **BDR** per length

  Limit given by:

  - surface field E_s (Kilp.) *or*
  - modified Poynting vector S_c + scaling law (X, K-band)

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  [E_s, S_c, pulse length, temperature, repetition frequency]

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- **Applying found limit to future designs**
  - ensure reliable operation
  - optimize RF structures (efficiency, length, cost)

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  - ensure reliable operation
  - optimize RF structures (efficiency, length, cost)

→ single-cell test cavity

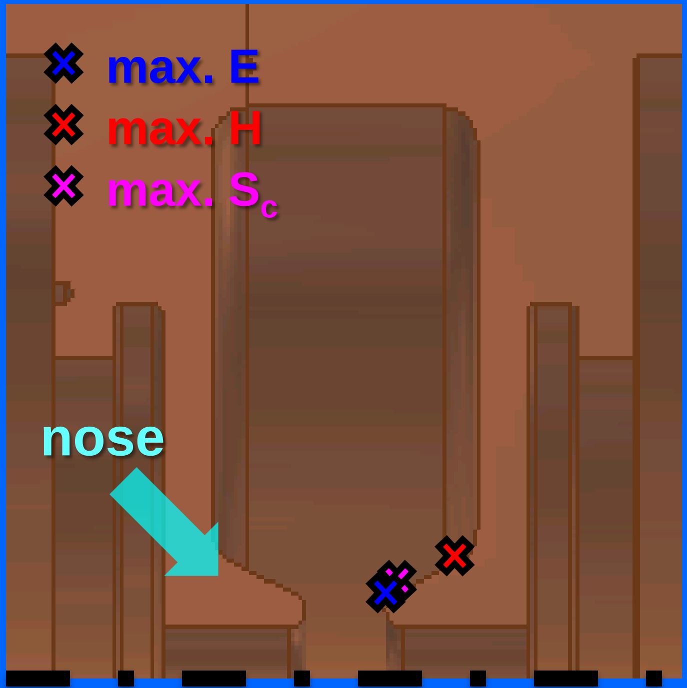
RF & mechanical design

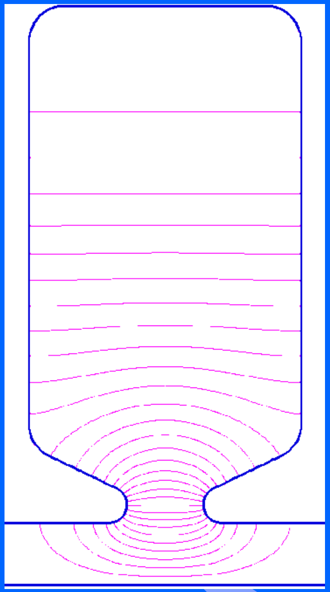
β= 0.38 (E_{kin}=70 MeV)

f_0= 3000 MHz

Q_0= 9000

E_{max}/E_0 = 6.5



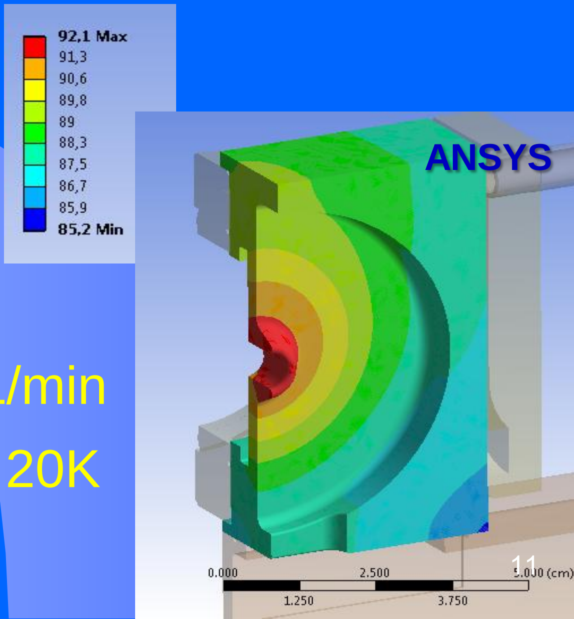


Cooling

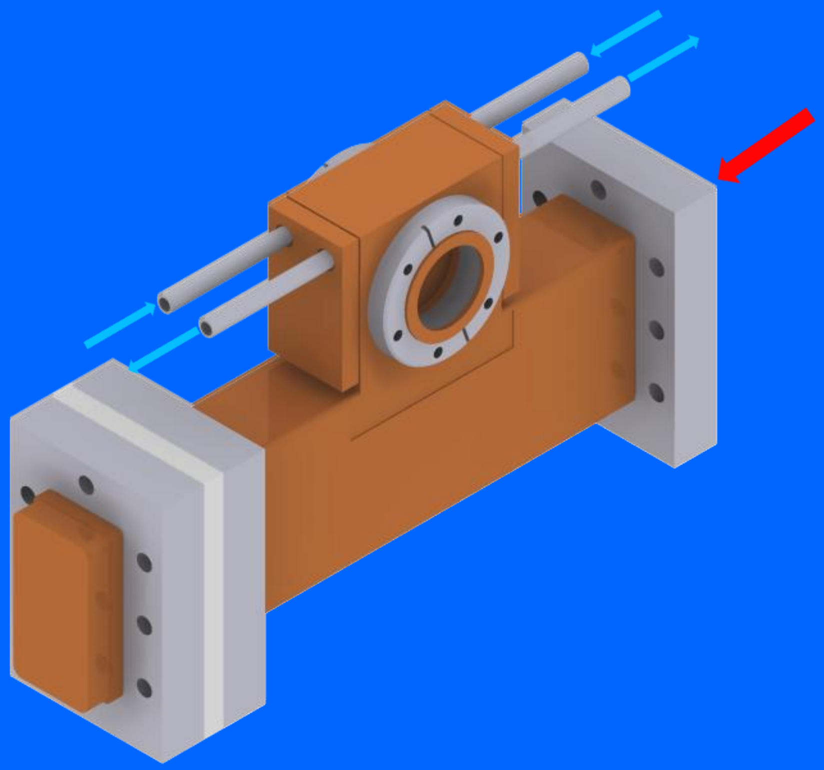
P_{ave} = 350 W

Mass Flow = 2.5 L/min

$\Delta f/\Delta T$= -1.1 MHz / 20K



Production



- OFE copper
- 0.02 mm tolerance
- 0.4 µm roughness

Accelerating cell @ 3 GHz
(two unsymmetrical half cells)

RF coupling system
(waveguide, short circuit)

Cooling system
(two plates, in-out pipes)

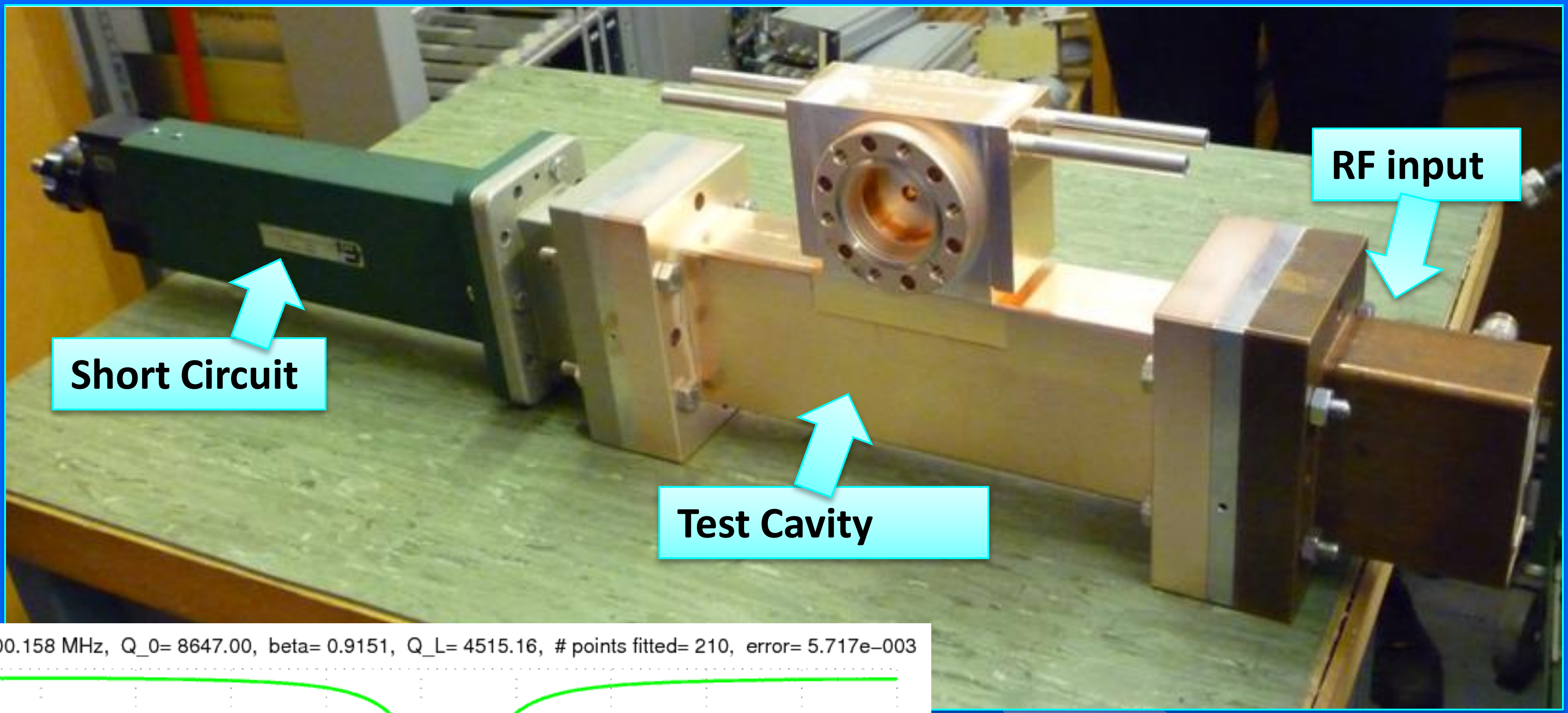
Connection to data acquisition
(through CF flanges)

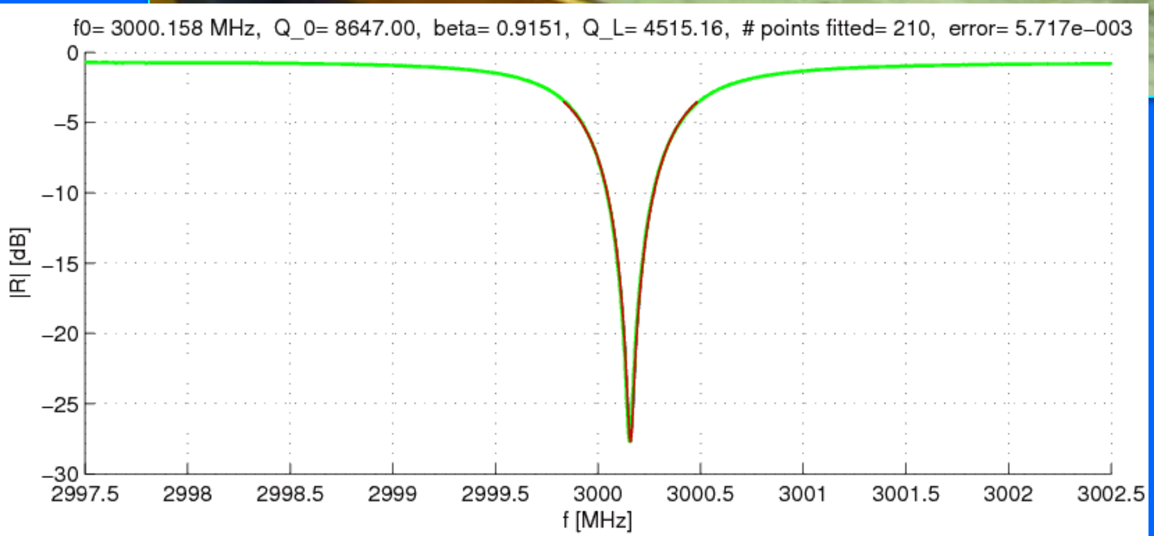
Production

- Machining at Veca (Modena, Italy)
- Cleaning at CERN (Geneva, Switzerland)
- (vacuum) Brazing at Bodycote (Annecy, France)

Done in less than one month!

Low power test





f_0= 3000.2 MHz
Q_0= 8650 (96% $Q_{0,sim}$)
β = 0.92, Γ=-27 dB

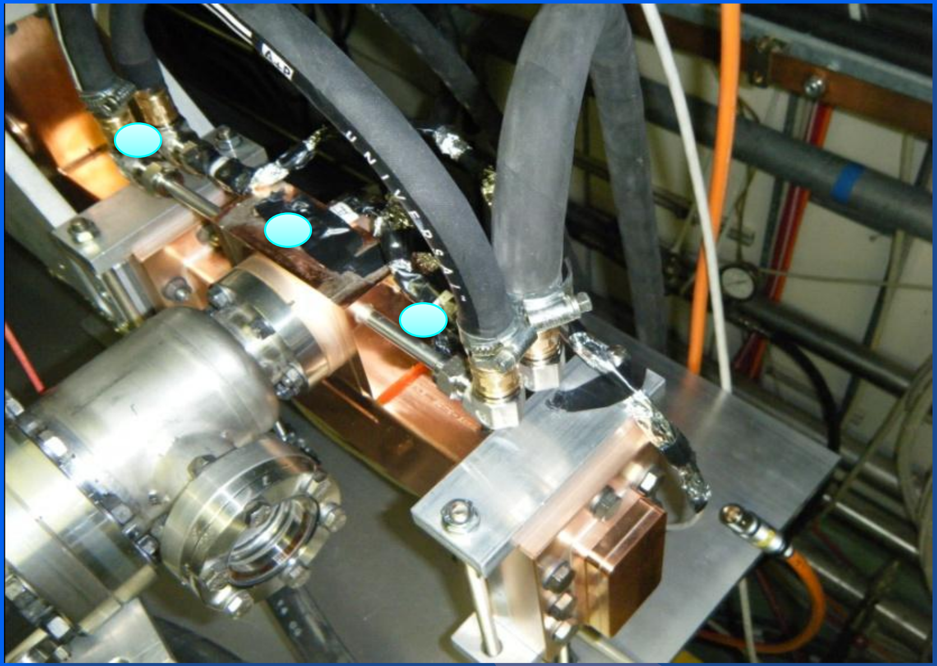
First high-power test: objectives

- <u>Debugging</u> test <u>set-up</u> and <u>cavity</u>
- First check of <u>cavity behaviour</u> under high-power
- Finding <u>improvements for precision test</u> to evaluate scaling laws [BDR(E_s, T_p, f_{rep})]

Only 1-2 weeks foreseen for test

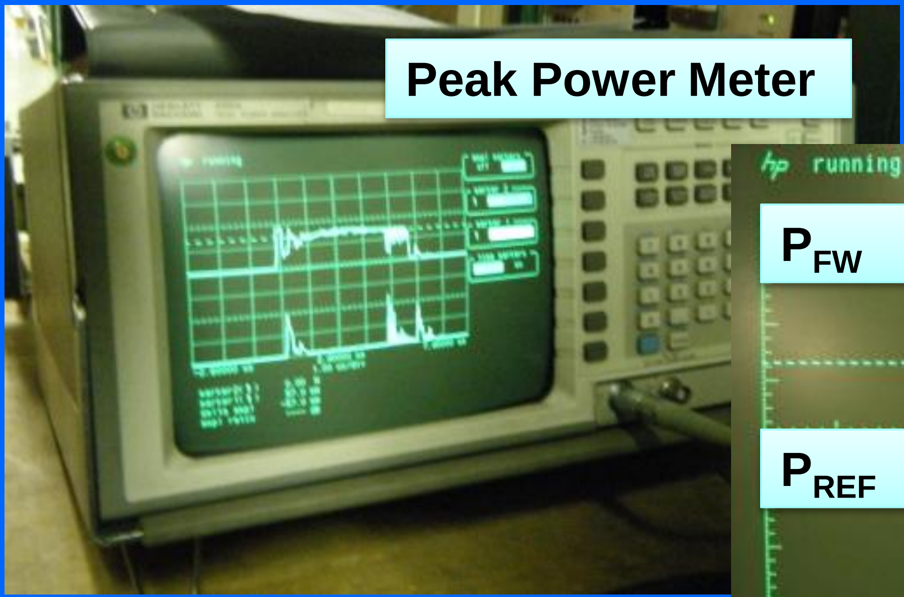
High power test: *set-up*

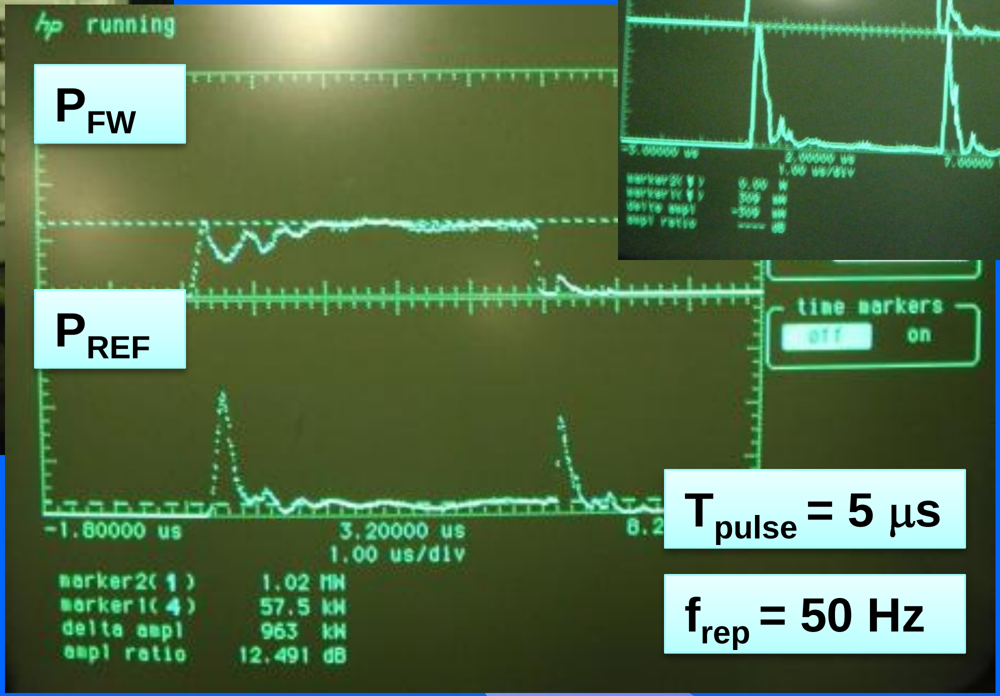
@ CTF3



- ✓ Faraday Cup
- ✓ Peak Power Analyser
- ✓ Temperature sensors
- ✖ no Data Acquisition System
- ✖ no control system for stabilising frequency & amplitude
- ✖ no RF Pickup

High power test: *measurements*





- *no RF Pickup* → relying on power measurements

$$P_{cav} = P_{FW} - P_{RF}$$

⇓

$$E_{acc}$$

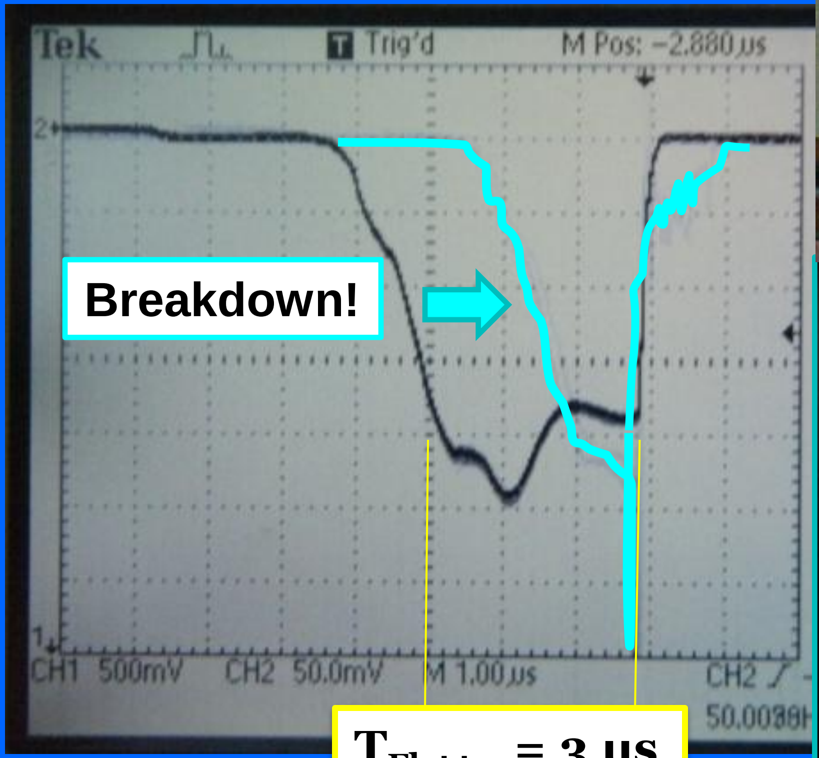
At resonance:
adjusting frequency until
$P_{REF}(f) < 10\%\ P_{FW}(f)$

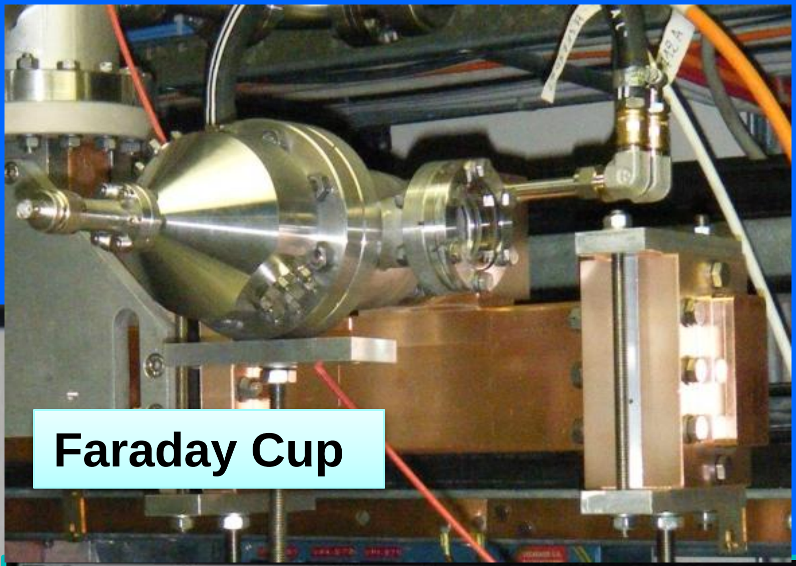
Hot cavity

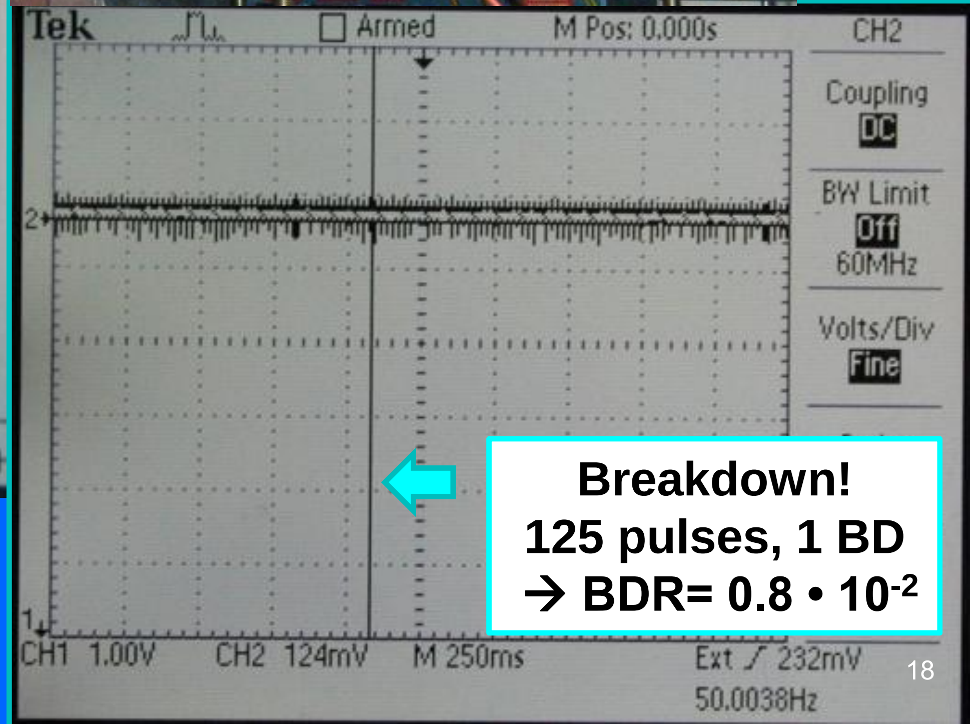
$E_S = E_{S,calculated} * 0.93$

TERA

High power test: *breakdown evaluation*



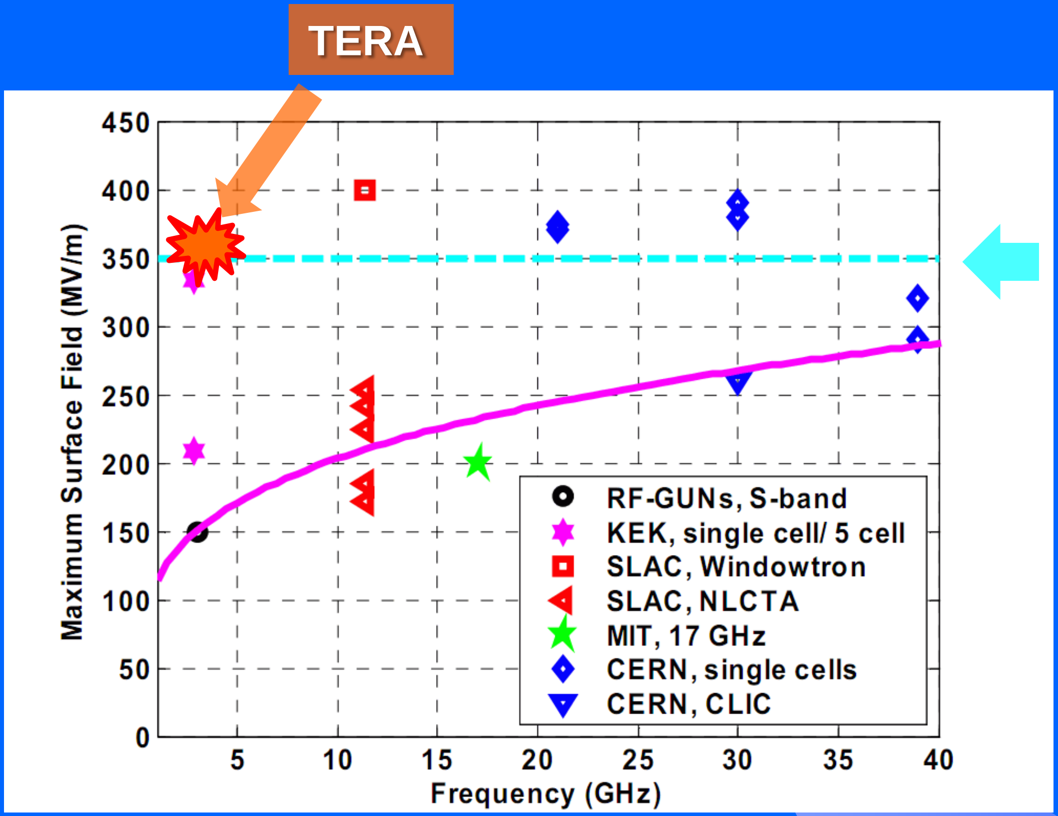




High power test: *first results*

# Set	t_{FLAT} [μs]	P_{ABS} +/- ε [kW]	E_S [+/- 10 MV/m]	S_c [MW/mm2]	BDR/L [bpp/m]	Kilp.
1	1.5	830 +/- 40	380	2.4	5.E-02	8.1
1	1.5	850 +/- 40	390	2.4	5.E-02	8.2
1	1.5	900 +/- 50	400	2.6	6.E-02	8.4
2	2.0	120 +/- 10	150	0.4	--	3.1
2	2.0	120 +/- 10	150	0.4	--	3.1
2	2.0	300 +/- 20	230	0.9	4.E-03	4.9
2	2.0	300 +/- 20	230	0.9	4.E-03	4.9
1	2.0	400 +/- 20	270	1.2	--	5.6
2	2.0	520 +/- 30	300	1.5	3.E-02	6.4
2	2.0	520 +/- 30	300	1.5	4.E-02	6.4
2	2.0	600 +/- 30	330	1.7	4.E-02	7.0
1	2.0	790 +/- 40	370	2.3	5.E-02	7.9
2	2.0	820 +/- 40	380	2.4	8.E-02	8.0
1	2.0	860 +/- 40	390	2.5	1.E-01	8.3
1	2.5	590 +/- 30	320	1.7	6.E-02	6.9
2	2.5	590 +/- 30	320	1.7	4.E-02	6.9
1	2.5	720 +/- 40	360	2.1	7.E-02	7.6
1	2.5	800 +/- 40	380	2.3	8.E-02	8.0
2	2.5	800 +/- 40	380	2.3	9.E-02	8.0

High power test: *comparison to other tests*



Limit in copper to surface field by breakdown surface damage

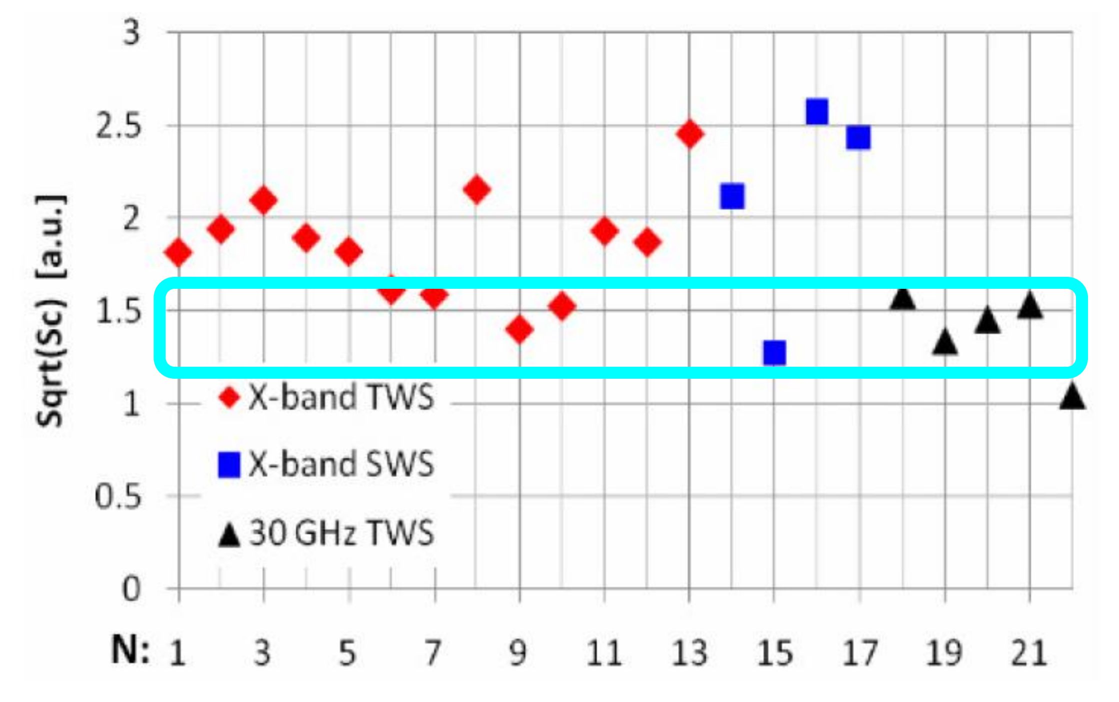
Gradient limitations for high frequency accelerators,
S. Döbert, SLAC, Menlo Park, CA 94025, USA (2004)

High power test: *comparison to other tests*

The modified Poynting vector as an RF constraint to high gradient performance

The square root of S_C has been scaled to t_{pulse} **=200 ns** and BDR=**10^{-6} bbp/m**

$$\sqrt{S_C^{equiv}} = \sqrt{S_C} \cdot \left(\frac{t_{pulse}}{t_{pulse}^{ref}}\right)^{\frac{1}{6}} \cdot \left(\frac{BDR^{ref}}{BDR}\right)^{\frac{1}{30}}$$

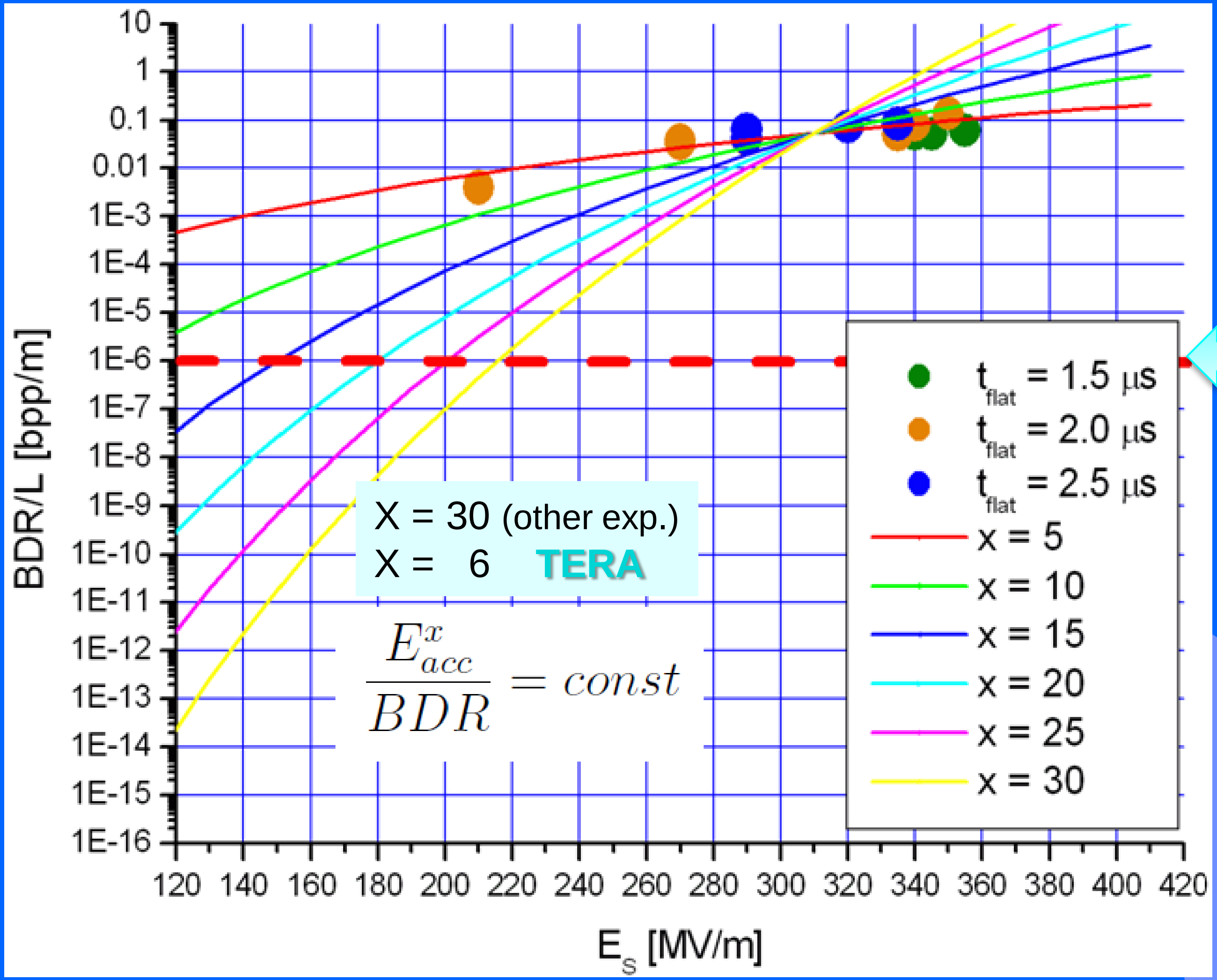


first results

Sqrt(S_c) ϵ [1.3-1.6]

A New Local Field Quantity Describing the High Gradient Limit of Accelerating Structures, A. Grudiev, S. Calatroni, and W. Wuensch, Phys.Rev. Accel. Beams (2009) 102001

High power test: *scaling laws*



$$\frac{E_{acc}^{x}}{BDR} = const$$

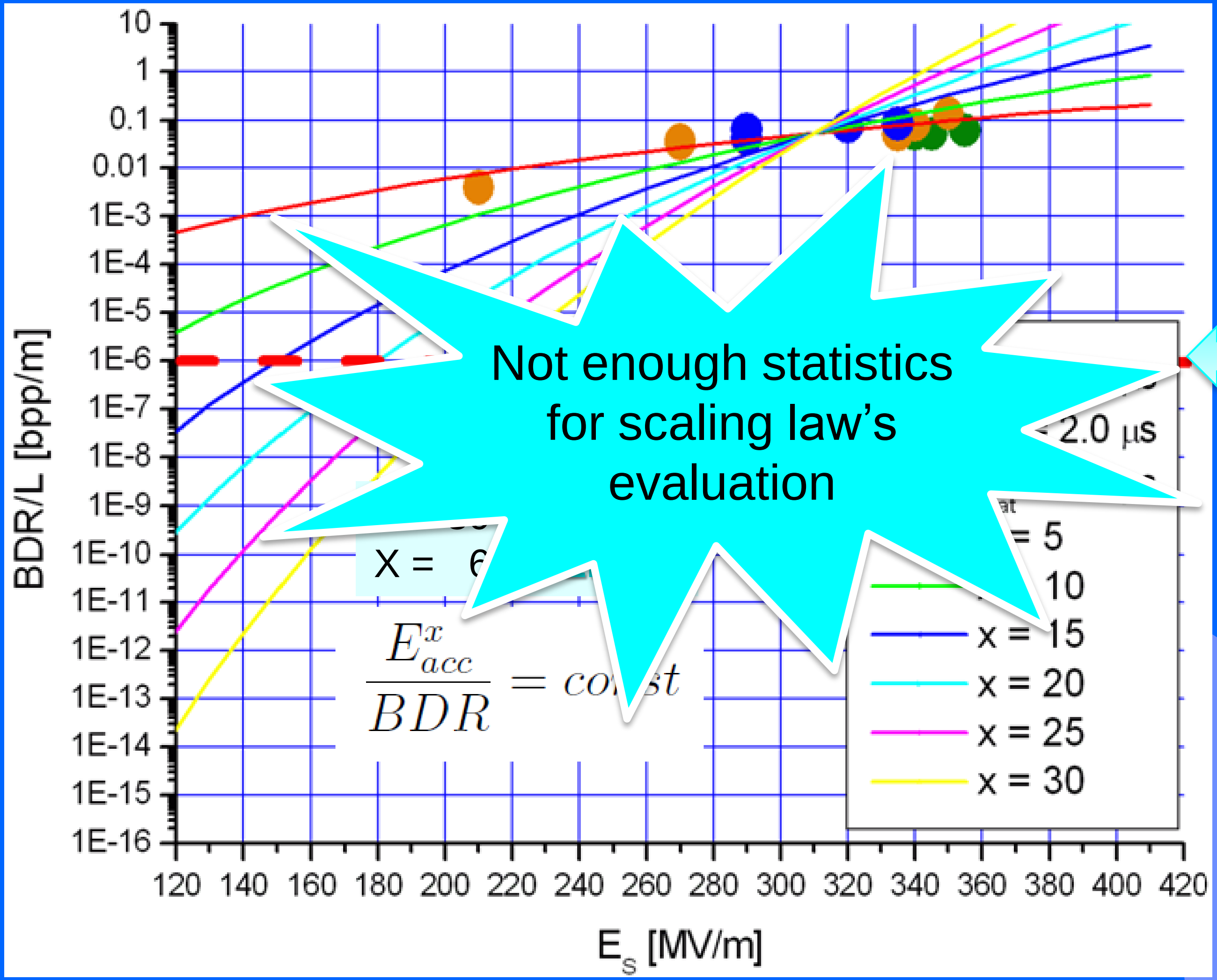
Treatment Session:

3 minutes @ 400 Hz

Max. *1 BD per session*

Max.BDR:
10^{-6} bpp/m

High power test: *scaling laws*



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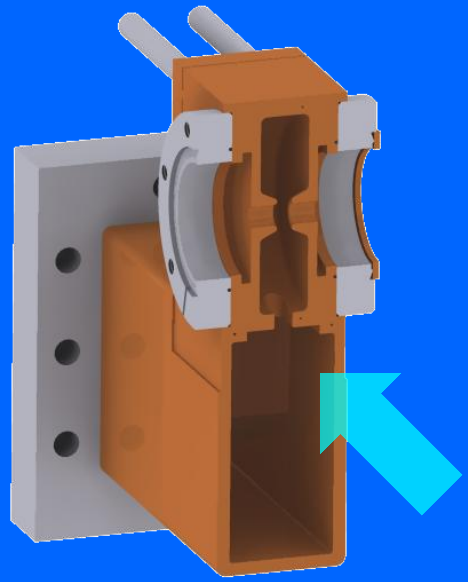
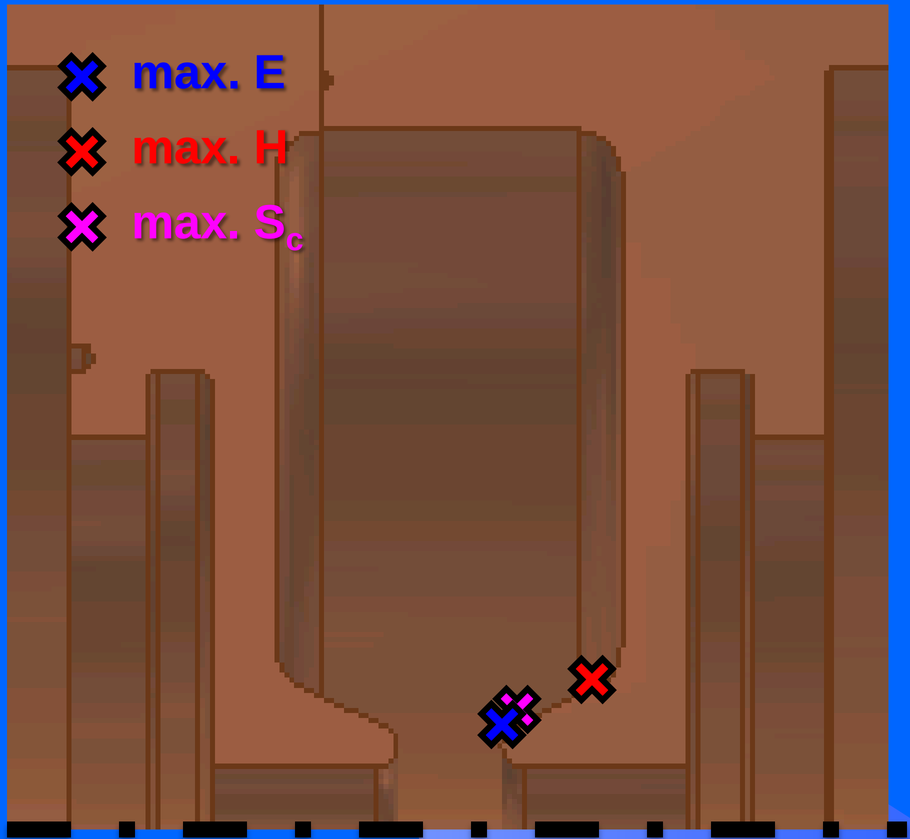
Surface inspection around nose region

[90X Optical Microscope]

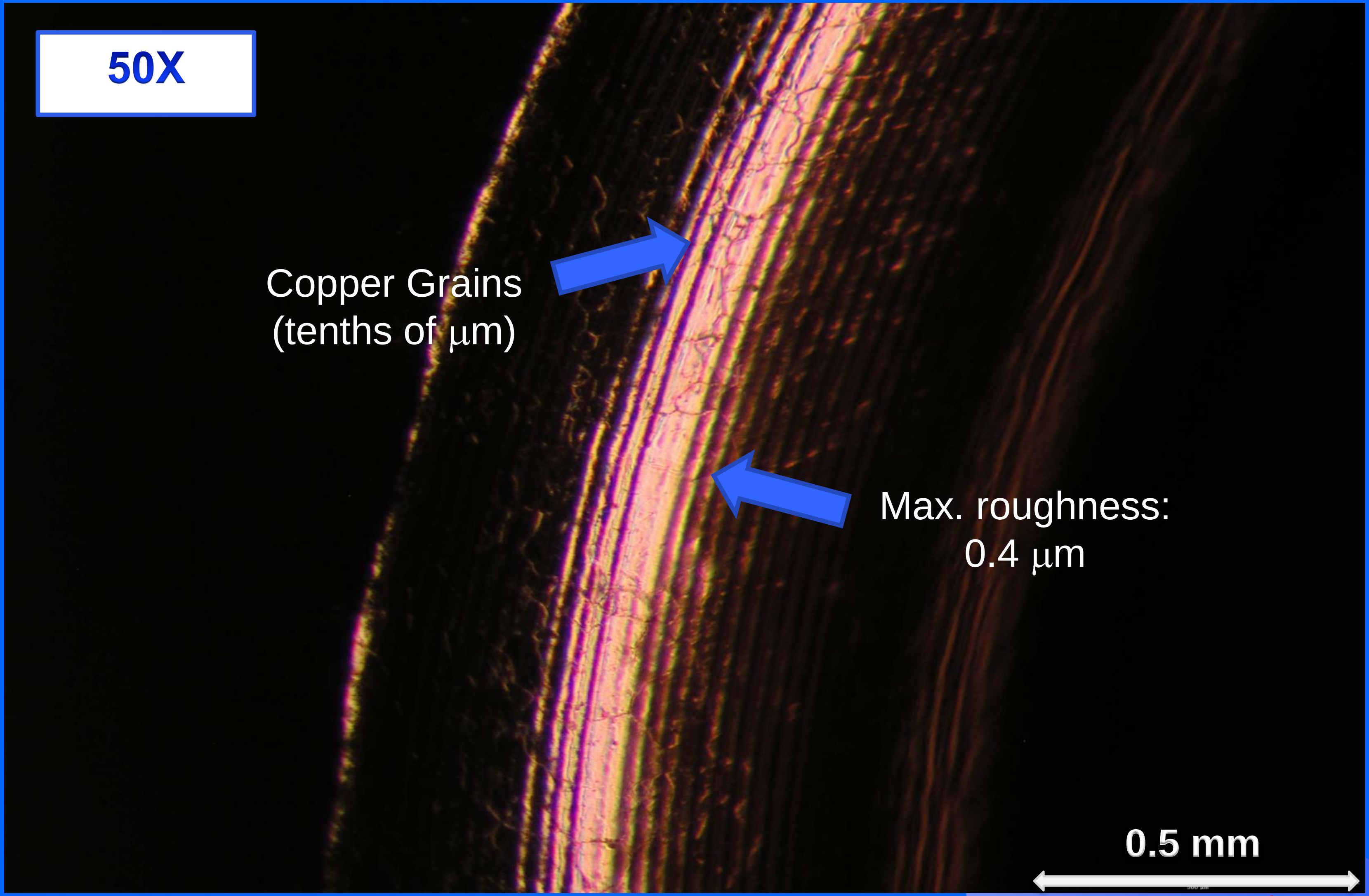




<u>*Activity in the cavity*</u>*:*

~ 14000 breakdowns

Surface inspection around nose region



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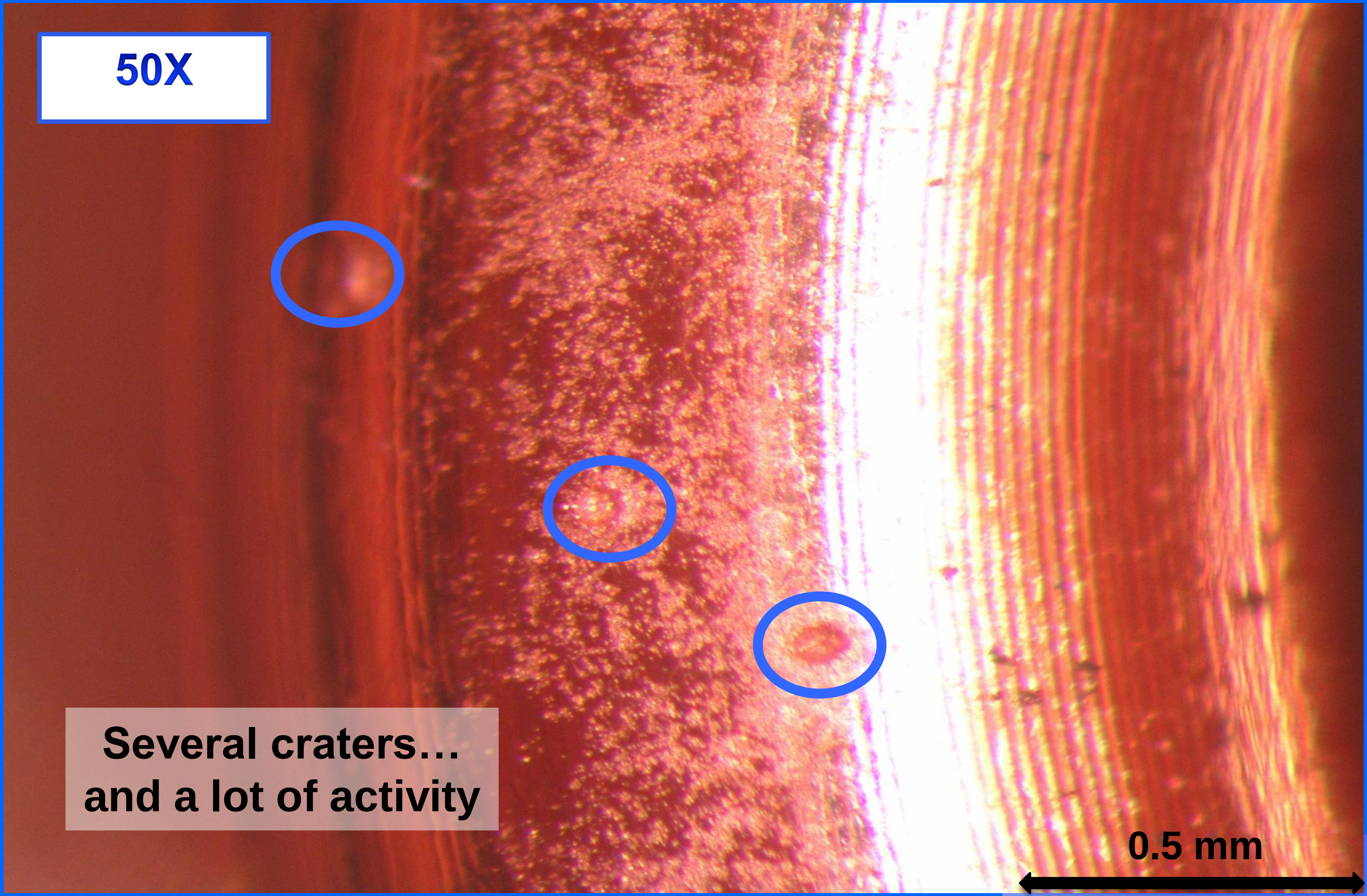

Summary

- Excellent Pre-Test, cavity works, even first results

SYSTEM	RESULTS / IMPROVEMENTS
Vacuum system	very good
Cavity - low power	very good >96% Q_0, f_0 ok, β=0.92 (Γ<-27dB)
Cavity - high power	very good E_S > 350 MV/m, BDR < $2 \cdot 10^{-1}$ /m, T_{pulse} = 2 μs
Cooling	freq. shift too big => water flow too small

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- Improvements for high-precision test
  - cooling / water flow control
  - data acquisition ($P_{forward}$, $P_{reflected}$, $\varphi_{forward}$, $\varphi_{reflected}$, $V_{faraday\ cup}$, vacuum)
  - control system for stabilising frequency & amplitude

Next steps: *a lot to do!*

- High-precision high-power test of the 3GHz test cavity

- Design, construction and high-power test of another single-cell cavity operating at 5.7 GHz
  - to evaluate scaling laws
  - learn more about breakdown phenomena

→ *Design has already begun; to be tested before the end of 2010!*

Thanks to…

- CLIC RF and Breakdown Group
- CTF3 Group
- CERN General Services
- VECA, Bodycote, ADAM
- Vodafone

All the Cyclinac team for their support

And all of you for the attention!

The research leading to these results has received funding from the Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 215840-2.


TERA -Cyclinac team

BACK-UP SLIDES

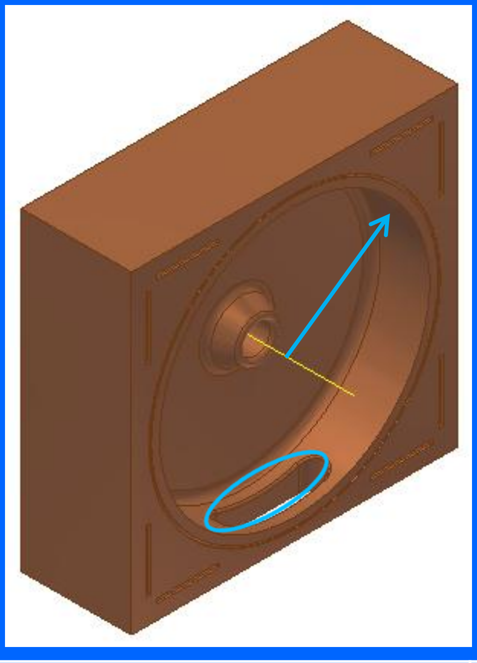
RF & mechanical design

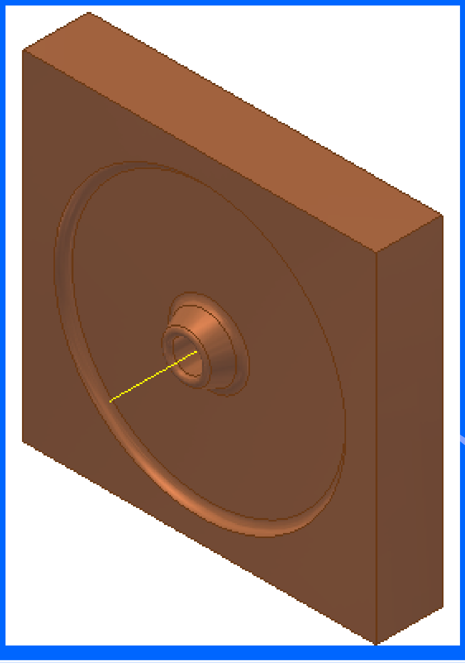
- Requirements
  - Average power to cool (350 W)
  - Nº of parallel circuit (2)
  - Turbulent flow
  - Avoid erosion/corrosion
  - Reference temp. for coolant properties (37ºC)
  - High heat transfer coefficient

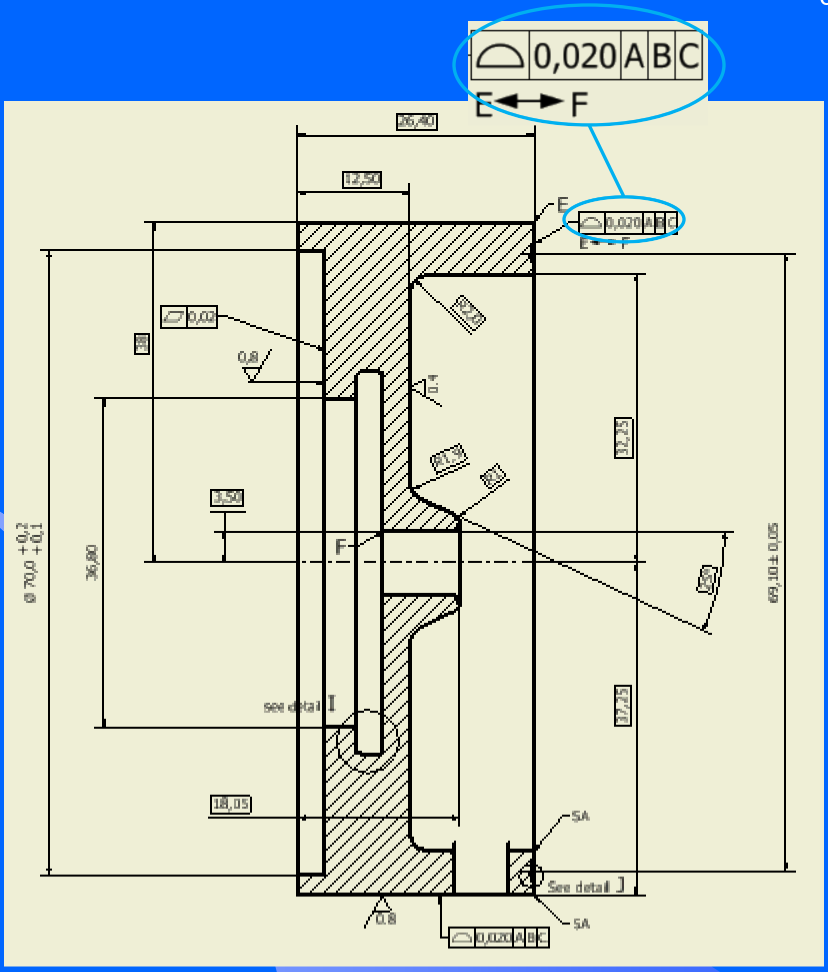
- Choices
  - $dT_{in\text{-}out} = 1^oC$
  - $D_{eq} = 5.5$ mm
  - $Re = 13900$
  - $v = 1.77$ m/s
  - $h = 10020$ W/m2/K

- Mass flow 2.5 l/min
- $\Delta f_o / \Delta T_{RF} = -1.1$ MHz / 20 K

Halfcell design

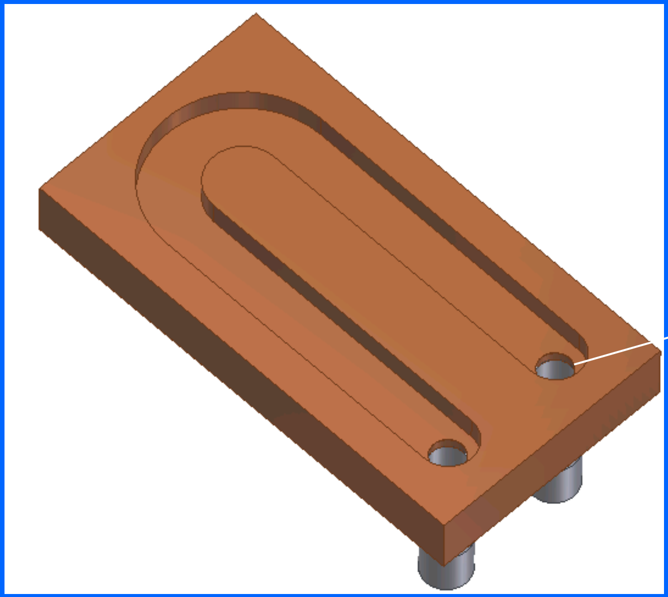


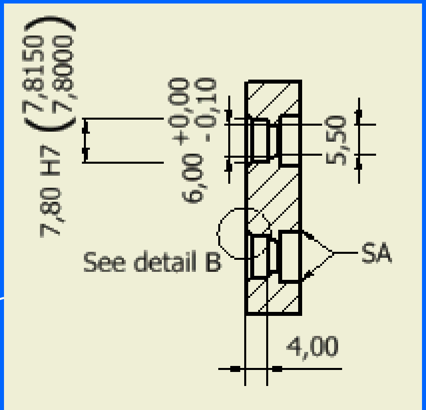


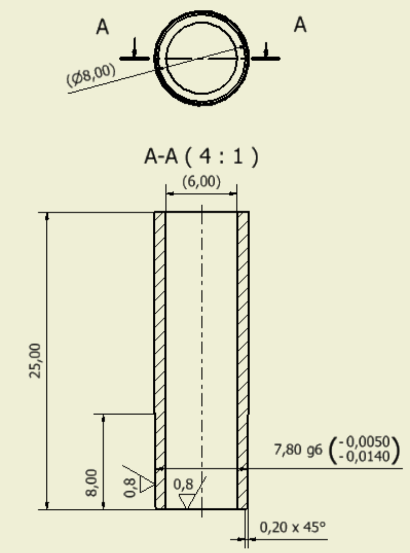


Øcell [mm]	64.50
coupling slot [mm]	25.75 x 6.00
cavity profile	0.02 mm tolerance Ra 0.4
material	OFE copper

Cooling design





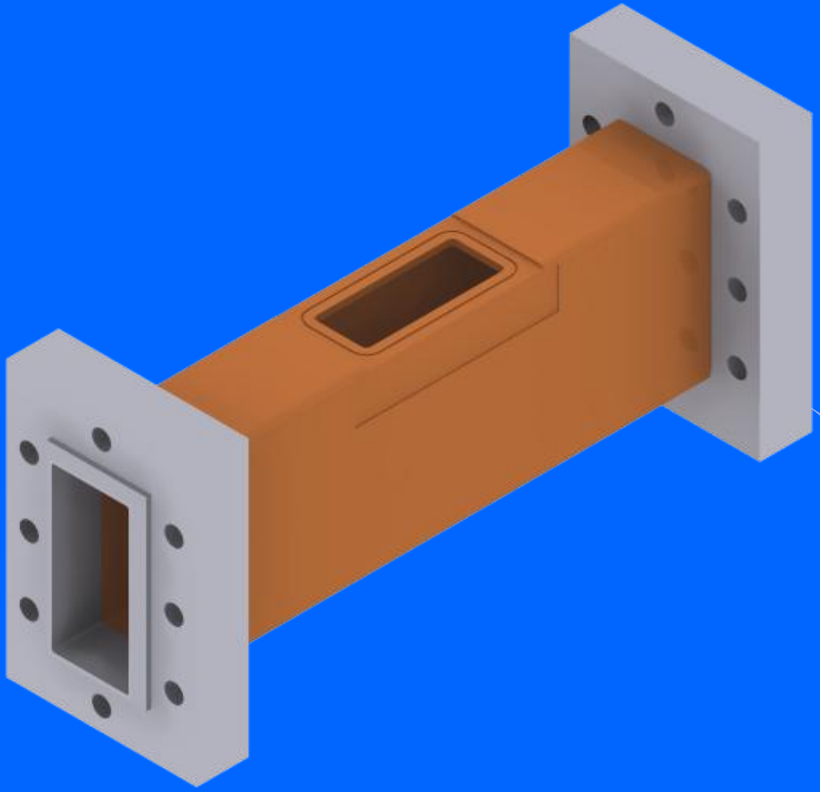


OFE Copper / 316 L

Two pipes coated and brazed to cooling plate

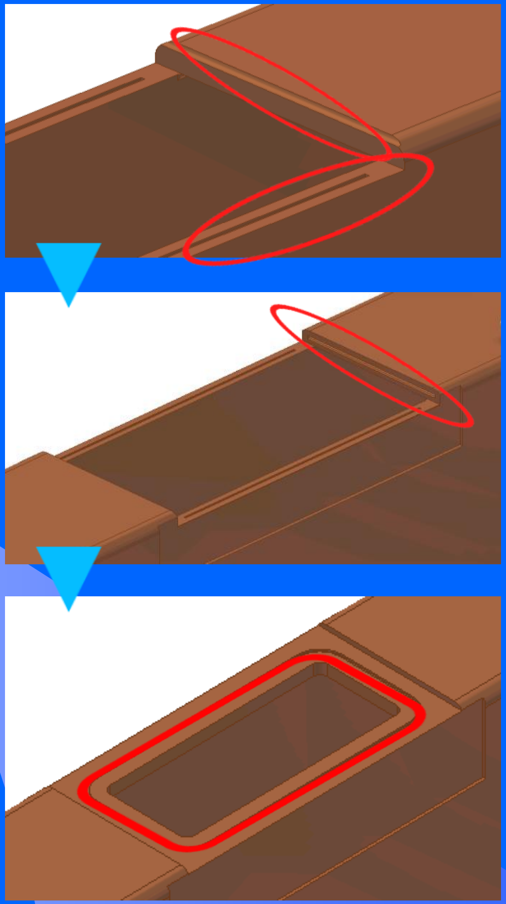
Q_{water} < 2.5 l/min

Waveguide design



Standard WR-284   (OFE copper)
with two LIL flanges for connection to RF source and short

Design evolution:



Cavity Performance

S F

E_S= 150 MV/m S_C= 0.46 MW/mm²

E_S/E_0 = 6.5   P = 128 kW

E_K= 47 MV/m

Measure   Measure   Measure

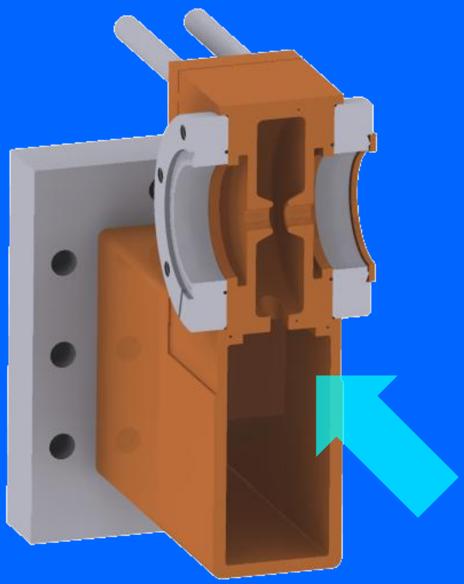
t_{FLAT} [μs]	P_{ABS} [kW]	E_S[MV/m]	E_0[MV/m]	Sc [MW/mm2]	BDR/L [bpp/m]	Kilp
1.5	670	340	53	2.39	5.2E-02	7.3
1.5	680	345	53	2.44	5.1E-02	7.4
1.5	720	355	55	2.57	6.0E-02	7.6
2.0	100	130	20	0.35	--	2.8
2.0	100	130	20	0.35	--	2.8
2.0	240	210	[illegible]	0.87	3.9E-03	4.4
2.0	240	210	[illegible]	0.87	4.1E-03	4.4
2.0	320	240	[illegible]	1.15	--	5.1
2.0	420	[illegible]	[illegible]	1.50	3.2E-02	5.8
2.0	420	270	42	1.50	3.8E-02	5.8
2.0	480	290	45	1.73	4.0E-02	6.2
2.0	630	335	51	2.28	5.0E-02	7.1
2.0	660	340	52	2.37	7.8E-02	7.3
2.0	690	350	54	2.48	1.4E-01	7.4
2.5	470	290	44	1.70	6.3E-02	6.2
2.5	480	290	44	1.71	4.1E-02	6.2
2.5	570	320	49	2.06	7.2E-02	6.8
2.5	640	335	52	2.30	8.2E-02	7.2
2.5	640	335	52	2.31	8.6E-02	7.2

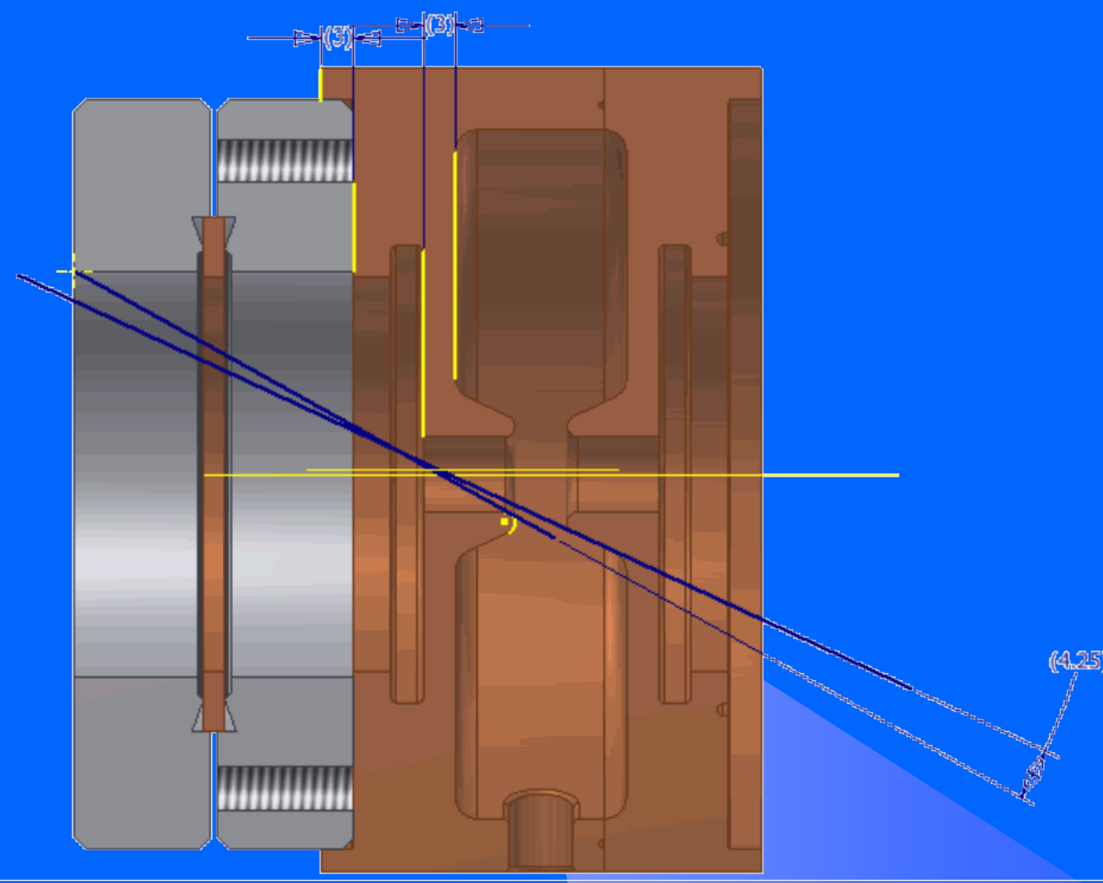
Old values

MAX

Surface inspection around nose region

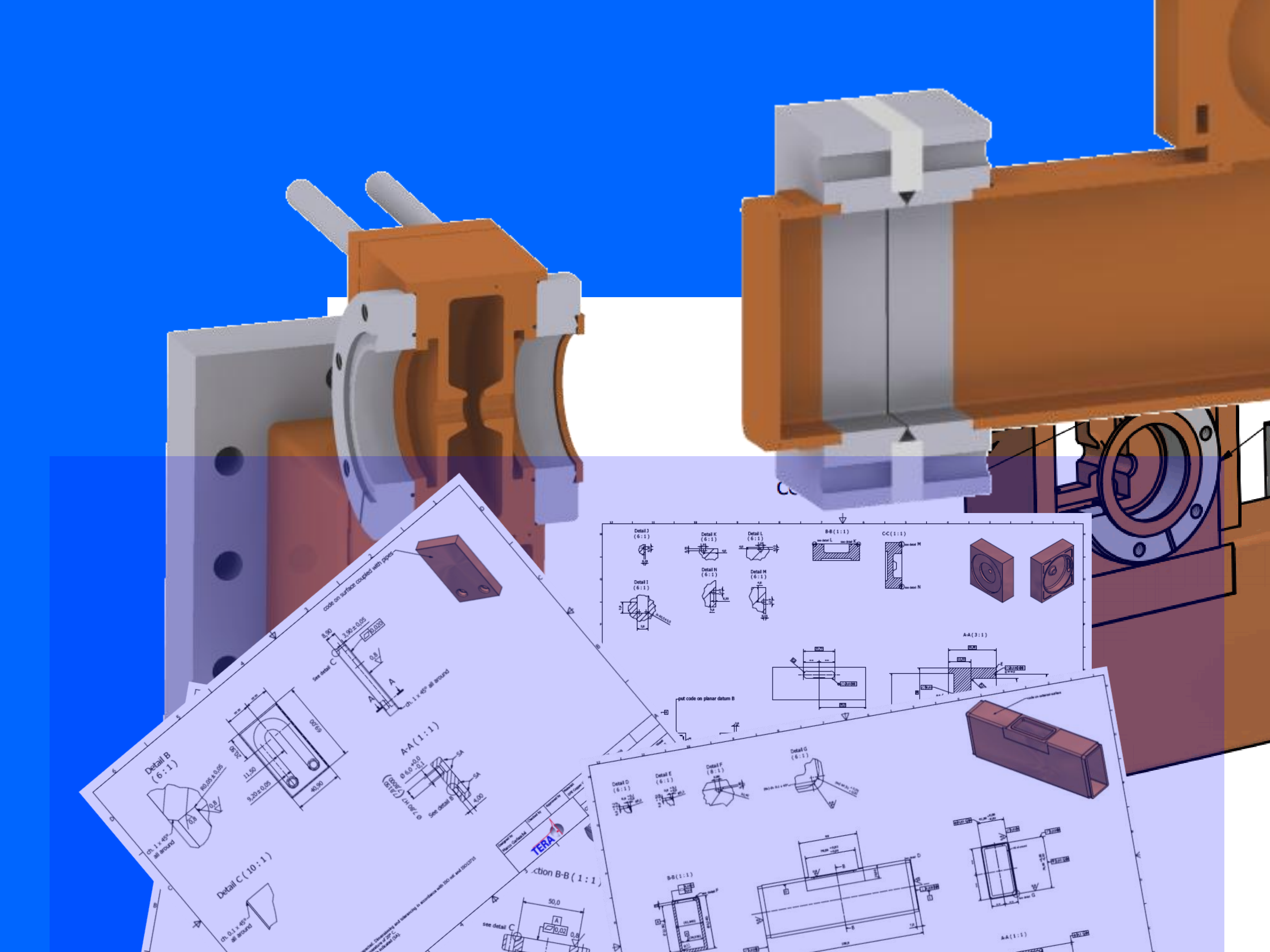
[90X Optical Microscope]





<u>*Activity in the cavity*</u>*:*

~ 14000 breakdowns


Detail B (6 : 1)
Detail C (10 : 1)
A-A (1 : 1)
code on surface coupled with pipes
ch. 1 x 45° all around
ch. 0,1 x 45° all around
See detail C
See detail B
TERA
Section B-B (1 : 1)
put code on planar datum B
B-B (1 : 1)
A-A (1 : 1)