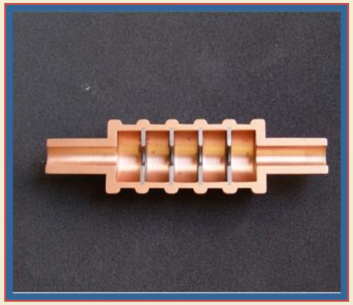
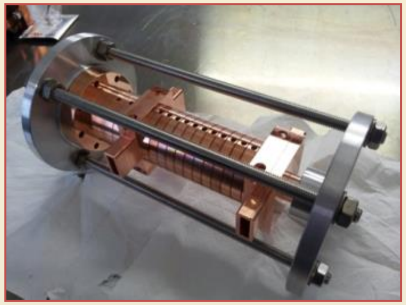
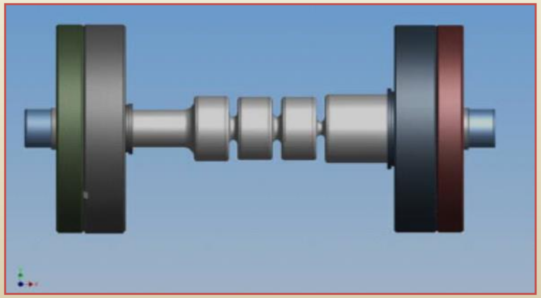
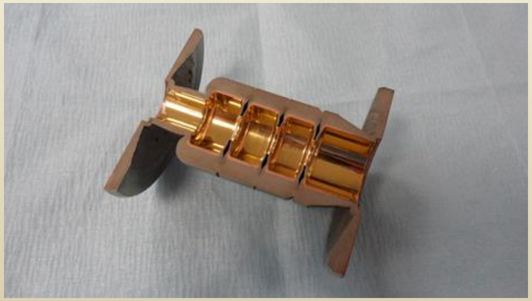
Achievements and activities on X-band accelerator structures at LNF

presented by Bruno Spataro
on behalf of NORCIA experiment INFN-LNF


4° International Workshop on Mechanism of Vacuum Arcs
(MevArc 2013) 4 - 7 November 2013 Chamonix

Contributors

This work is made possible by the efforts :

NORCIA Group, INFN - LNF

A. Marcelli, INFN-LNF and NSRL/USTC (P.R. China)

V. Rigato, INFN - LNL

V. Dolgashev, S. Tantawi , A.D. Yeremian, SLAC

Y. Yigashi, KEK

L. Palumbo, University of Roma 1

J. Rosenzweig, UCLA

SUMMARY

- Status of the technological activity
- Advancements on electroforming
- Resistivity measurements of Mo films
- Morphological characterization of surfaces after RF higher power tests
- How to achieve a higher peak field on the cathode working with a 11.424 GHz hybrid photoinjector?

NOvel Researches Challenges In Accelerators

http://www.lnf.infn.it/gr5/website_norcia/home.html

Cu brazed

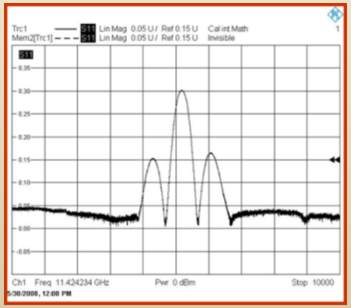
Applied Physics Letters 97, 171501

Molybdenum brazed

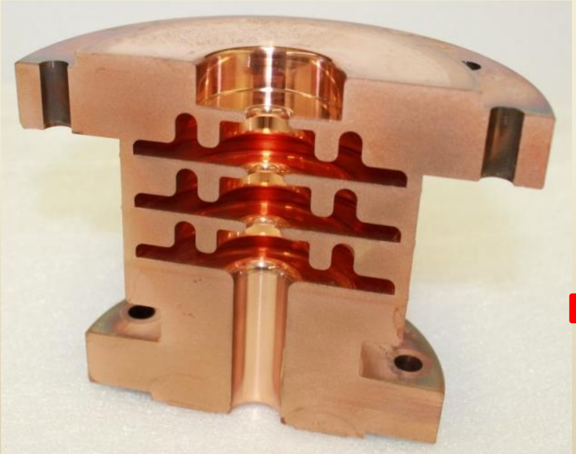
NIM-A-657 (2011) 114-121

Cu electroplated (hard copper)

NIM-A-657 (2011) 88-93



Pi mode field profile



Triple-choke

Cu electron-beam welded

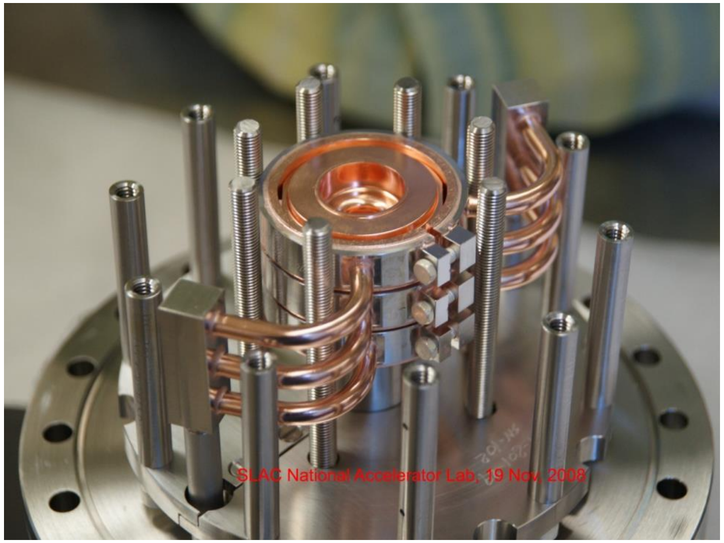
(studies in progress)

(A.D. Yeremian, V.A. Dolgashev, S.G. Tantawi, SLAC)

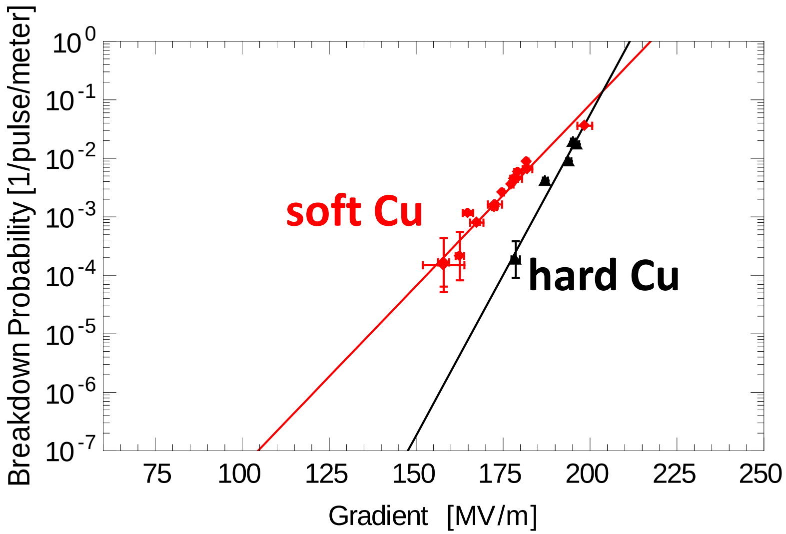
Development of Hard Copper Structures

(V.A. Dolgashev, S. Tantawi et al. SLAC)

- We had to develop an apparatus for testing accelerator structure without brazing
- The results show a great improvement of possible gradients at very low breakdown rates
- It is now possible to talk about reliable gradient higher than 150 MV/m



1C-SW-A2.75-T2.0
copper structures,
200ns flat pulse



Moreover, additional tests at SLAC on hard 'initial CuAg 'alloy' are better !!

Sintered molybdenum (bulk) issue

long time for machining the cavity

~ 250 nm roughness using 'tungsten carbide' tools

It is not easy to braze.
It is likely to have a gas contamination and an uneven loading stress in the braze region (joints are not completely filled with alloy).

New technologies are required for multi-TeV line*ar* colliders, x-ray FELs, etc.

The research project is devoted to the R&D of key components for existing accelerators and for the next generation of accelerators

Approach:

New materials and manufacturing techniques including single and multi-layer surfaces with precision-controlled properties

X-band device realisation issues

Guidelines:

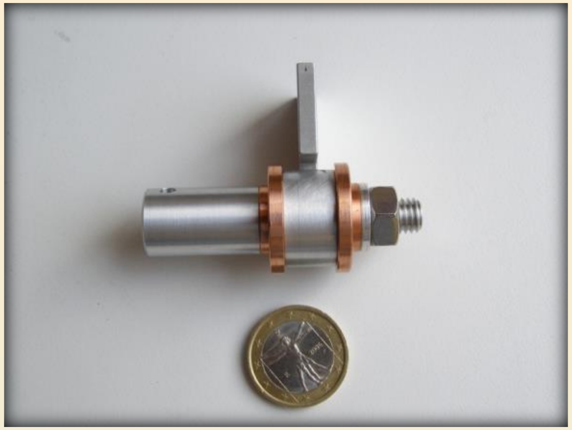
How to improve the high power performance (e.g. discharge rate) ?

- **using materials with higher fusion temperature;** → **R&D on materials**
- **avoiding the device heating at high temperature as done in conventional brazing** → **R&D on fabrication techniques**

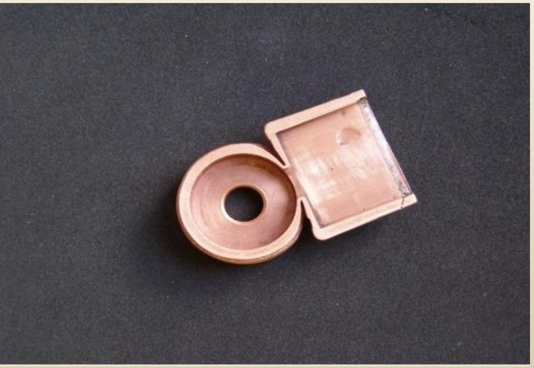
R&D on material →
- **Sintered Molybdenum (Bulk)**

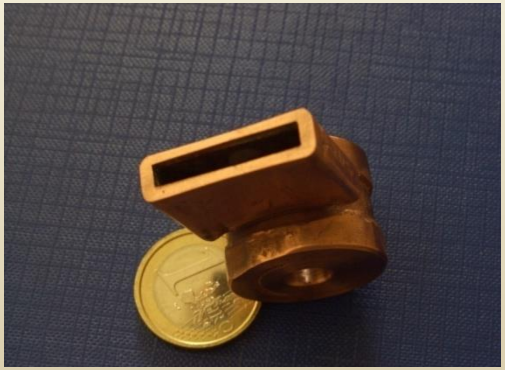
R&D on fabrication techniques →
- **Electroforming**
- **Soft Bonding**
- **Molybdenum sputtering on Copper**
- **EBW (Electron Beam Welding)**

Aluminium mandrel of the RF coupler and cell ready for the electroforming

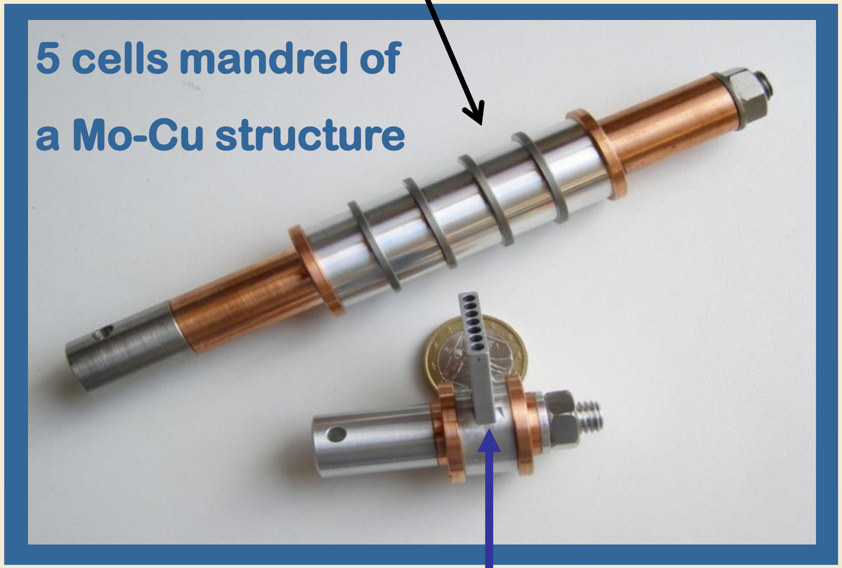


Electroformed RF coupler and cell





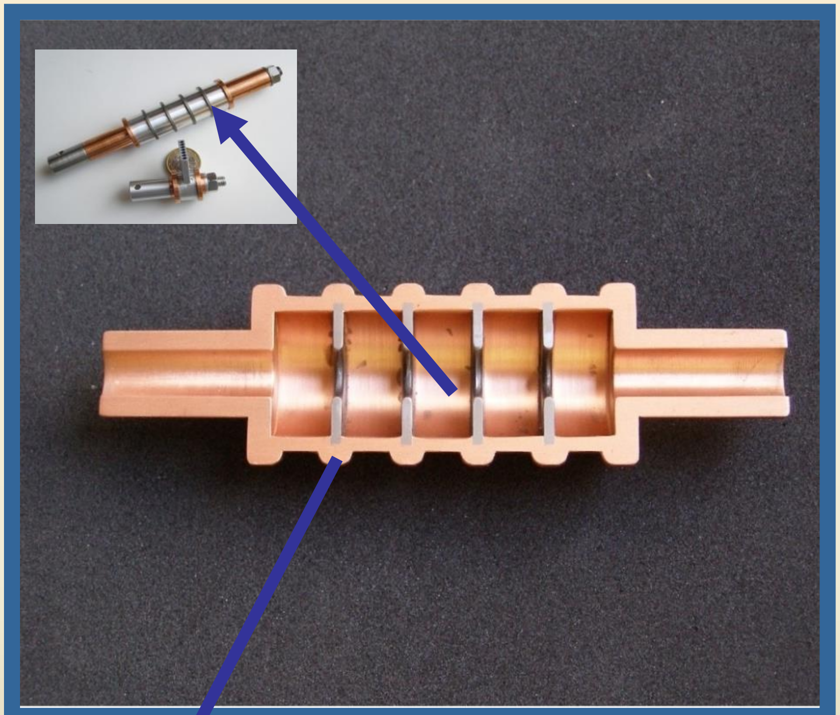
Mo discs are already machined to be the iris of the electroformed cell



Another view of the coupler mandrel is shown

…… *Electroforming R&D and Test*

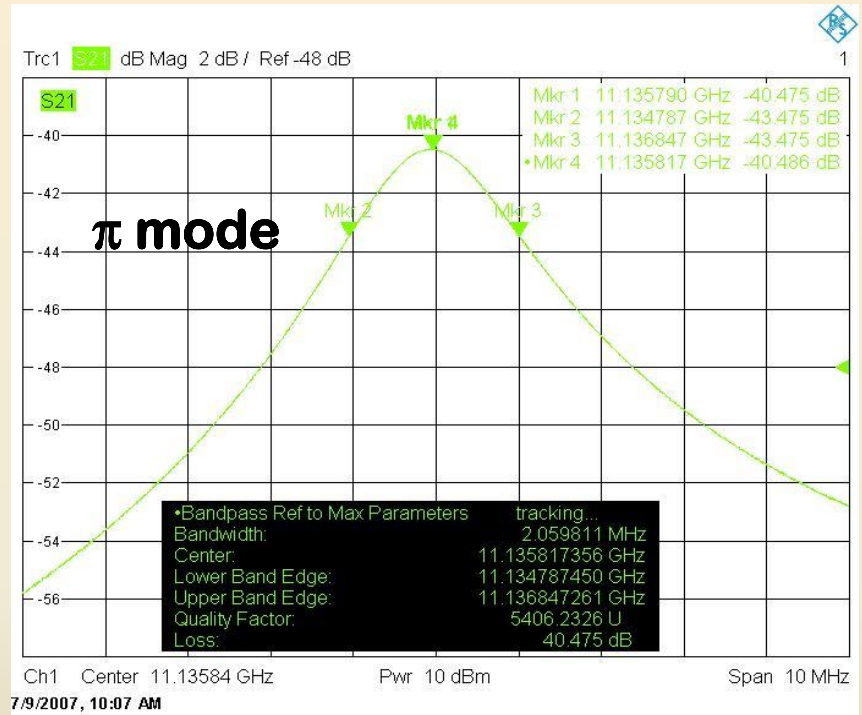
RF cells after removing the aluminium core with alkaline solution (sodium hydroxide NaOH). Cross section of a Mo-Cu electroformed structure.



The Mo discs improve the mechanical properties with the external ribs .

Fundamental mode response of Cu-Mo electroformed structure

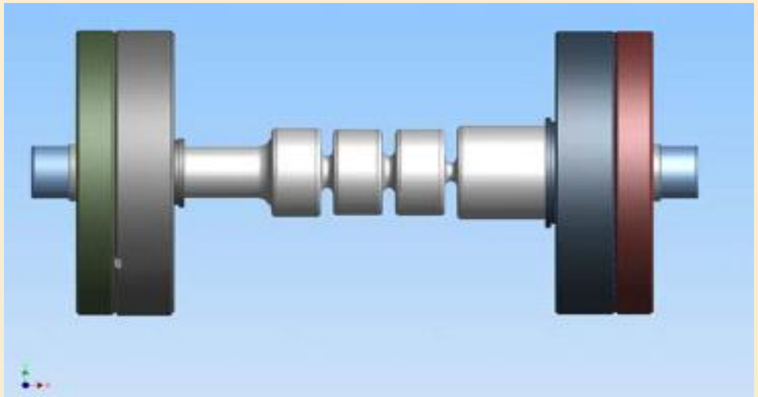
$Q_0 = 5406$



Next step: to improve the quality of the Cu surface altered by the alkaline solution depositing silver or gold on the core or using other methods ….

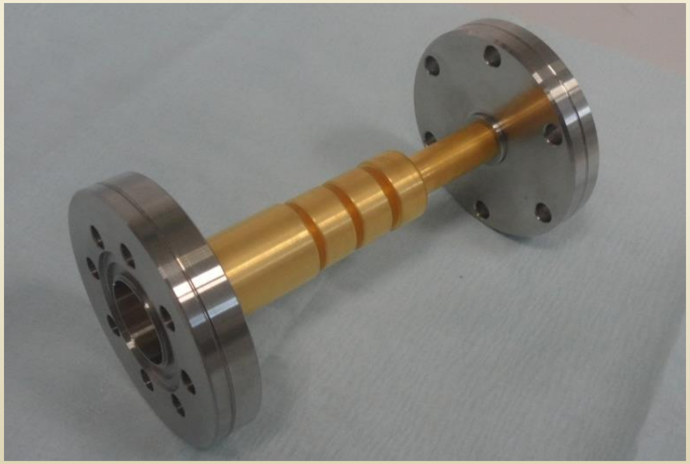
In addition to improve the Mo surface roughness (~ 250 nm !!)

NORCIA's prototypes made by COMEB and MLT Companies



Prototype mandrel
for the electroforming

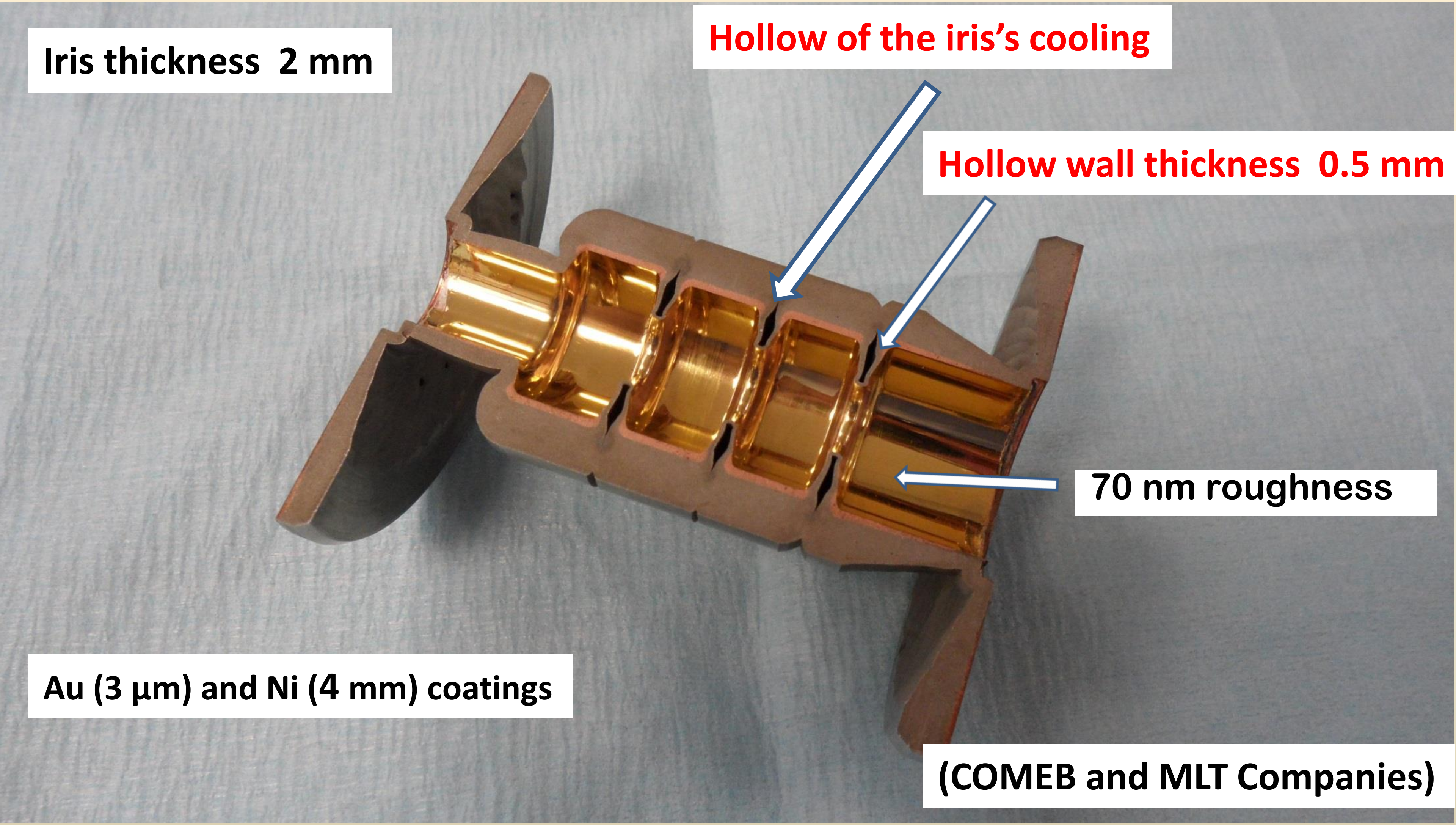
3 µm thick Au coating



Fitting test between mandrel
and CF flanges

Au coated structure with
a 4 mm thick Nickel coating

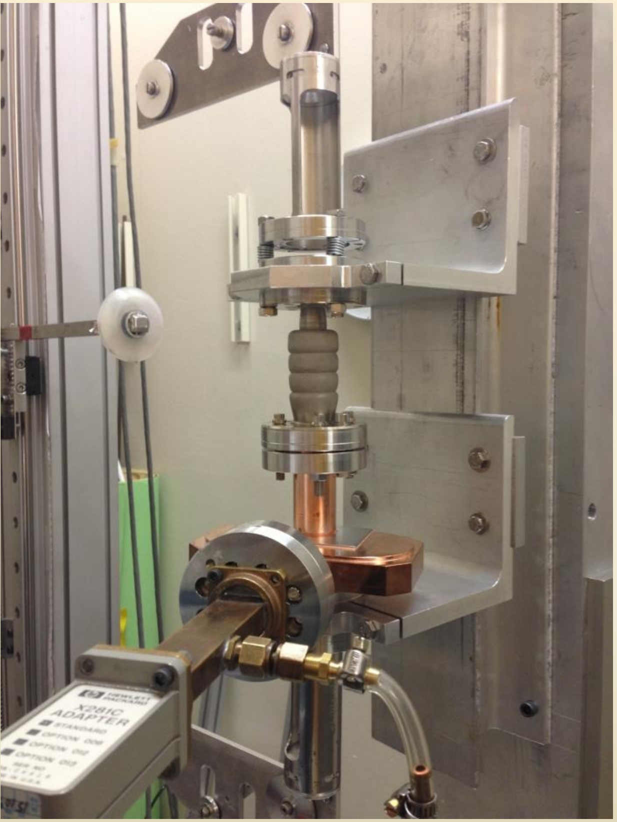
11.424 GHz cross section of the electroformed cavity (Au-Ni)



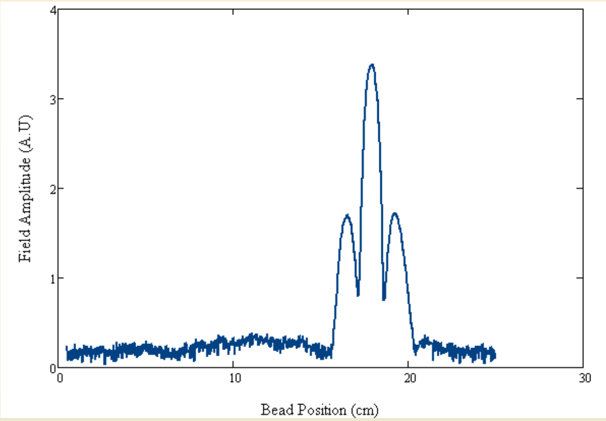
Iris cooling (COMEB & MLT Company)

Summary of RF QC for 1C-SW-A3.75-T2.6-Electroformed-Au-Frascati-#1

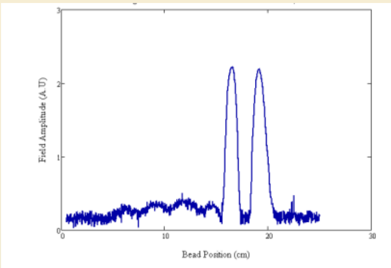
Mode	Freq(GHz)	Qzero	Ql	Qext	Beta
Pi	11.4154	5786	3486	8774	.659
Pi/2	11.3214	6621	1847	2561	2.58
Zero	11.2692	7090	1949	2688	2.64



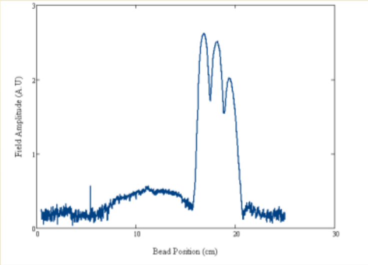
Bead-pull setup



On-axis field amplitude, Pi- mode, 11.4154 GHz



On-axis fields of Pi/2 Mode, 11.32825GHz



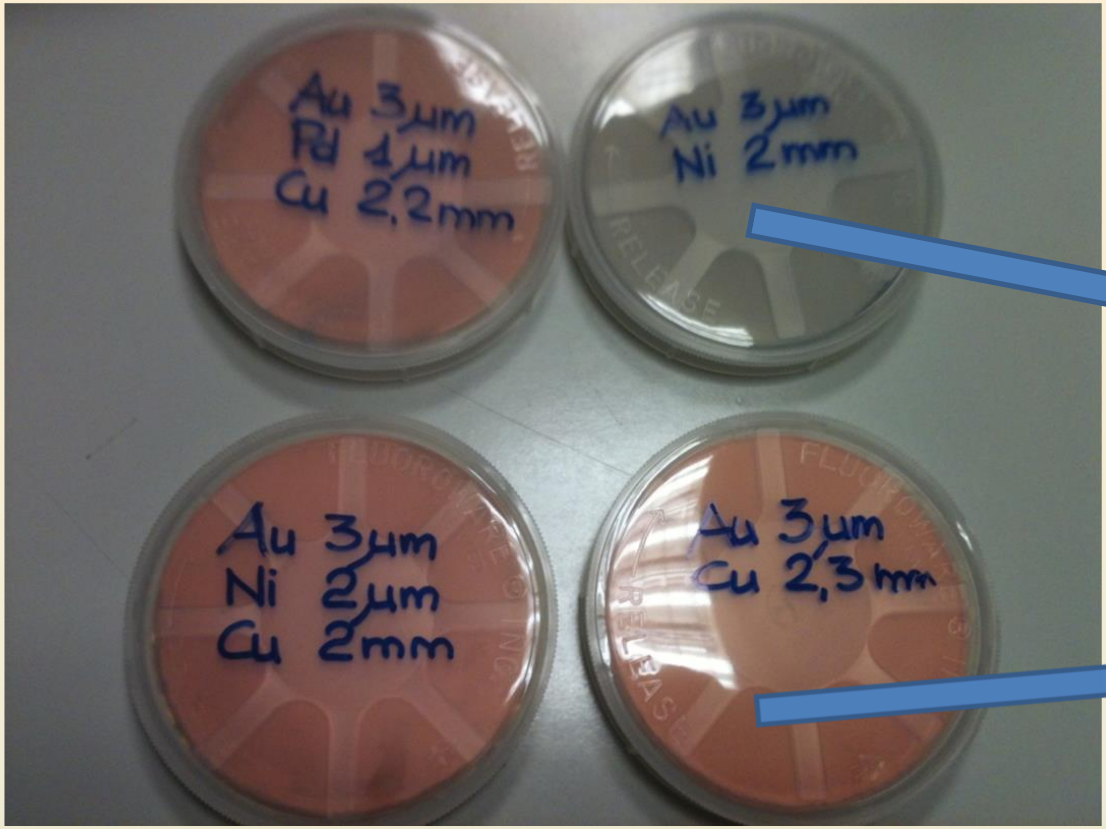
On-axis fields of 0 Mode, 11.2692 GHz

Pi mode
Frequency ~ 9 MHz off
Qzero is a little poor: conductivity has to be improved !!

SLAC NATIONAL ACCELERATOR LABORATORY

Jim Lewandowski, SLAC, 31 May 2013

Flat samples for the resistivity measurements



These flat samples have resistivity ~ 1.2 worse than Cu (SLAC- V. Dolgashev et al.)

The first flat samples have been prepared using combination of :

PVD Au (200nm)+ Galvanic Gold (4 micron)

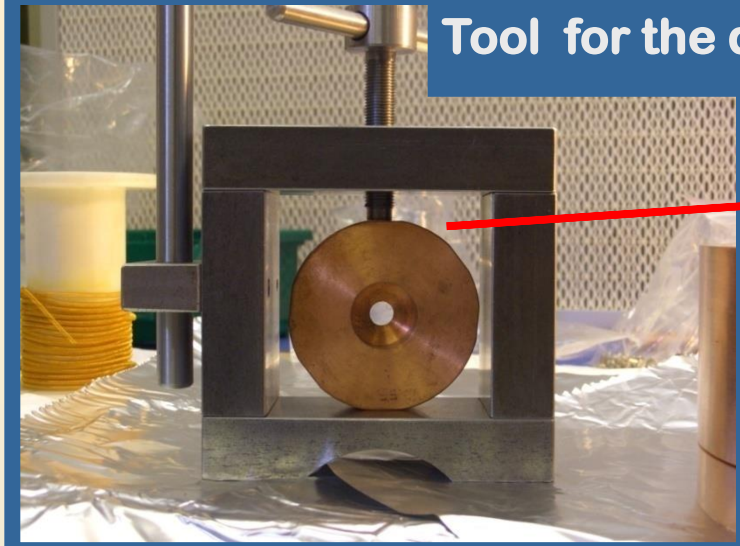
Flash adhesion layer PVD or galvanic (Pd, Ni)

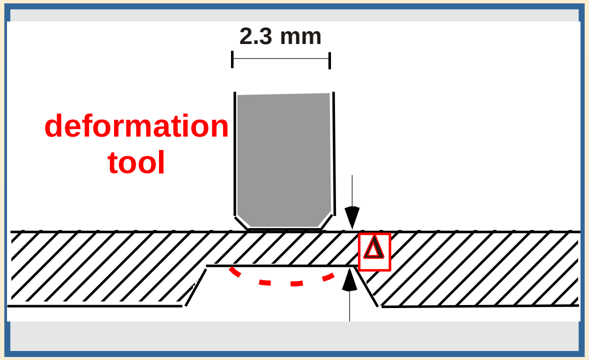
typically 0.5 micron; E-formed Ni or Cu

(COMEB & MLT Companies)

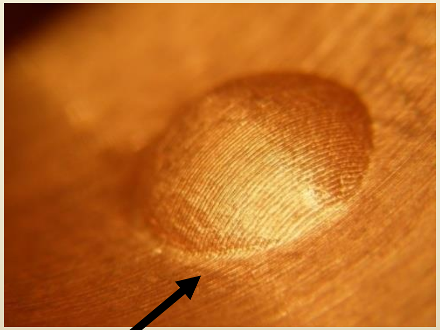
Tuning with the wall deformation

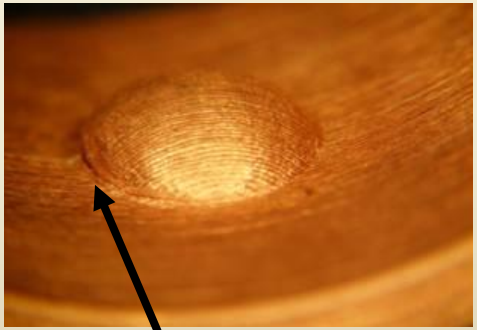
Tool for the deformation test

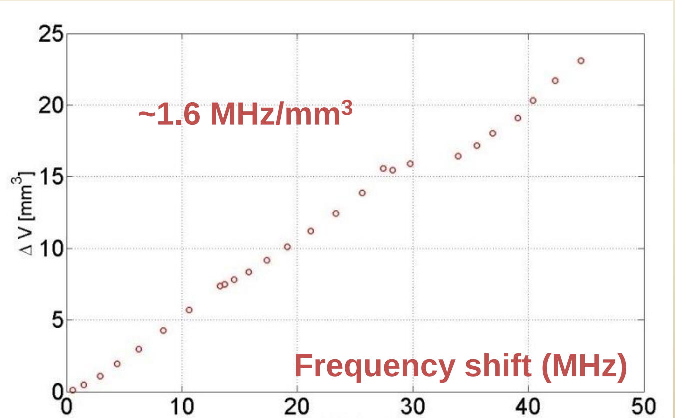




CU	MO
Δ = 0.9 mm	Δ = 0.8 mm
deform ≤ 0.6 mm	deform ≤ 0.3 mm



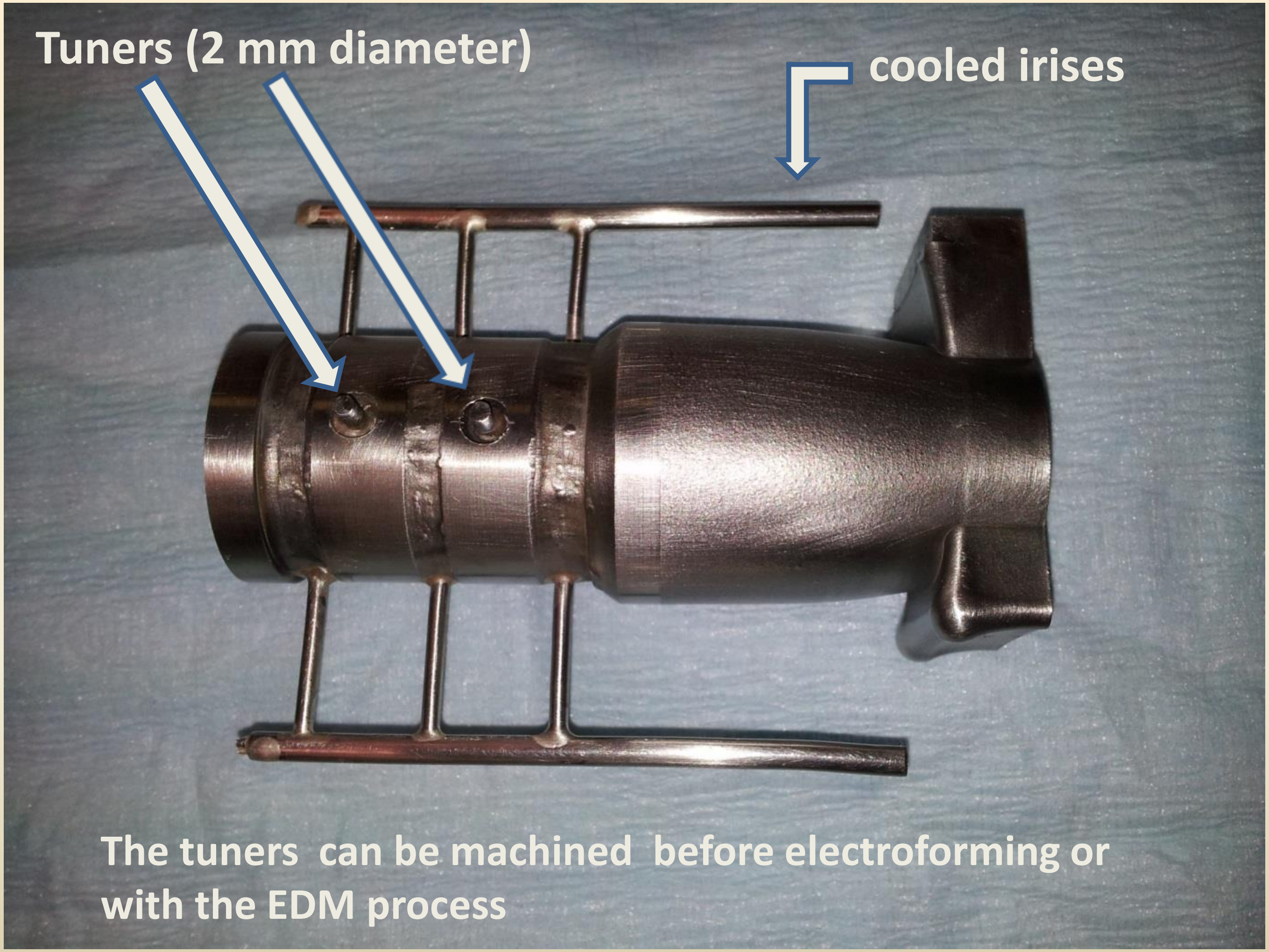




Detail of the maximum deformation obtained inside the cell [Master thesis of M. Ronzoni – University La Sapienza – Rome]

Breaking limit

X band Galaxie gun prototype (J. Rosenzweig - UCLA) with cooled irises
Manufactured with the electroforming process



(COMEB & MLT Companies)

First conclusions and Open problems
(on electroforming activities)

We built two structures: Au-Ni and Au-Cu. The field profile and frequency are satisfactory for both sections.

Flat samples resistivity is ~1.2 worse than Cu (SLAC - V. Dolgashev et al.)

Structures resistitivity is ~2.5-3 worse than Cu (SLAC - V. Dolgashev et al.). The deposition with the galvanic process occurring at grazing angles affects the film's compactness (due mainly to the porosity inside the film)

The sodium hydroxide (NaOH) removes the Al mandrel but does not affect the Au deposited film. The latter is required to stop the erosion of the mandrel.

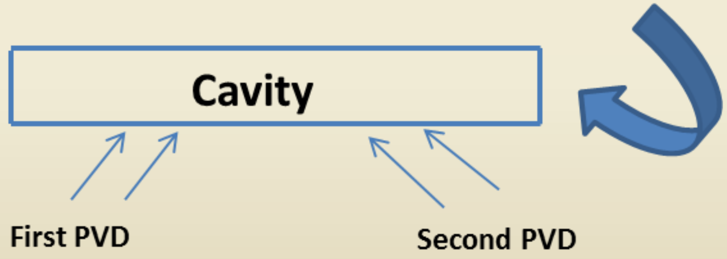
The cooling of the iris with a 2 mm thickness was successful !

Possible alternative approach to the galvanic process in order to improve the film's conductivity

In general coatings with PVD processes resulted with a much better purity compared to galvanic ones

The PVD gold has highest purity with respect to the galvanic gold.

We propose to perform two film deposition steps of PVD gold with an angle, while the mandrel is turning (continuous rotation).
This layout may deposit at an angle of ±30 deg growing a layer of Au more homogeneous and with a lower porosities.
(tests are planned on dedicated prototypes)



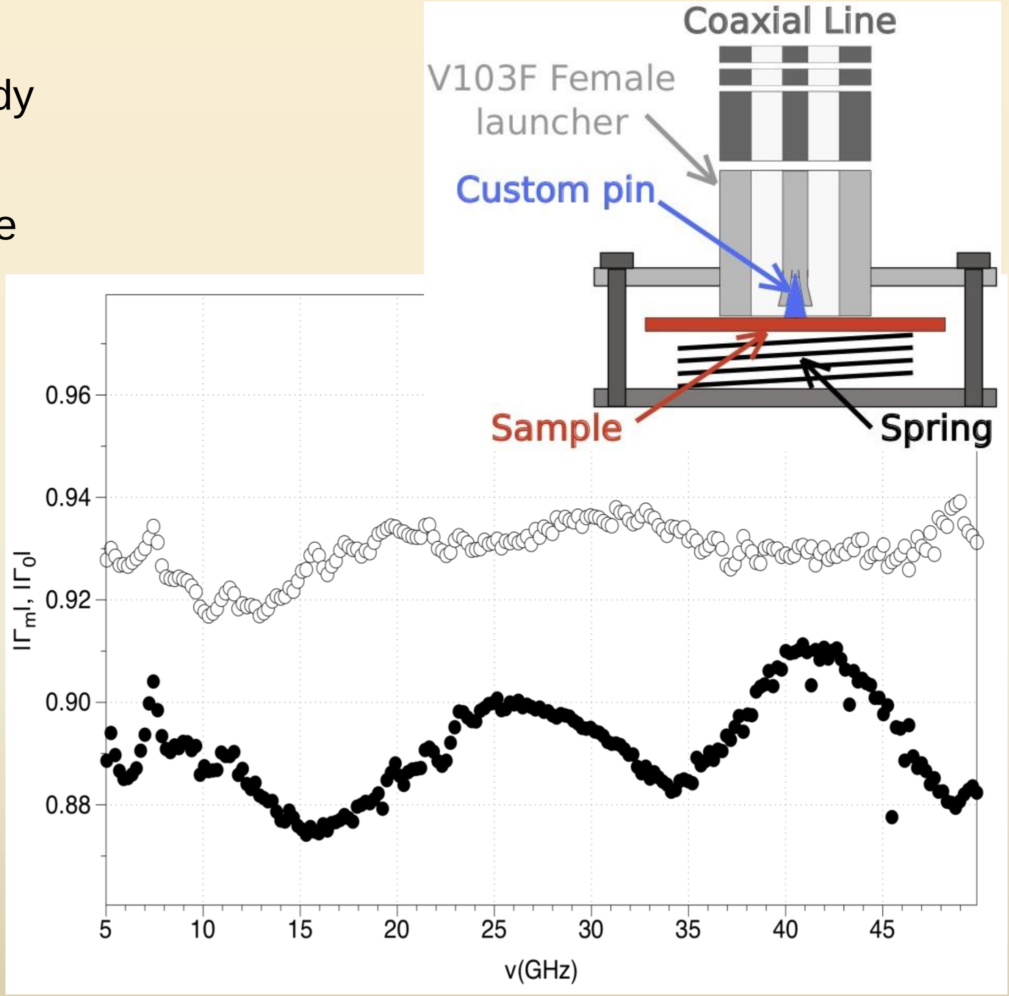
Film deposition onto trenches region (as the iris) with an aspect ratio 3-4 by using the IONIZED MAGNETRON SPUTTERING may improve film structure and density (tests are planned on dedicated prototypes)

Resistivity measurements of the Mo film deposited on a insulating layer

- Reflection coefficient of a line terminated onto the film under study (full symbols)
- Subtract the contribution due to the uncalibrated line segment (open symbols)
- Obtain resistivity:

$$\frac{\rho}{d} \simeq Z_0 \frac{1+\Gamma_0}{1-\Gamma_0}$$

Where Z_0 is the impedance of the line.



S. Ganchev, N. Qaddoumi, S. Bakhtiari, R. Zoughi, IEEE Trans. Instr. Meas 44, 1023 (1995)

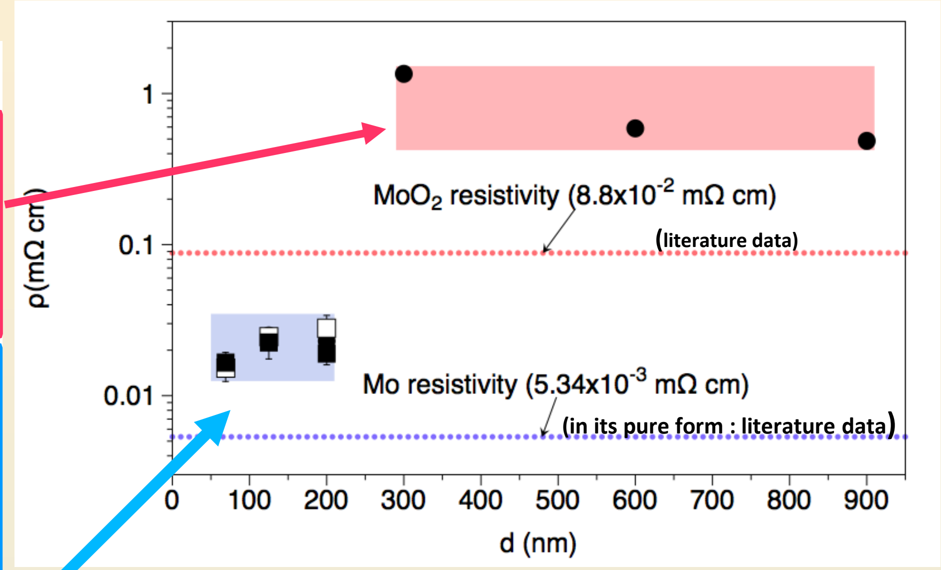
N. Tosoratti, R .Fastampa, M. Giura, V. Lenzi, S. Sarti and E. Silva, Int. J. Mod. Phys. B 14, 2926 (2000)

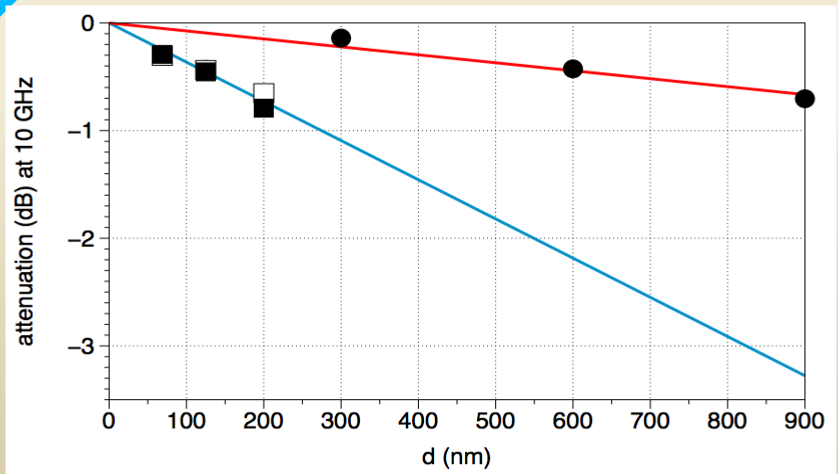
Resistivity measurements of Mo films

XAS (X-ray Absorption Spectroscopy) and X-ray Diffraction (XRD) esperiments are in progress at Diamond Light Source (UK) in order to characterize the chemical status of Mo film

Additional measurements carried out at Catania are in agreement with our results

Substrate	O_2 pressure	thickness (nm)	ρ (mΩ cm)
Glass	10^{-2}	300	1.35
Glass	10^{-2}	600	0.59
Glass	10^{-2}	900	0.49
Glass	1.5×10^{-2}	70	1.6×10^{-2}
Glass	1.5×10^{-2}	125	2.5×10^{-2}
Glass	1.5×10^{-2}	200	2.3×10^{-2}
Glass	10^{-3}	70	1.5×10^{-2}
Glass	10^{-3}	125	2.5×10^{-2}
Glass	10^{-3}	200	2.8×10^{-2}
Al_2O_3	10^{-3}	70	1.7×10^{-2}
Al_2O_3	10^{-3}	125	2.2×10^{-2}
Al_2O_3	10^{-3}	200	1.9×10^{-2}



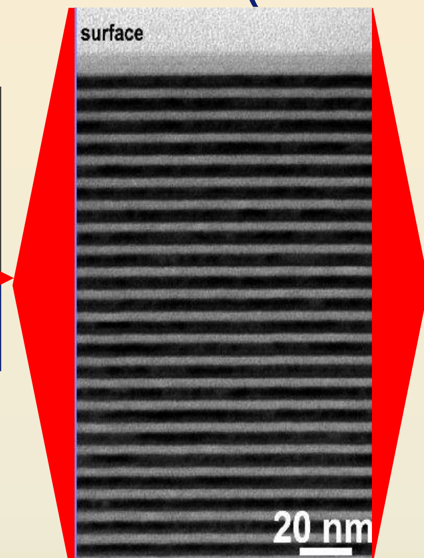


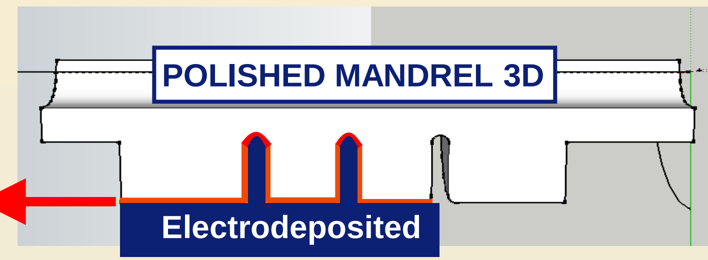
Chinese Physics C 36, (2012)

Chinese Physics C 37, (2013)

TECHNOLOGY ADVANCES OUTLINE

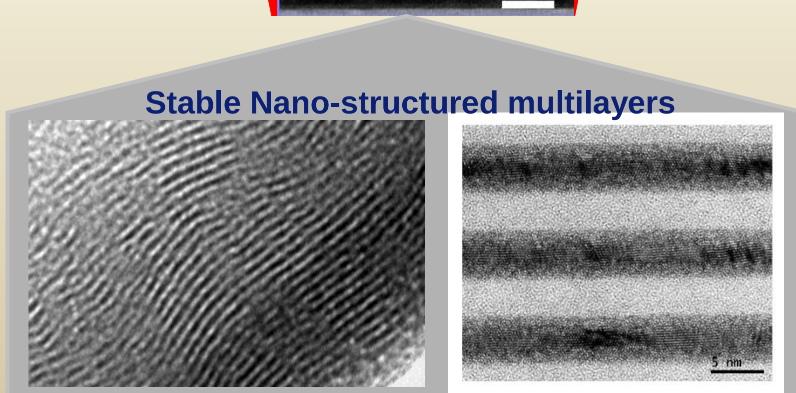
- STEP 1 = MANDREL PRODUCTION (INFN Design, outside manufacture e.g. diamond turning, super-polishing)
- STEP 2 = DEPOSITION OF NANOSTRUCTURED MULTILAYER (LNL)
- STEP 3 = ELECTRO-DEPOSITION OF THICK BODY STRUCTURE (external partnership)
- STEP 4 = MANDREL REMOVAL / DISSOLUTION (both INFN and external partnership)





R&D ON FLAT SAMPLES: year 2013-2014

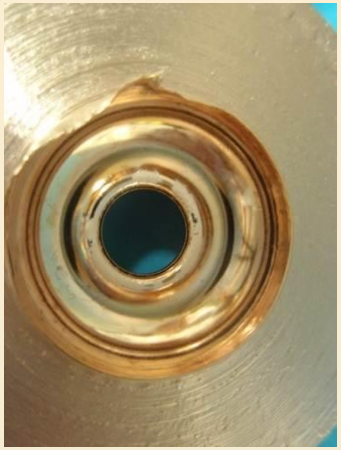
R&D ON 3D CAVITIES: year end-2013 - 2014

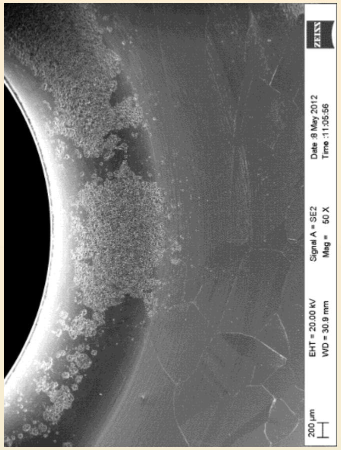


Cross sections preparation and defects analysis

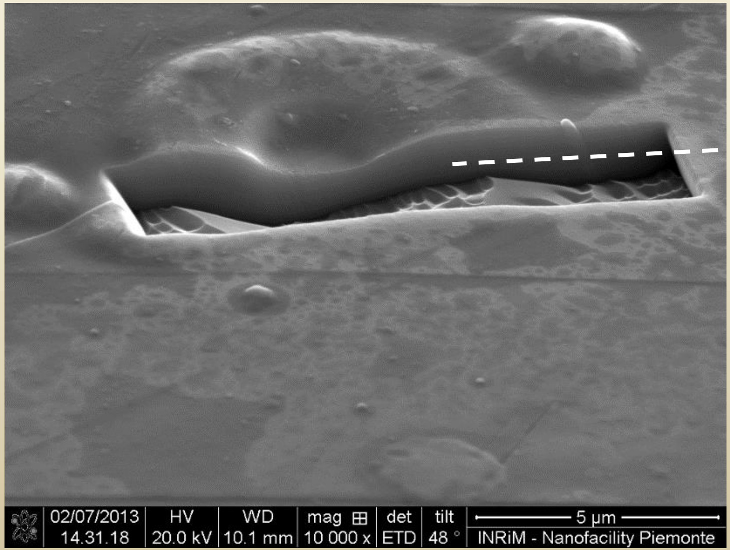
(preliminary morphological characterization)

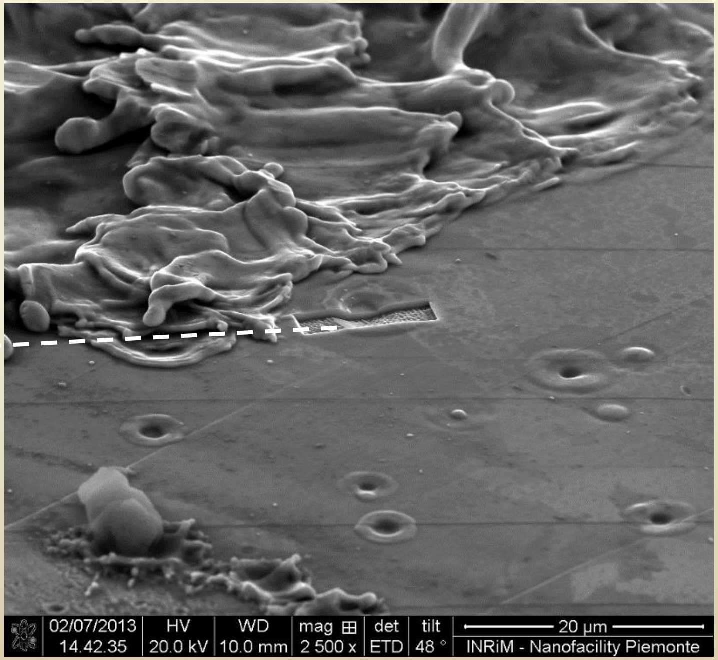
- **1C-SW-A3.75-2.2-Cu-SLAC-1 (Elliptical design) 2013 – provided by SLAC (courtesy V. Dolgashev) after high power microwave tests**
  - **Sample for cross section analysis with electron microscopy**
  - **Electron microscopy (SEM-FEG + FIB)**





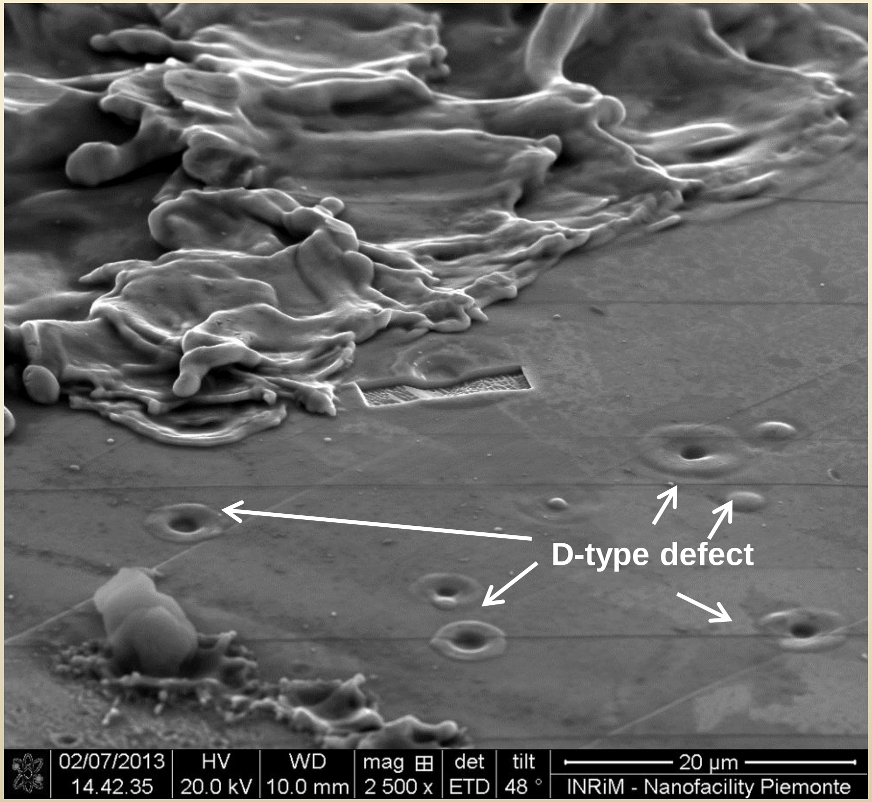
FIB cross section of an isolated defect at the edge of a damaged region (~800 um from the edge of the iris)

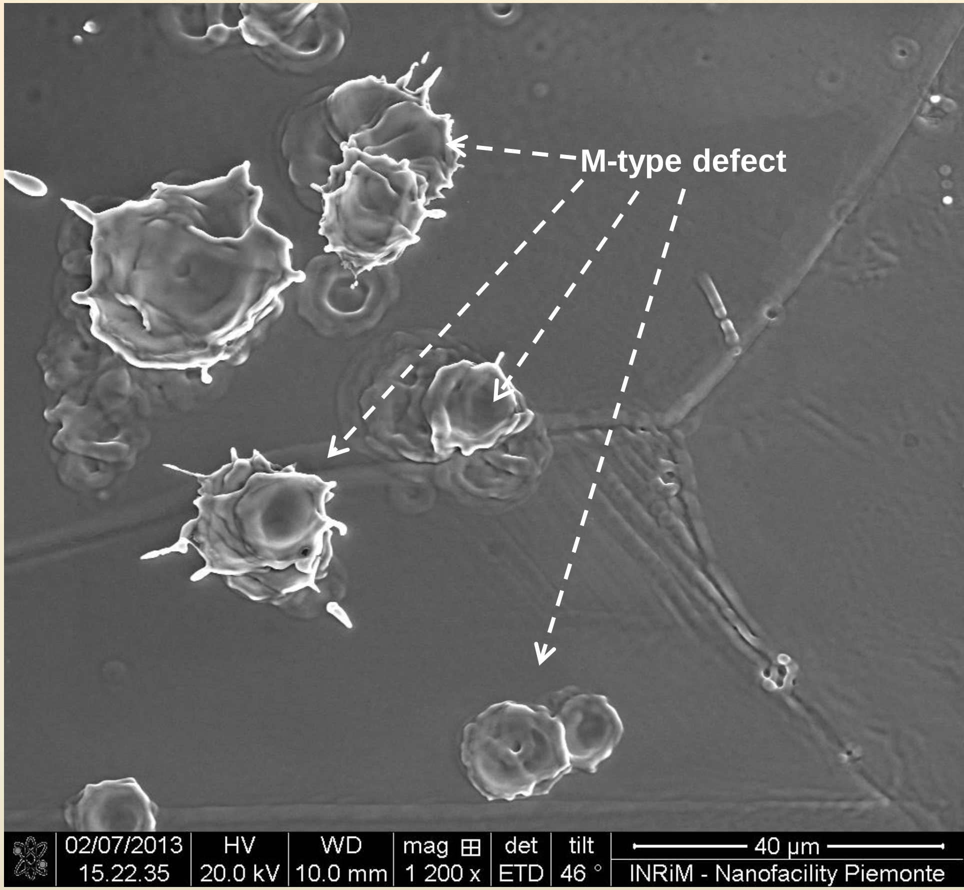




ISOLATED SURFACE DEFECTS (II)
(preliminary morphological characterization)

- **Isolated defects are interesting to understand the degradation phenomenon for X-band cavities**





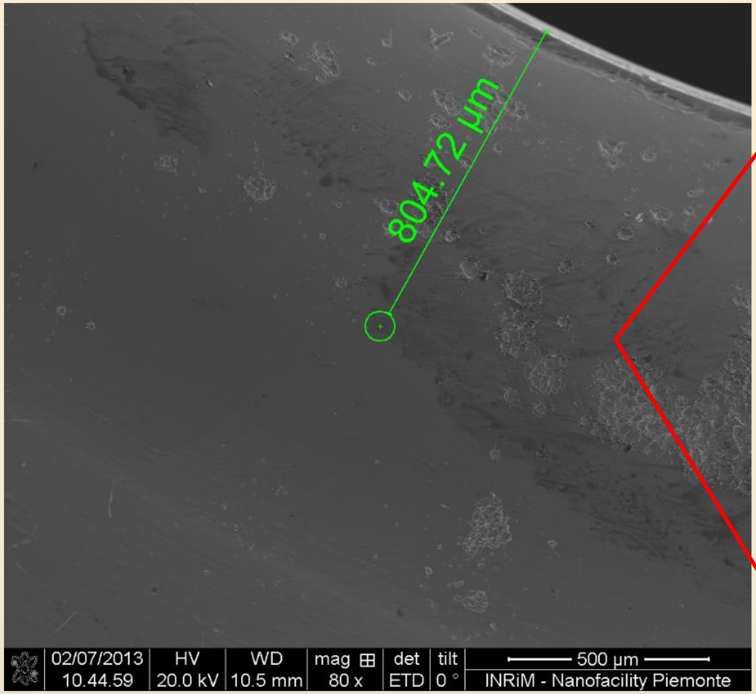
D-type and M-type defects seem to be of the same origin, but the process of melting/explosion is limited in D-type by the power delivered locally.

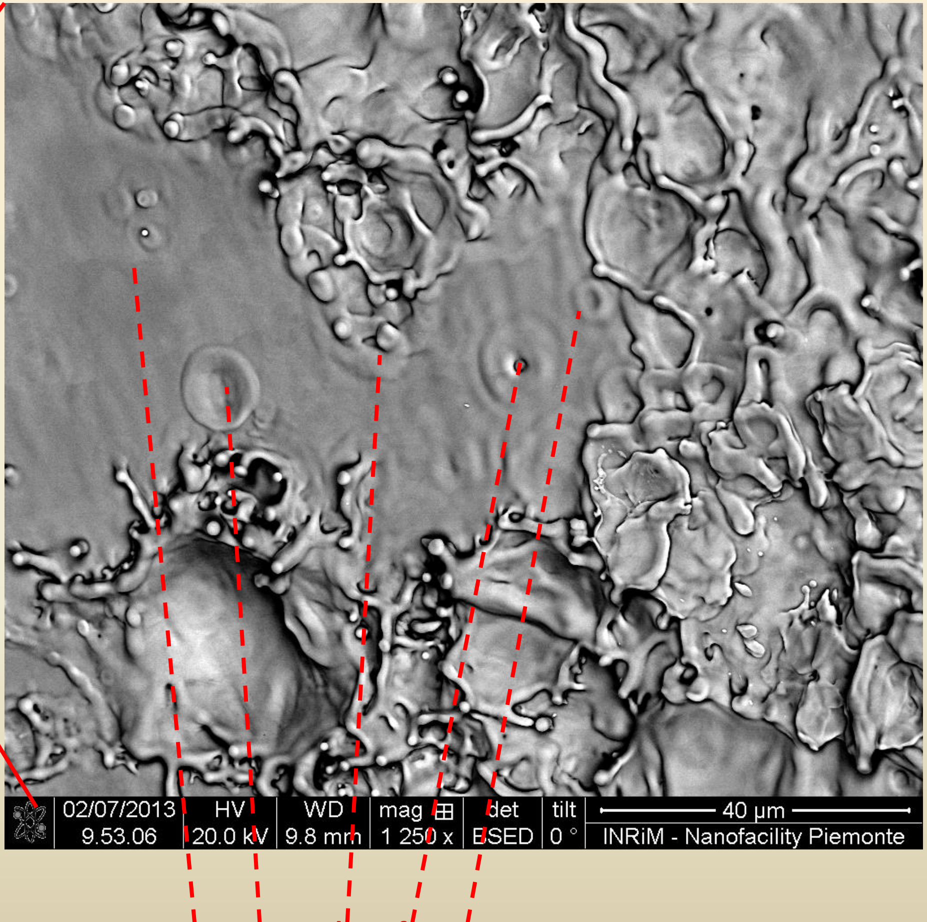
D stands for «Doughnut»

M stands for «Melted»

SURFACE at micrometer scale (sample provided by V. Dolgashev)

- Extended zones evidence melting of copper in the region up to about 800um distance from iris tip.
- Melting of copper is almost continuous near iris tip
- Isolated defects are seen at border-line region at distances about 800um from iris tip





- Analysis of isolated defects is important to understand deterioration phenomena, it is assumed that they may be «precursor» of melted spots (i.e., the early stages of a process of incomplete localized melting)

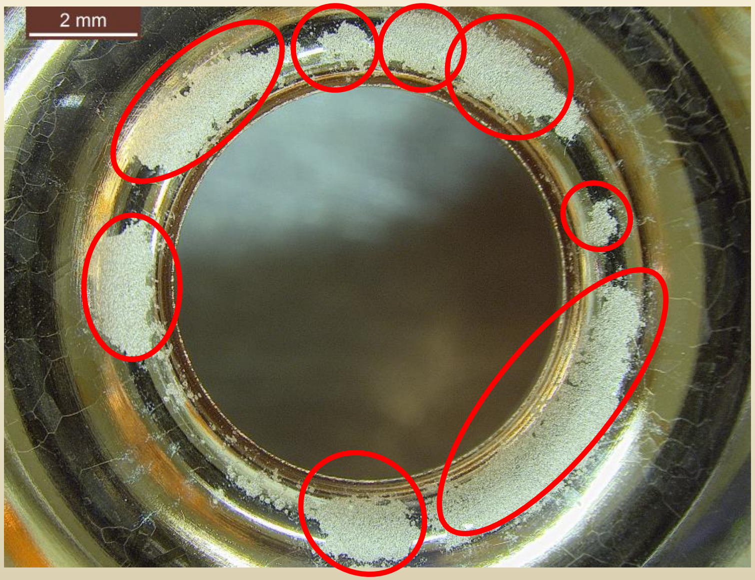
Why 3D X-ray Imaging of IRIS?

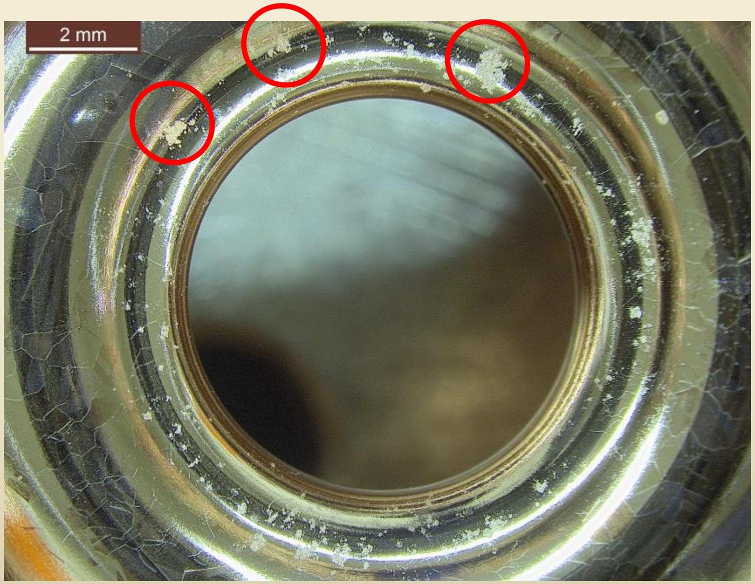
Damaged "patches", typical for single-cell-standing-wave-structure tests

We are interested in crystal defects and voids 0…..100 micron under these patches

See GE x-ray computed –tomography imaging machines for industrial applications:
http://www.ge-mcs.com/en/radiography-x-ray/ct-computed-tomography/nanotom-s.html

We can carry out test on an entire iris  ⟵ **Iris sectioned from the original part**





1C-SW-A3.75-T2.2-Cu-SLAC-1

Photo by Lisa Laurent, SLAC, 7 February 2013

MicroXCT vs. NanoXCT ?

The device has an imaging resolution with length scale from several mm to tens of nm

- Unique Power
- Non-destructive
- High Resolution

Length scale 1 mm (1000 µm) 1 µm (1000 nm)

mm | µm | nm

NanoXCT → 1 nm

MicroXCT

Advantages of X-ray Imaging

- *Short wavelength for high resolution*
- *Rich image contrast mechanism: absorption, chemical state, phase, diffraction, polarization*
- *Element specific: absorption edges and characteristic fluorescence*
- *High penetration for nondestructive imaging*
- *No charging effect on image resolution*


Iris sectioned from the original part

- For the requirement of basic research and industrial material studies, x-ray imaging facility in China will provide:

✓ Brilliance of 10^{21}-10^{22}ph/s/mm^2 mrad^2/0.1% BW

✓ Focus spot down to 1mm (for coherent diffraction) or 10 nm (for nano-probe)

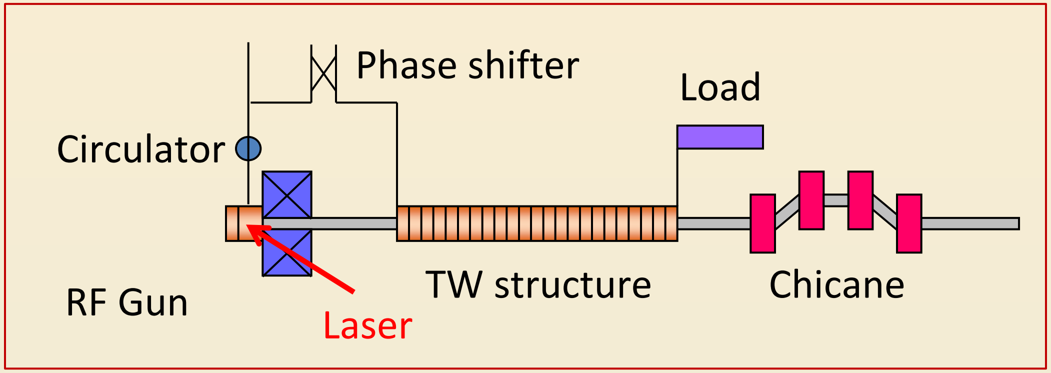
✓ Photon energy up to 300 keV

Courtesy Wu Ziyu

Conventional photoinjector vs. Hybrid photoinjector: RF properties

The photoinjector design employs a combination of two accelerating structures: a standing wave gun and an accelerating linac

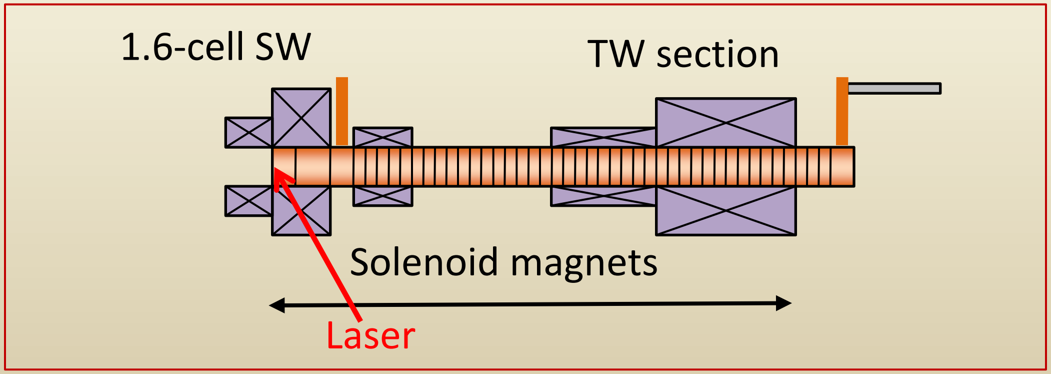
Conventional photoinjector



- **The SW and TW structures are fed independently**
- **The SW structure reflects nearly all of the input power at the beginning of the RF fill process**

circulators are necessary in order to protect the RF power source

Hybrid photoinjector



- **The SW RF gun section is coupled on-axis to the TW section through a coupling cell that serves as feeding system to both SW/TW.**

This enables to build a RF gun at higher frequency where no adequate high power circulators yet exist

X-band hybrid photoinjector: first step

- S-Band hybrid + Scaling Laws

S-Band Main parameters:

-Frequency : 2.856GHz
-Total length : 300cm
-Peak field in SW : 60MV/m
-Charge : 1n

DIMENSIONS **α 1/f**
FIELD **α f**
CHARGE **α 1/f**

Scaling factor
2.856GHz
*4
11.424 GHz

X-Band Main parameters:

-Frequency : 11.424GHz
-Total length : 75cm
-Peak field in SW : 240MV/m →200MV/m
-Charge : 250pC

While scaling the design from S-Band to X-Band is conceptually simple

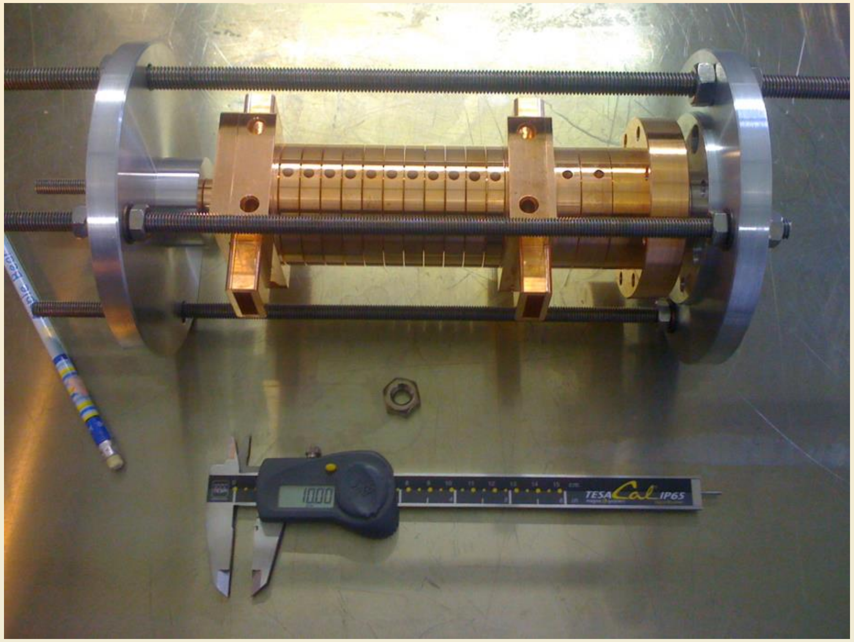
Pratical limits require some changes in both RF and magnetostatic designs:

- **It is necessary to evaluate a different design for an appropriate configuration of magnets**
- **We limited the electric field to 200MV/m and so to reach 3.5MeV (energy level nedeed for the applications that we are investigating) the SW section must be expanded to 2.6 cells.**

New materials or multilayers are needed in order to get 240 MV/m !!

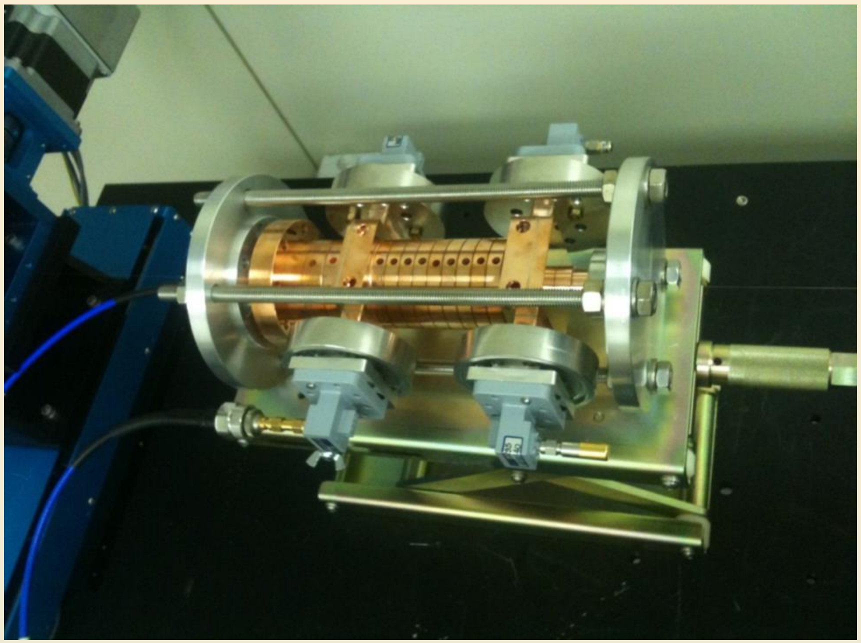
Charge and Wavelength Scaling of RF Photoinjector Designs", J.B. Rosenzweig and E. Colby, *Advanced Accelerator Concepts* p. 724 (AIP Conf. Proc. 335, 1995).

11.424 GHz Hybrid gun fabricated at INFN-LNF

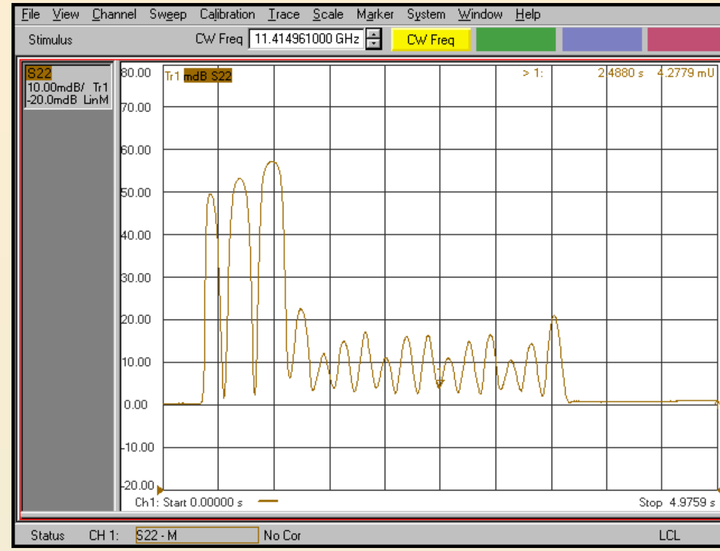


The hybrid gun has been designed at UCLA
[J. Rosenzweig and Ph.D. thesis of A. Valloni]

11.424 GHz hybrid gun prototype under test (with the untuned device and no brazing).



11.424 GHz hybrid photoinjector longitudinal electric field profile (with the untuned device and no brazing) . Mode frequency is ~7 MHz off



11.424 GHz hybrid photoinjector longitudinal phase advance (with the untuned device, no tuners and no brazing). Mode frequency is ~7 MHz off

Machining precision is ± 2.5 µm while roughness is ~60 nm.

The surface finishing was obtained directly by mechanical machining with custom cutting tools (diamond mono-crystal)

Future activities

Higher power tests at SLAC on the electroformed structure

R&D to increase the conductivity of Au films

We will continue developing technologies suitable for practical structures of new shapes and with new materials (e.g., multilayers)

Brazing and higher power tests on the 11.424 GHz hybrid gun and additional studies with a multilayers film in order to increase the peak field in the SW region (up to 240 MV/m !!)