Welcome and Introduction

Attendees

ESA

- Enrico Lia
- Sophio Pataraia
- Alessandra Ostillio
- Marco Belloni
- Cosimo Saccomando

STT

- Christian Schori
- Serge Grop
- Xavier Défosse

Agenda

Chapter 01

Project Management

Contract References

REFERENCE

ESA Contract No. 4000117664/16/NL/HK “COMPACT ULTRA-HIGH STABILITY ATOMIC CLOCK FOR SPACE APPLICATIONS”

AMENDED BY
CONTRACT CHANGE NOTICE
Reference: 117664 CCN 1 (termination)
Date: 13.11.2024
CCN Title: Termination of contract

CCN for termination

Description of change

The parties have agreed to terminate the Contract by mutual agreement on the conditions mentioned below:

- Part of the work under Task 4, and the entire Task 5 will not be performed, and as such, the Contract corresponding to payment Milestone 4, will not be achieved;
- Milestone 3 shall be considered as the Final settlement under the Contract considering the progress of the work achieved. No further payments under this Contract will be made thereafter, and the Contractor further agrees that no indemnities will be claimed under Clause 31.3. The duties of either Party will be discharged and ESA Contract 4000117664/16/NL/HK terminated; and
- No additional deliveries will be claimed by the Agency apart from deliverables D1 to D7, and the Final Report.

Reason for change

In this activity, Safran Timing Technologies (STT) encountered difficulties in the design of the hardware displaying high background noise over the desired signal which causes stray light to saturate the photo-multiplier tube due to a combination of issues (poor light trap design and high scattering in direct path, parts of vacuum tube not coated and tube surface acting as reflector).

A common decision between the Agency and STT was taken to de-scope the activity due to elongation of the project and its management after a considerable effort were made by STT team in trying to progress with the TCR milestone as well several meetings between STT and suppliers, simulations and a mitigation plan in finding solutions to the observed issues.

Deliverables status

Extract from Contract Closure Document_draft

- List of deliverables
- No HW deliverable

Conform to CCN status

Type	Ref.	Name / Title	Description (issue/version/ model/ serial number, part number, as applicable)	Replacement Value (EUR)/ Other	Location	Property of EU	Rights granted / Specific IPR conditions
Documentation	D1	Statement of Compliance to ESA Technical Requirements	Included in deliverable D2	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D2	Design Definition and Justification File - PDR	IT02-SPT-DDJ-0001 Issue 02	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D2	Design Definition and Justification File - DDR	IT02-SPT-DDJ-0002 Issue 02	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D2	Optics Package – Technology Review and Preliminary Design	MIFS-OHB-TN-0010 Issue 03	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D2	Optics Package – Detailed Design	MIFS-OHB-TN-0020 Issue 02	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D3	EBB-PP Manufacturing File	Assembly process included in deliverable D7	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D4	EBB-EP Manufacturing File	Assembly process included in deliverable D7	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D5	EBB-PP preliminary material and part list	IT02-SPT-PMP-0001 Issue 04	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D6	EBB-EP preliminary part list	Included in deliverable D5	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
	D7	EP&PP Detailed Assembly, Verification and Optimization plan	IT02-SPT-MAO-0001 Issue 01	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
		Final Report	IT02-STT- RP-0001 Issue 1.0	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
		Contract Closure Documentation	IT02-STT-CCD-0001 Issue 1.0	NA	ESA/ESTEC	Yes	Rights as stipulated in the contract
Hardware		No HW delivery					
Software		No SW delivery					
Other		NA					

Deliverables status

Extract from Contract Closure Document_draft

- Items deliverable under Article 4 of the Contract

The “contract inventory” of items produced or purchased under the Contract (other than those falling under the Article 2 of the contract) with an individual or batch value equivalent or superior to 5.000 euros is as follows:

				ESA Decision		
Item name	Part/Serial Reference Number	Location	Value	Transfer Ownership to ESA (delivery at end of the contract or delivery postponed to end of loan agreement)	ESA renunciation to claim ownership and delivery (with/without financial compensation or special instructions)	Leave in (Sub-) Contractor's Custody and postpone transfer of ownership to ESA
RGA	RGA300	STT-NEU #303a	$9075			
e-GUN	EGA-1114	STT-NEU #303a	$5950			
e-GUN	EGA-1114	STT-NEU #303a	$5950			

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TRL status

STT Engineering judgment regarding TRL level achieved within the project is the following one:

Initial TRL	Planned TRL as activity outcome	Actual TRL at end of activity
3	4	3/4

Levels

1	Basic principles observed and reported
2	Technology concept and/ or application formulated
3	Analytical and experimental critical function and/ or characteristic proof of concept
4	Component and /or breadboard validation in laboratory environment
5	Component and /or breadboard validation in relevant environment
6	System/ subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and 'flight qualified' through test and demonstration
9	Actual system 'flight proven' through successful mission operations

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Payment Plan and Status

Milestone (MS) Description	Schedule Date	Payments from ESA to Prime Contractor (in Euro)	Country (ISO code)
Progress (MS 1): Upon successful completion of Task 1 (PDR) and acceptance of all related deliverables	September 2016	320,000 (paid)	CH
Progress (MS 2): Upon successful completion of Task 2 (DDR) and acceptance of all related deliverables	March 2017	355,000 (paid)	
Progress (MS 3): Upon successful completion of Task 4 (TCR) and acceptance of all related deliverables, including a Final Report. As per this CCN 1, MS 3 is considered the Final Settlement.	~~December 2017~~ October 2024	174,957	
~~Final Settlement (MS 4): Upon the Agency's acceptance of all deliverable items due under the Contract and the Contractor's fulfilment of all other contractual obligations including submission of the Contract Closure Documentation~~	~~June 2018~~	~~150,000~~ Decommitted as per this CCN 1	
TOTAL		~~999,957~~ **849,957**	

<u>Current Milestone Payment Plan – CCN included</u>

- ✓ MS1 is closed
- ✓ MS2 is closed

- MS3 should be closed after the delivery of the updated documentation considering ESA RIDs, approval of the Contract Closure Documentation, uploading of the documentation in ESA system, and approval of the Final Review through the Minutes for Contract Close-out.

Company Name	Vendor Code	Type P/Prime; SI/Subco Indirect	Country (ISO Code)	Total Amount in Euro
SpectraTime	1000008079	P	CH	~~900,000~~ 750,000
OHB	1000003293	SI	DE	99,957

Orolia Switzerland	*CH*	OHB System AG	*DE*
MS1	300,000	MS1	20,000
MS2	300,000	MS2	55,000
MS3	150,000	MS3	24,957
~~MS4~~	~~150,000~~		
TOTAL	900,000	TOTAL	99,957

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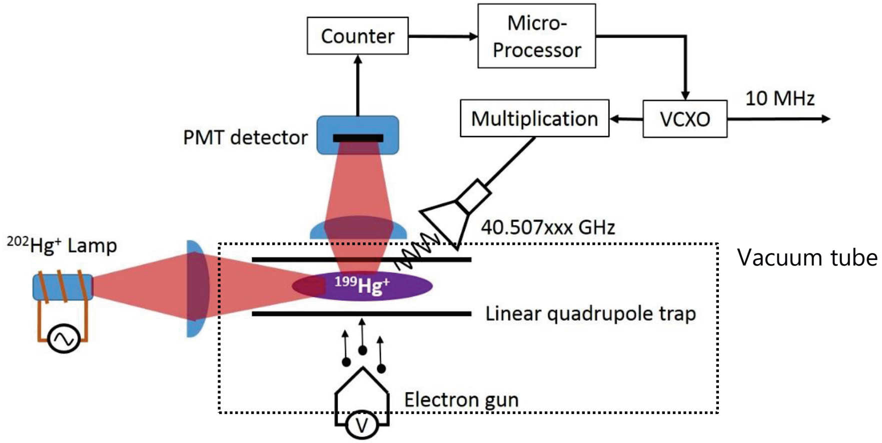
Chapter 02

MIC (=MIFS) Clock Overview

MIC – Mercury Ion Clock – Operating Principle (1)

- **Step 1: Ion cloud trapping**
  - UHV vacuum tube back-filled with :
    - Neutral ^{199}Hg (<1E-10 mbar)
    - Neon (1E-6 – 1E-5 mbar)
  - Electron gun generates Hg+ by collision impact
  - Hg+ is trapped by a linear QP (cigar shape)
- **Step 2: Optical pumping and detection**
  - ^{202}Hg+ plasma lamp for optical pumping/detection
  - Ion cloud fluorescence (weak) is detected on PMT
- **Step 3: Microwave interrogation**
  - MW antenna probes the hyper-fine clock transition (40.5 GHz)
  - Slow servo-loop (> 10 seconds) disciplines USO crystal oscillator at 5/10 MHz



«The MIC technology traps a cloud of mercury ions in free space with no wall collisions, leading to very low environmental sensitivity and frequency drift»

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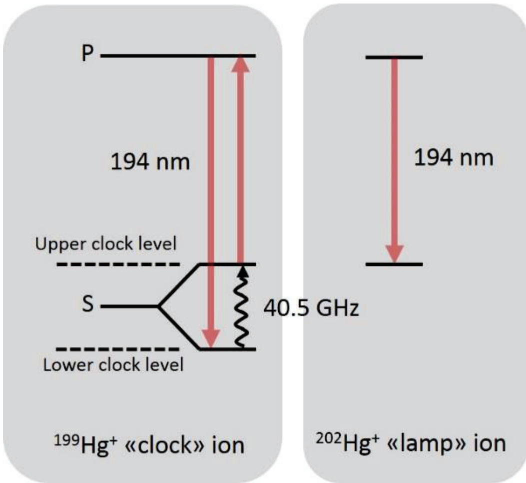
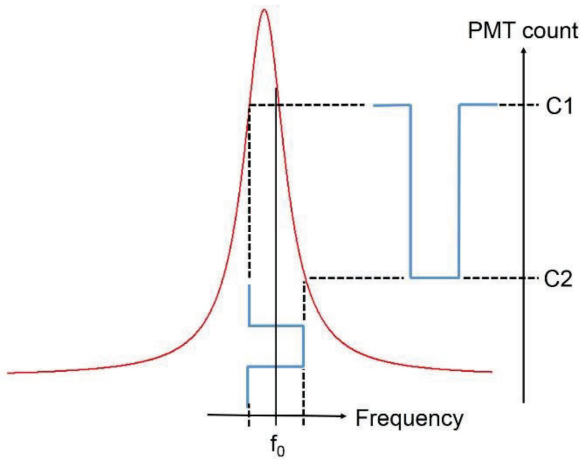
MIC – Mercury Ion Clock – Operating Principle (2)

- Simplified energy level structure in mercury isotopes ^{199}Hg and ^{202}Hg.
- Same level-structure as hydrogen maser (I=S=1/2 -> F=0,1)



- Microwave clock resonance
- Similar to RAFS double-resonance interrogation (but much slower)



«The MIC technology traps a cloud of mercury ions in free space with no wall collisions, leading to very low environmental sensitivity and frequency drift»

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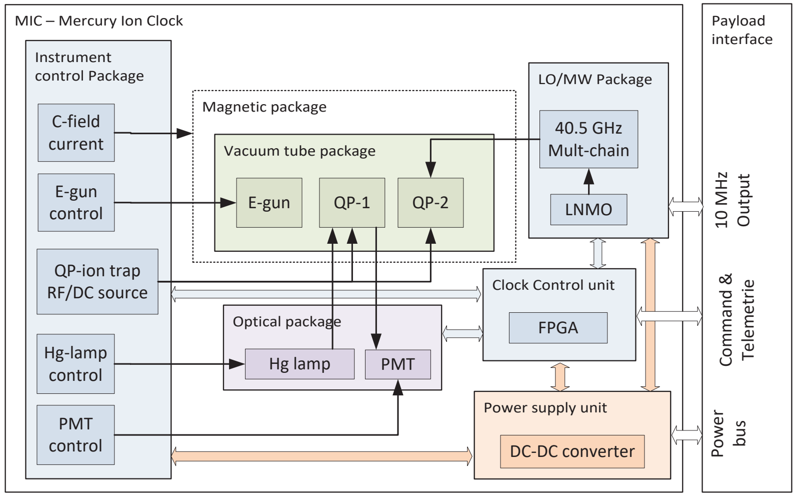
MIC Block Diagram

- **vacuum package:**
  - double QP ion trap, electron gun, vacuum tube, and NEG pump
- **magnetic package**
  - C-field coil, 3-layer magnetic shield
- **instrument control package**
  - drive electronics for the RF ion trap, e-gun, C-field, UV lamp, and PMT detector
- **optical package**
  - UV lamp, UV filtering- and imaging optics, PMT detector
- **LO/MW package**,
  - stable OCXO crystal oscillator, tuneable 40.507xx GHz microwave multiplication chain, and waveguide- coupler and -antenna.
- **Clock control unit**
  - including a FPGA-based clock controller
- **Power supply unit**
  - including the payload power supply system with DC-DC converter



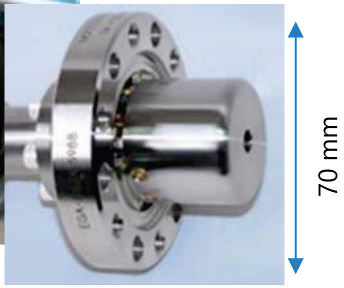
Chapter 03

Elegant Bread-Board clock (EBB) Design and MAIT

Heritage and EBB objectives

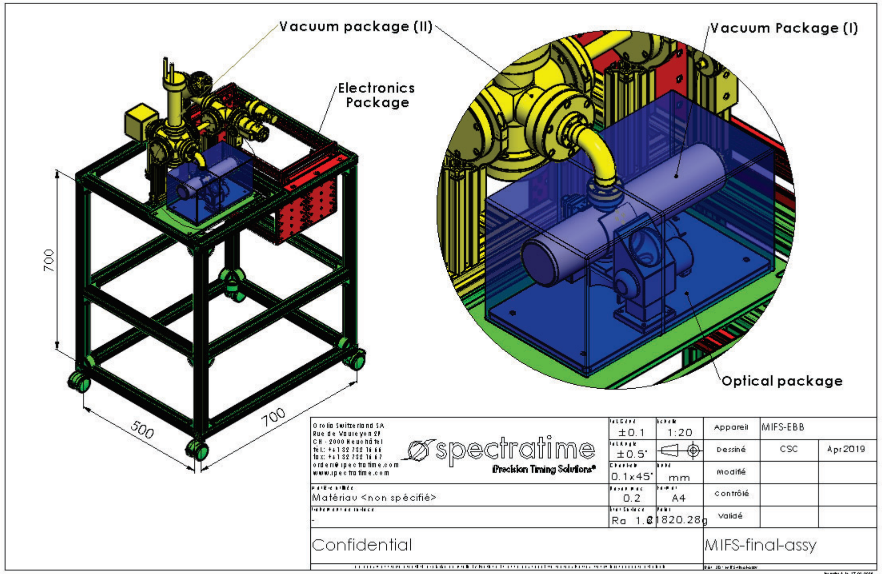
- **MIFS-1 Heritage**
  - Laboratory demonstrator
  - TRL3
  - COTS PP parts (CF40 flanges, e-gun, windows, etc.)
  - COTS EP parts (QP-trap, e-gun, MW-synthesizer, etc.
- **MIFS-2 objectives**
  - Design, MAIT of EBB MIC clock
  - Reduce size of PP vacuum tube (25x25x200 mm)
    - New custom e-gun
    - Replace CF40 flanges (70 mm) with weldable flanges (<20 mm)
    - Replace COTS windows with custom brazed/welded sapphire windows
  - Develop custom EP drivers to replace COTS:
    - 40.5 GHz multiplication chain
    - HV QP ion trap driver
    - E-gun driver

MIFS-1 Lab demonstrator



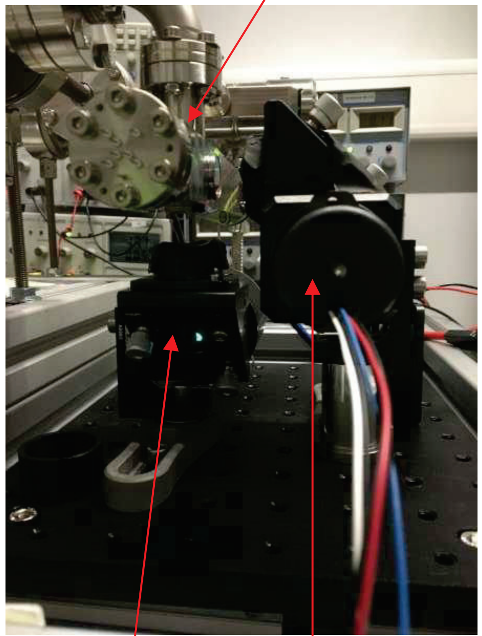
COTS egun

EBB clock design and assembly



Vacuum tube

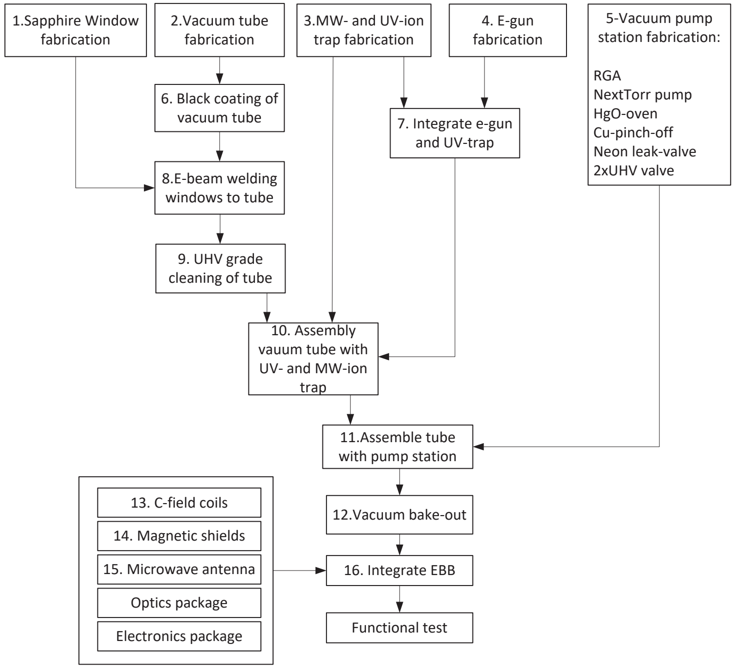
Vacuum tube

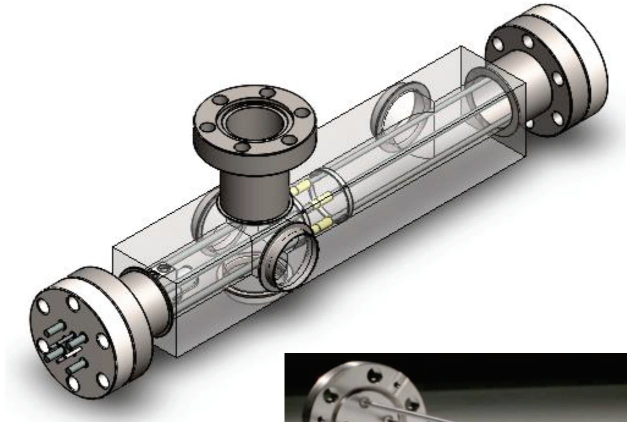


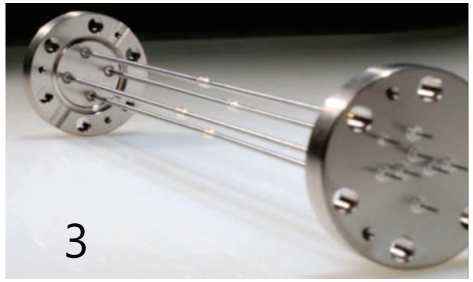
Optical input

Optical output

Vacuum package assembly flow







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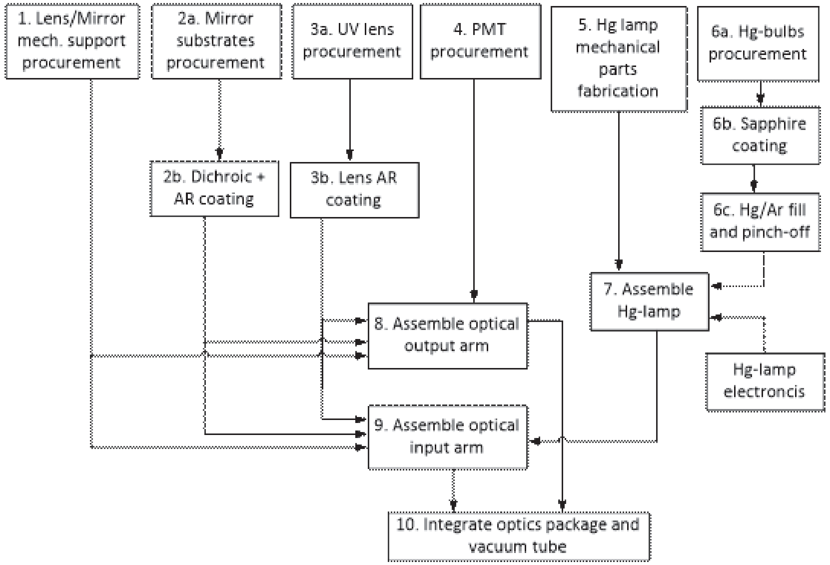
Vacuum package (I+II) bakeout

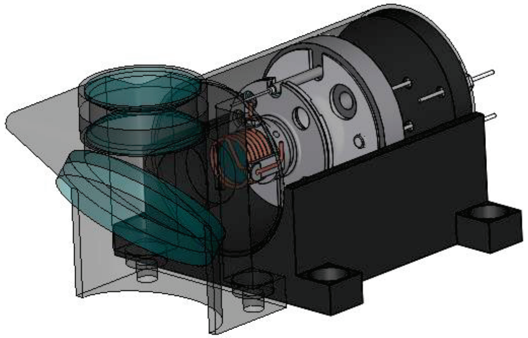
- **Vacuum tube mounted on "pump-station"**
  - RGA resisual gas analyzer
  - NexTorr pump (NEG + IP)
  - HgO oven (mercury oxide oven)
  - Neon variable leak-valve
  - Pinch-off copper tube

- **Bake-out and NEG activation**
  - 200°C bake-out, 3 days
  - Day 3: NEG activated by resistive heater (400°C, 1 hour)

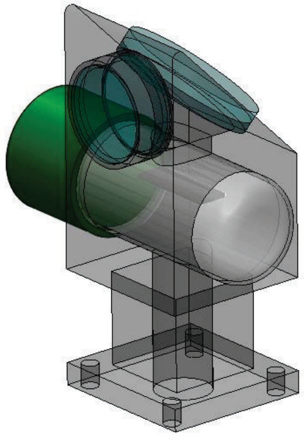
  - Industrialization path:
    - Bake-out tube at 400°C in guard vacuum oven (double-vacuum)
    - NEG is placed directly into vacuum tube
    - NEG is activated at the peak of the bake-out (450°C)

Optical package assembly flow (I)





Optical input arm



Optical output arm

2

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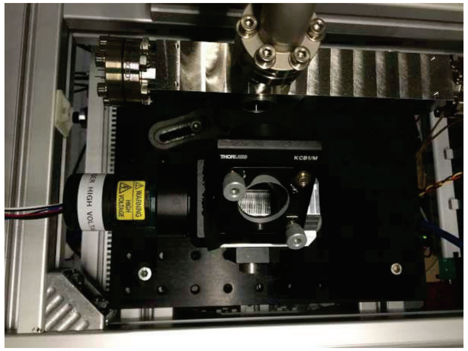
Optical package assembly flow (II)

Hg-lamp

Dichroic filter mirror

Bi-convex UV imaging lens

Optical input arm



Optical output arm

2

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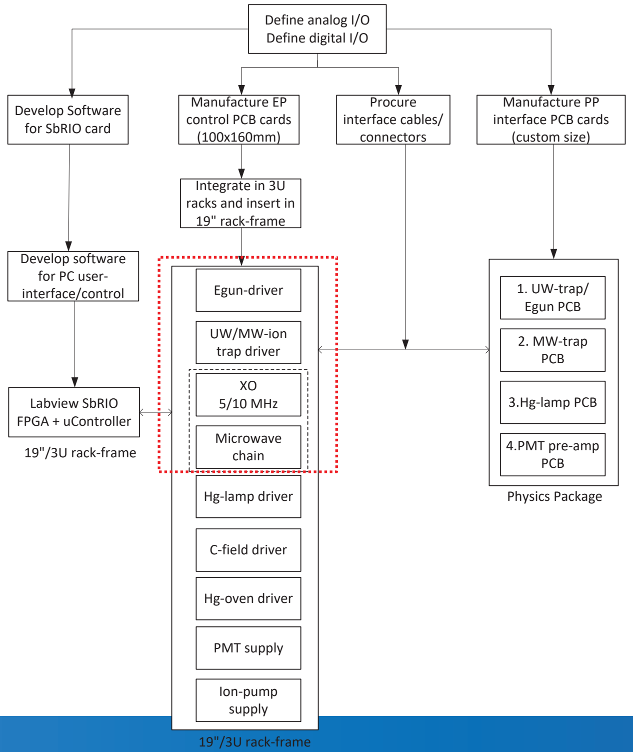
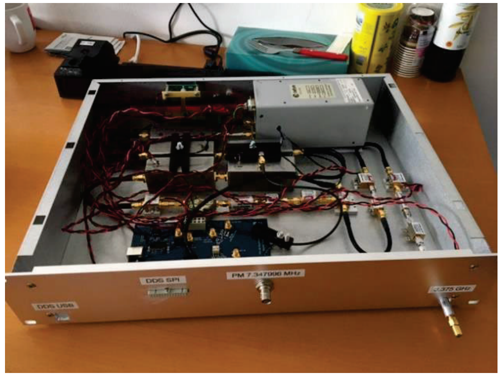
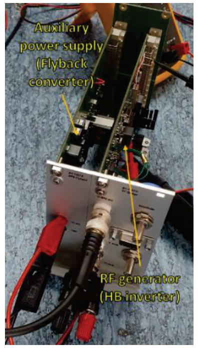
Electronics package assembly



40.5 GHz chain





HV QP-trap

E-gun driver

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Chapter 04

Functional test of sub-systems

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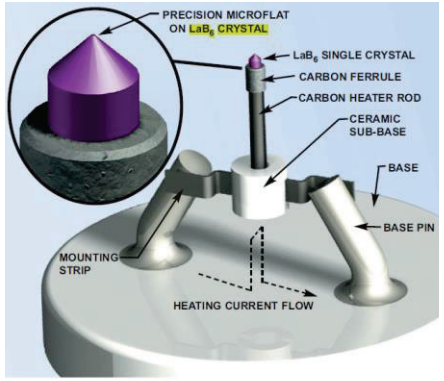
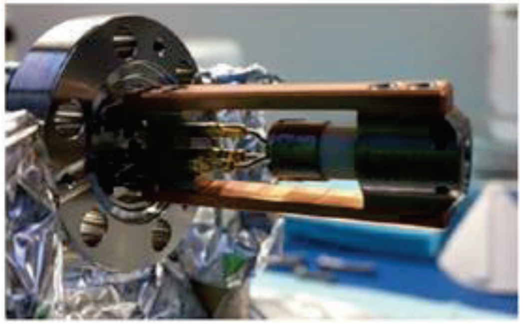
Functional test of e-gun (I)

- **LaB6 cathode**
  - Adapted for low beam energy (~60eV)
  - Adapted for low beam current (~10 uA)
  - Lifetime predictable (theory)
    - Crystal evaporation rate well studied
    - Crystal size can be selected for lifetime spec.
  - US supplier, but EU supplier available
  - No space heritage (except DSAC mission, 2 year LEO)
- **Custom egun**
  - No COTS part identified
  - STT engaged in custom development with US supplier
  - Long (3+ year) development cycle





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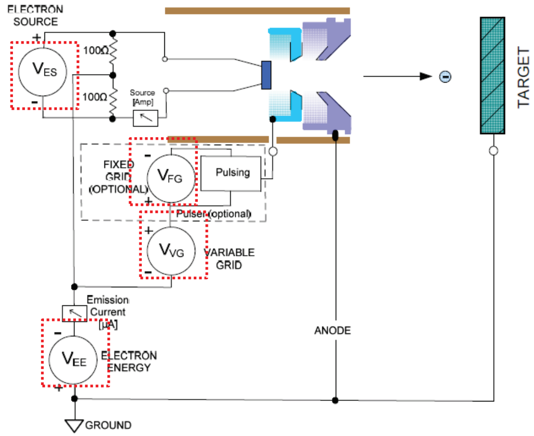
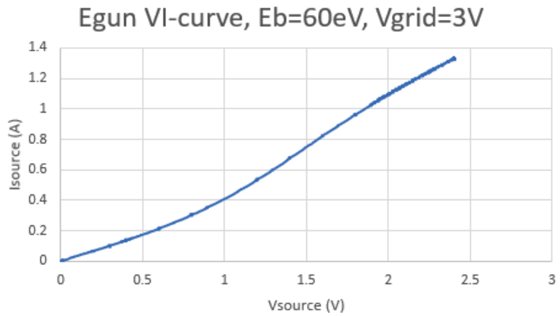
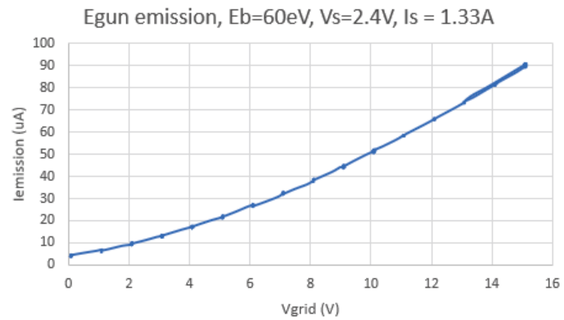
Functional test of e-gun (II)



- **Test parameters**
  - V_{ES} : Beam current (uA)
  - V_{EE} : Beam energy (eV)
  - V_{VG} : Beam focus (V)
  - V_{FG} : Beam on/off (V)

- **Results**
  - ✓ VI-curve
  - ✓ Egun emission
  - ✓ Beam focus
  - ✓ Beam on/off





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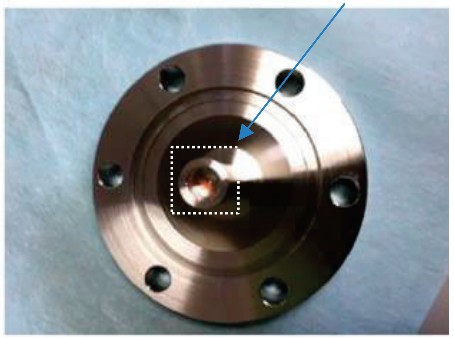
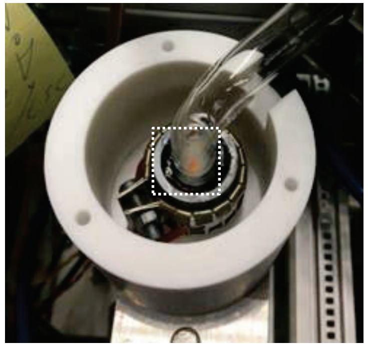
Functional test of HgO oven

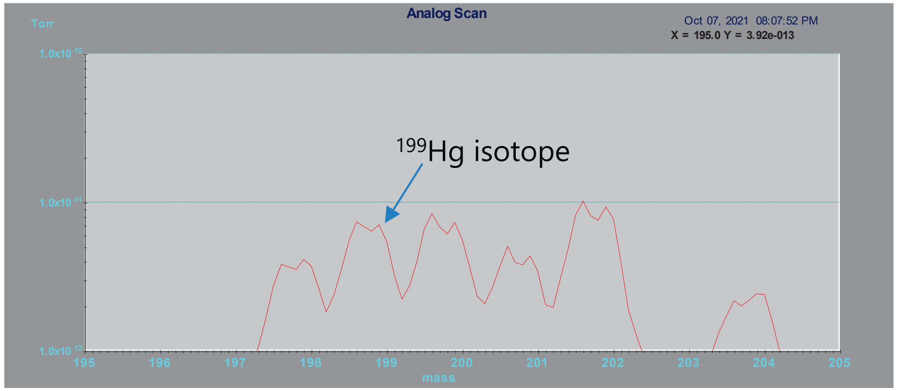
- **HgO oven parameters**
  - Few mg of ^{199}HgO (>90% isotopic)
  - Thermal decomposition of oxide:
    - 2HgO -> 2Hg + O2 (>200°C)
  - Oven test done with natural isotope mix

- **Results**
  - Old design with pyrex finger (OK)
  - New design with 304-steel (not ok)
    - Too high out-gassing rate from steel

HgO powder (orange)







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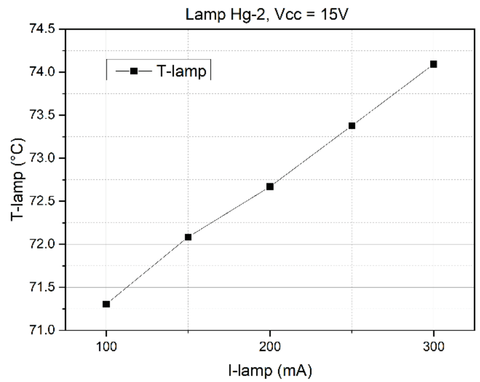
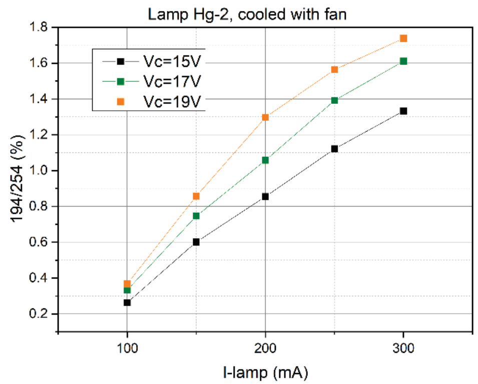
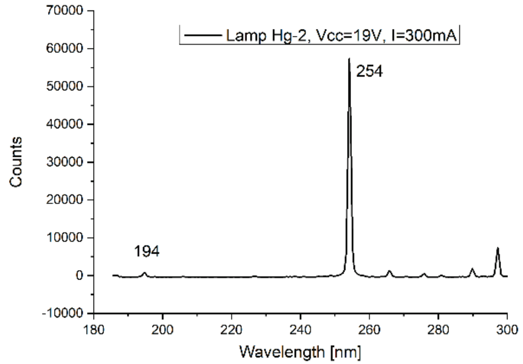
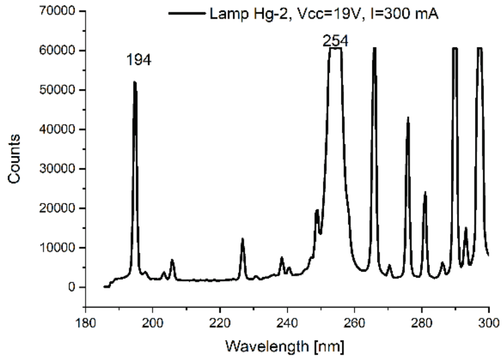
Functional test Hg-lamp

- **New lamp bulbs developed**
  - Old: Heraeus fused silica
  - New: Suprasil 310 (very clean SiO2)
- **Back-filling**
  - Few mg ^{202}Hg isotope (>90% pure)
  - Few mbar Argon
- **Lamp parameters**
  - Oscillator frequency (125 MHz) fixed
  - Oscillator power (or DC current)
  - Lamp bulb temperature







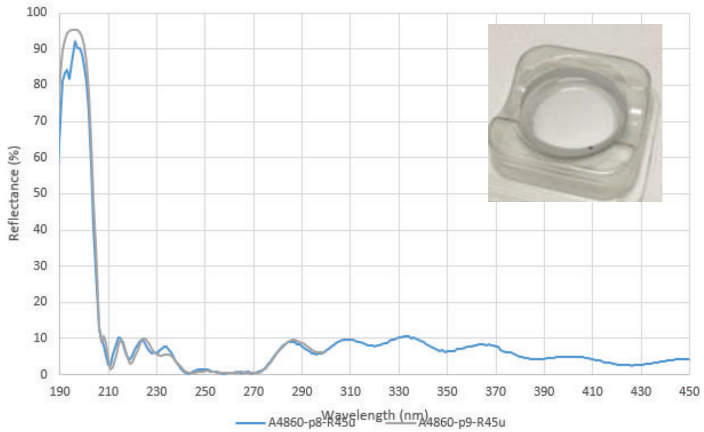


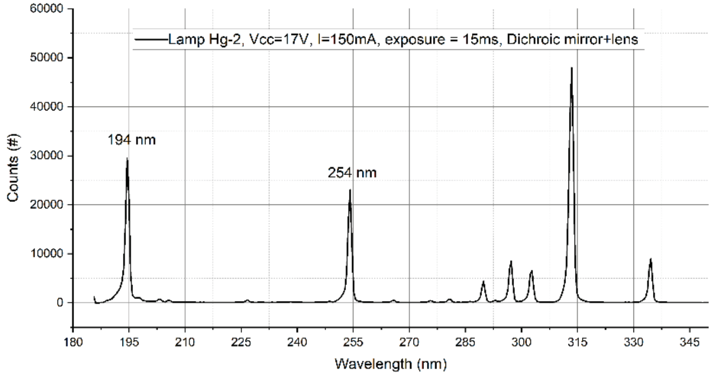
exposure = 8 ms

exposure = 400 ms

Functional test Dichroic mirror

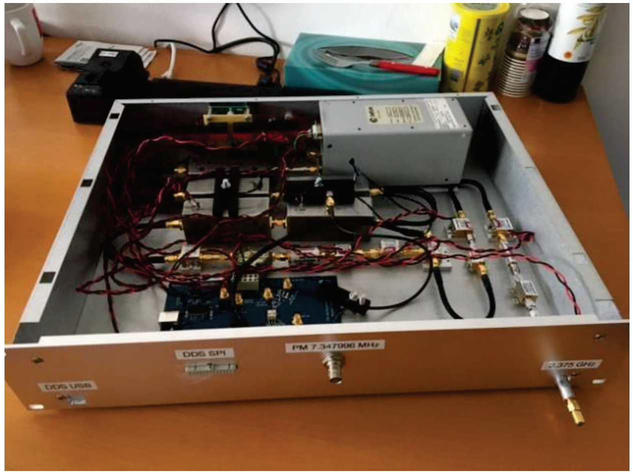
- **Custom development with supplier**
  - HR @194 nm
  - HT @254 nm
- **High 194/254 ratio**
  - Direct measurement by supplier
  - Test with Hg-lamp

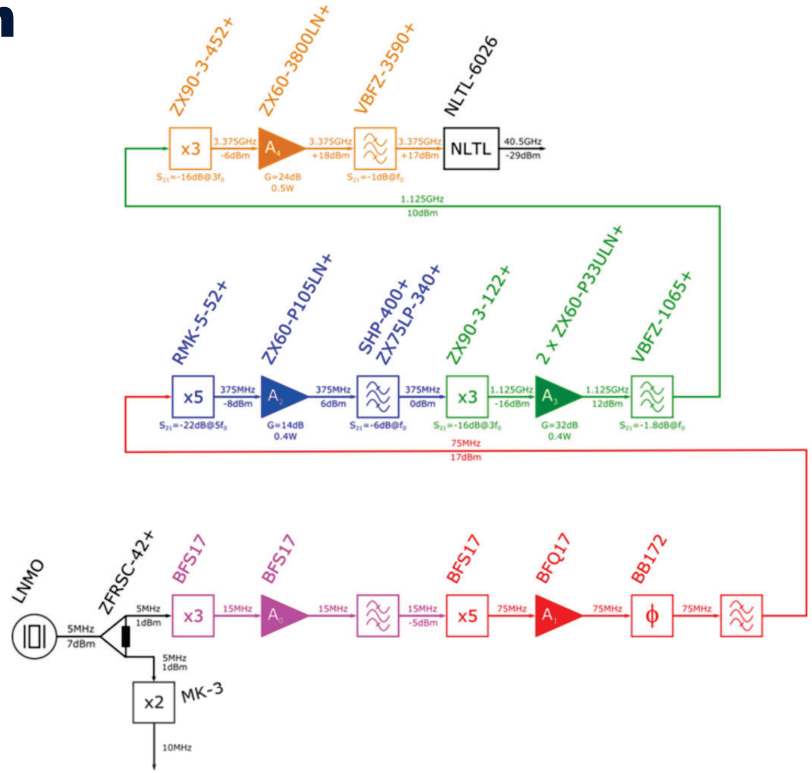




Functional test 40.5 GHz MW chain

- 5 multiplication stages (x675) from 5 MHz to 3.375 GHz
- NLTL multiplication stage (x12) from 3.375 GHz to 40.5 GHz
- PM modulation at 7.3xxx MHz (@75 MHz carrier)





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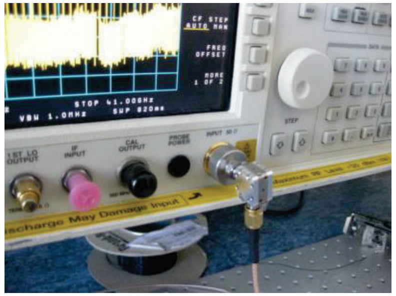
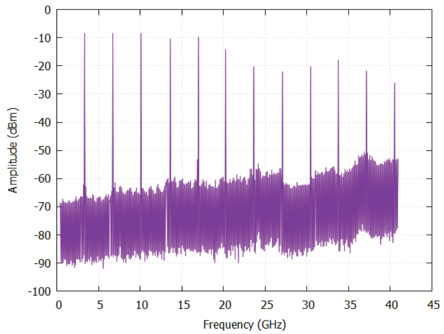
Functional test 40.5 GHz MW chain (II)

- **Results**
  - ✓ Characterization of NLTL
  - ✓ 5 stage multiplication
  - ✓ PM modulation
  - ✓ Spectral purity and power

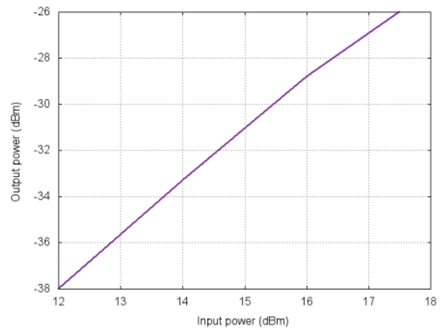
NLTL-6026

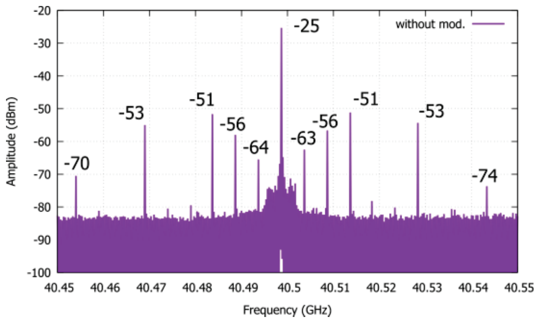


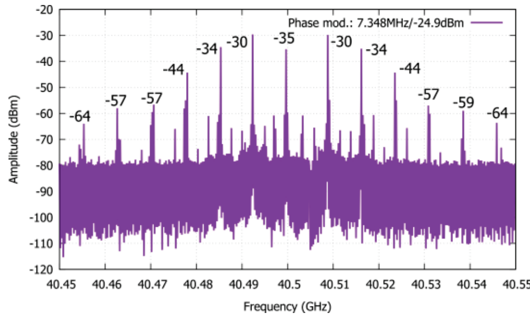
Input: 3.375 GHz/16 dBm

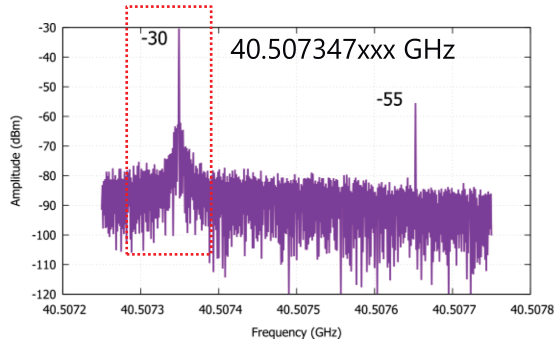


40.5 GHz out- vs input power









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Chapter 05

EBB integration and blocking point

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EBB integration summary

Step N°	Description	Checkpoint	OK /NOK	Remarks
1	**Vacuum System Integration & Verification**		**OK**	
2	**HgO Oven Integration & Verification**		-	
3	**Buffer Gas Leak Integration & verification**		-	
4	**Electron Gun Integration & verification**		-	
5	**Ion Trap Integration & verification**		-	
6	**Signal search and optimization (step 1): Electronic resonance detection**		OK	
6.1	Connect resonance detection circuit			
6.2	Set e-gun parameters			
6.3	Set initially ion trap parameters:			
6.4	Detect the presence of Hg+ in ion trap by: 1) slowly ramping Vrf amplitude 2) observe “dip” in external signal at 70 kHz due to resonant excitation of trapped ion-motion.	electronic resonance signal from trapped ions	OK	
7	**Input Optical Arm Integration**		OK	
8	**Output Optical Arm Integration**		OK	
9	**Signal search and optimization (step 2): Optical fluorescence detection**		NOK	Saturation of PMT detector
9.1	Set working points of Hg lamp and oscillator		OK	
9.2	Record the fluorescence from trapped ions.	Fluorescence signal from trapped ions	NOK	Saturation of PMT detector

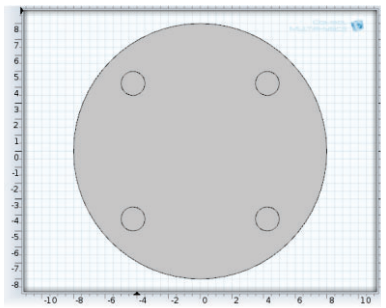
QP ion trapping check

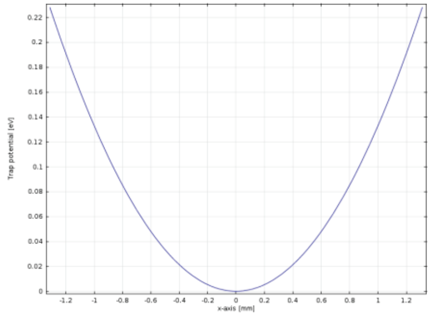
Ion trap fluorescence check

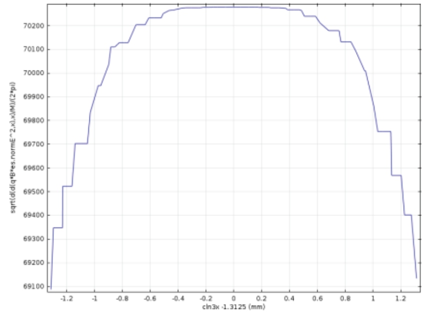
Step 6 – LC resonance detection of trapped ions (I)

- **Simulate trapping parameters to get 70 kHz secular trap frequency**

Ion	Electrode radius [mm]	Electrode to center [mm]	V_{pp} [V] (symmetric)	V_{pp} [V] (asymmetric)	f_{trap} [kHz]	$f_{Secular}$ [kHz]	Depth [eV]
$^{131}Xe+$	0.75	6	132	264	625	70	1.3
$^{199}Hg+$	0.75	6	201	402	625	70	1.9

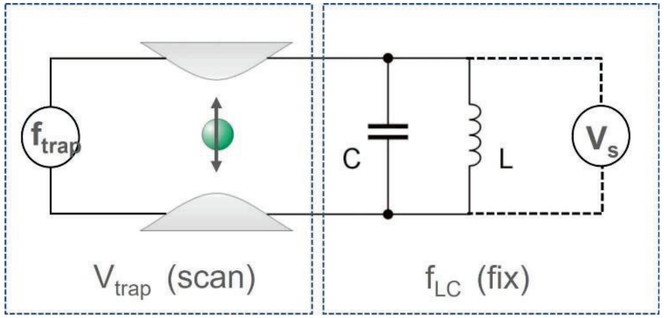

The QP ion trap cross-section view.


Ion trap potential

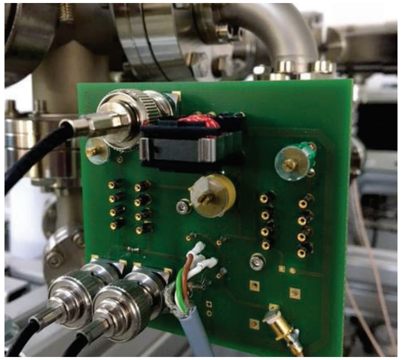

Secular trap frequency

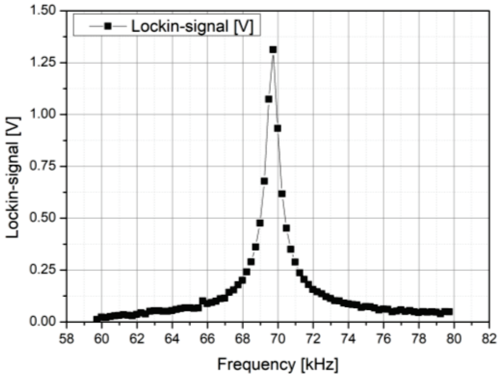
Step 6 – LC resonance detection of trapped ions (II)

- **Connect LC resonance across pair of electrodes**
  - Tune LC resonance to 70 kHz
  - Measure peak amplitude (lock-in)



Schematic of LC resonance detection

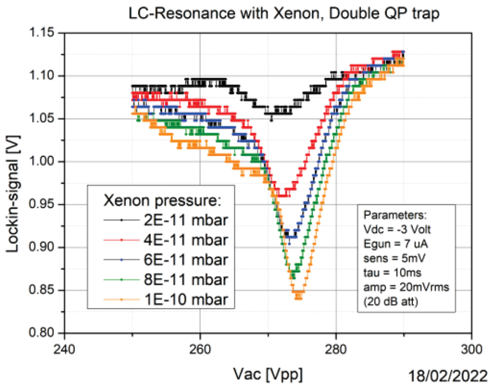




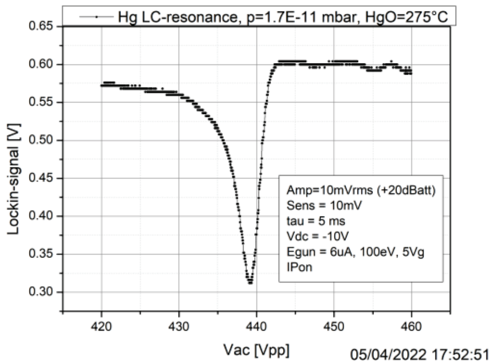
LC resonance PCB and signal

Step 6 – LC resonance detection of trapped ions (III)

- Back-fill Xenon or Hg (heat HgO oven)
- Scan peak-peak amplitude across ion trap electrodes (around simulated value)
- Record the LC resonance peak amplitude (**flat = no ions trapped, dip = trapped ions**)



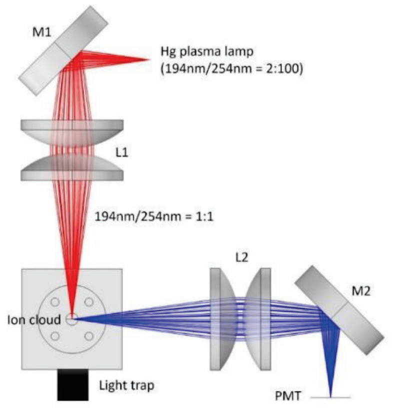
LC-signal dip from trapped Xe+

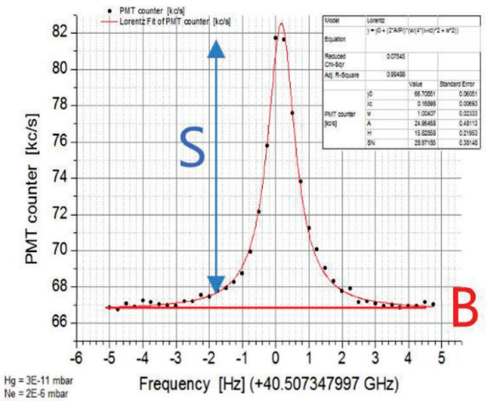


LC resonance dip from trapped ^{199}Hg+

Step 9 – optical fluorescence detection of trapped ions

- **Schematic of optical fluorescence detection**
  - The clock signal-to-noise ratio SNR on PMT detector:
    - Signal counts (S) from optical fluorescence (blue rays)
    - Background noise counts (B) from scattered stray-light (red rays)
- **Blocking point**
  - STT observed saturation of PMT detector (B>1E6 counts per second)
  - Root-cause analysis and mitigation actions
    - Poor light-trap design
    - Spherical aberration
    - Source position
    - Ghost reflections
- **Use ray-trace simulation for analysis (next slides)**





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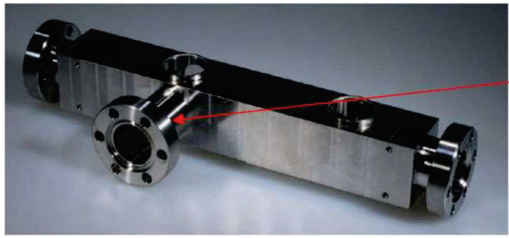
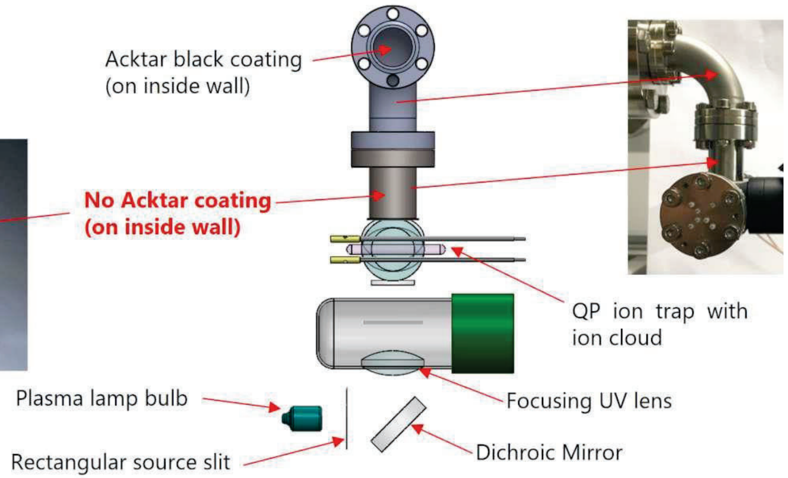
Poor light trap design

- **Light trap target design**
  - Goal to reduce stray background counts (B)
  - Target attenuation ~ 60 dB
- **No black coating close to ion trap**
  - Strong scattering of UV photons onto PMT





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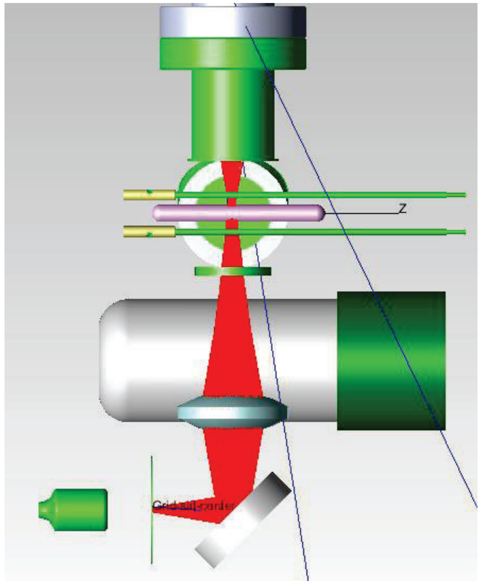
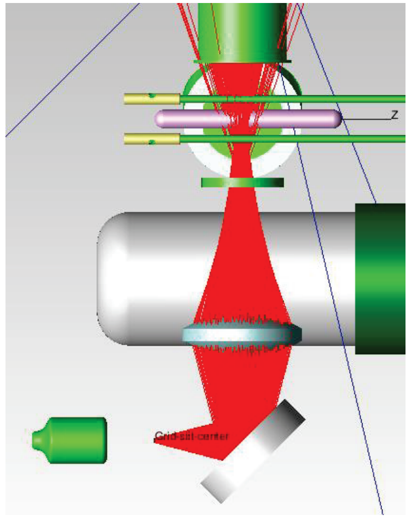
Spherical aberration

- **Focus with biconvex lens**
  - Two spherical surfaces
  - 1:1 image of aperture slit onto ion-cloud
- **Spherical aberration**
  - Rays close to optical axis focus 1:1 image
  - Rays far from optical axis have shorter focus
- **Stray light scattering**
  - Spherical aberration (right) leads to scattering from un-coated part of tube
  - Strong scattering of UV photons onto PMT





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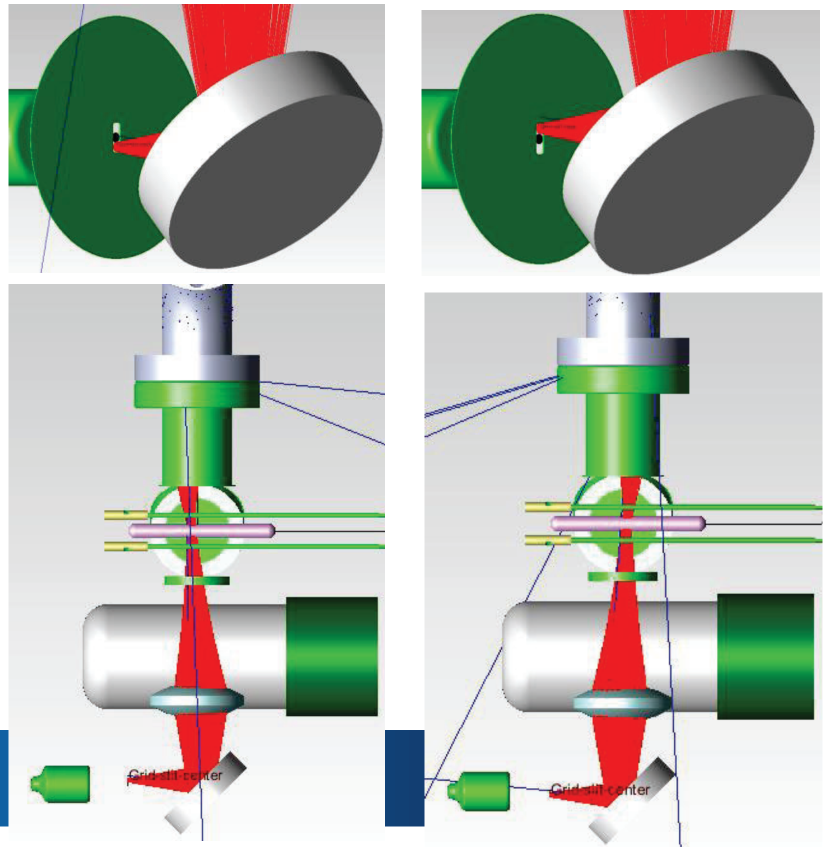
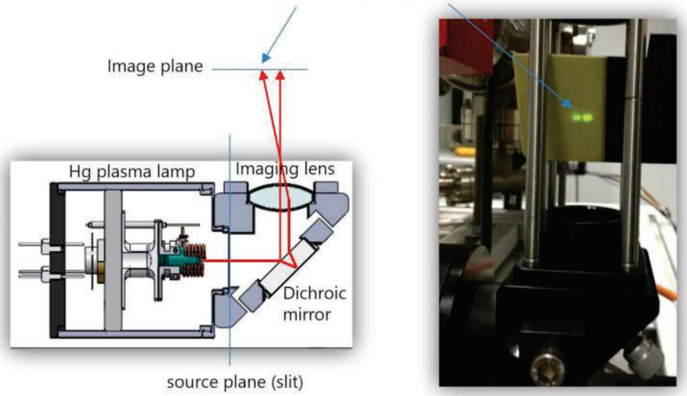
Source position on aperture slit

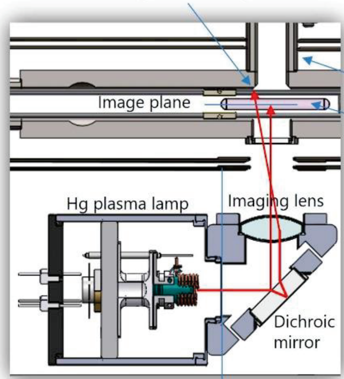
- **Rectangular source slit**
  - Goal to image slit 1:1 onto ion-cloud
- **Change source position**
  - Ray-trace simulation with +/-1 mm from slit center
  - Beam is again scattering off un-coated part of tube
  - Leads again to scattering of UV photons onto PMT



Ghost reflection

- **Ghost reflection**
  - Fresnel scattering from back-side of mirror
  - BK7 mirror substrate
    - 100% absorption of 254 nm
    - But transmission at other lamp lines (313 nm, 365 nm, ..)
  - Simple calculation gives reflection R=5%
- **Ghost reflection scattering**
  - Direct scattering *inside* vacuum tube
  - Leads again to scattering of UV photons onto PMT



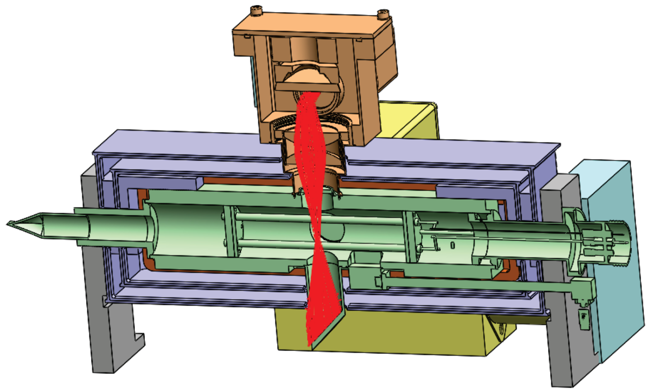


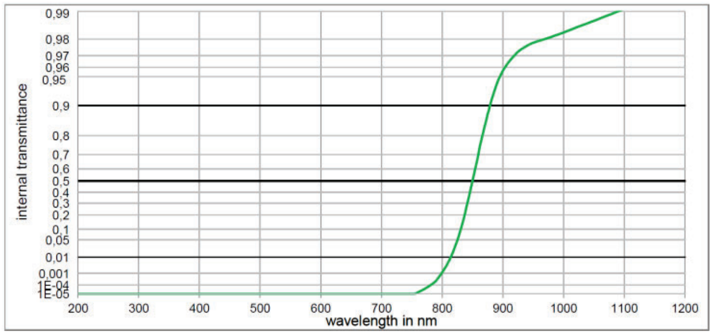
Chapter 06

Conclusion and lessons learned

Lessons learned

- **Light trap design**
  - Light trap shall be as close to QP trap as possible
    - Trade-off: attenuation vs. perturbation
  - New design with optimized light trap
- **Spherical aberration**
  - New design will use aspheric lenses
  - Bi-concave lens replaced with two plano-convex lenses
- **Source slit position**
  - New light trap design eliminates this source of stray light
- **Ghost reflections**
  - Mirror substrate BK7 eliminates only 254 nm
  - New mirror substrate RG850 eliminates all ghost reflection





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Conclusion

- **New development of compact MIC physics package (vacuum- and optical package)**
  - Compact titanium vacuum tube
  - Weldable sapphire window flanges
  - Double QP ion-trap design
  - Compact custom e-gun
  - Suprasil lamp bulbs
  - Custom dichroic filter mirrors
- **Project blocked by poor SNR**
  - Root-cause analysis (optical simulation) identified several issues:
    - Poor light trap design
    - Spherical aberration
    - Slit position
    - Ghost reflections
  - Lessons learned (and already being implemented in new projects)

Conclusion

- **TRL assessment**
  - TRL3 -> TRL4
- **De-risking of critical items**
  - Several critical items need de-risking activity:
    - Mercury plasma lamp lifetime and reliability
    - Vacuum tube lifetime
      - Hg consumption
      - Ne consumption
    - Enclosure of optical input arm to avoid UV-induced pollution of optical surfaces

Chapter 7

Q&A

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