# Status of RF Power and Acceleration of the MAX IV - LINAC

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ESLS RF Workshop

2015

# MAX IV Laboratory
## A National Laboratory  for synchrotron radiation at Lunds University

1981 – MAX-lab is formed
1986 – First experiments at MAX I
1997 – First experiments at MAX II
2005 – MAX IV Conceptual Design Report
2007 – First experiments at MAX II
2009 – Decision to build MAX IV
2016 – First experiments at MAX IV
2025 – First experiments at FEL !!!!!!!!!

“It’s too dangerous not to take the risks”
Mikael Eriksson

# MAX IV Laboratory - LINAC

- Why was MAX IV Linac projected in this way?
- What has MAX IV Linac in its composition?
- How it is MAX IV Linac built and it works?

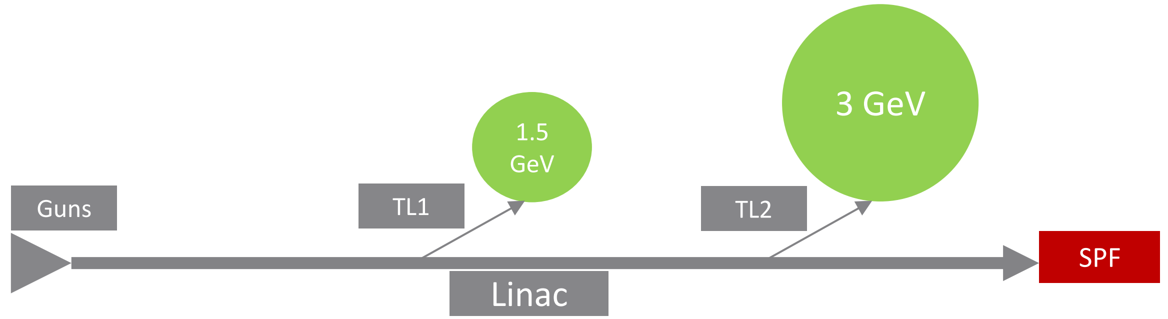
# MAX IV Laboratory - LINAC

- Why was projected in this way?
  - The demand for high energy and high quality electron beam
  - The historical reasons
  - Techniques achievement
  - Modularity
  - As simply as possible
- What is its composition?
  - RF Guns
  - RF Units
  - Accelerators structures
  - SLED cavities
  - Waveguide system
- How it is built and it works?
  - Assembling and installation
  - RF conditioning
  - Linac commissioning
  - Linac running

# Why was projected in this way?

1. The demand for high energy and high quality electron beam, to meet the needs of injection of two rings and SPF.

- Full energy Linac should delivers top-up shots to both storage rings
- Two deticated vertical (achromatic) transfer lines
- Therminic RF Gun injects at PRF 10Hz
- Injection into rings via DC Lambertson septum
- Extraction requires interruption of 100 Hz SPF operation (energy filter and extraction magnets need to ramp up)
- SPF - Short Pulse Facilities: Photocathode RF Gun, 3GeV, 100Hz




Quality requirements for Linac

**for the rings 1,5GeV & 3GeV**

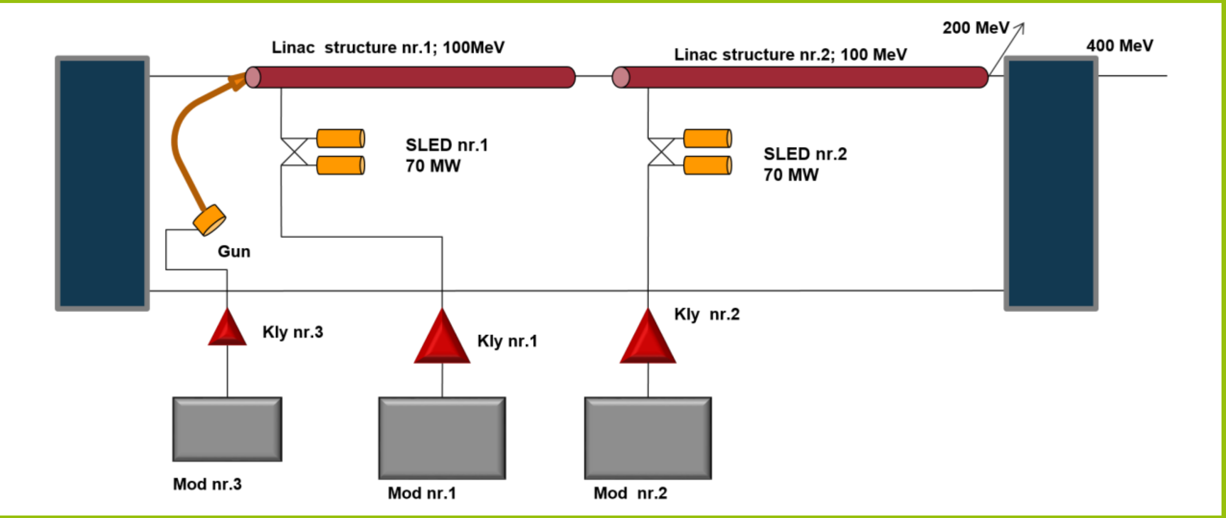
- Position at extraction within 100 micron
- Angle at extraction within 100 micro-rad
- Transverse normalized emittance around 10 mm mrad
- Energy spread within one S-band bucket better than 0.1%
- Energy spread over entire 100 ns train better than 1%
- Total charge of a 100 ns train 1 nC or better
- The train length >100 ns as long as the correlated energy spread <1%
- 500 MHz structure: every 6th S-band bucket passes the chopper -> 50 S-band bunches within the 100 ns train
- 100 MHz structure: every 30th S-band bucket the chopper lest 3-5 S-band bunches pass -> 30-50 S-band bunches within the 100 ns train
- Each S-band bunch must contain at least 20 pC

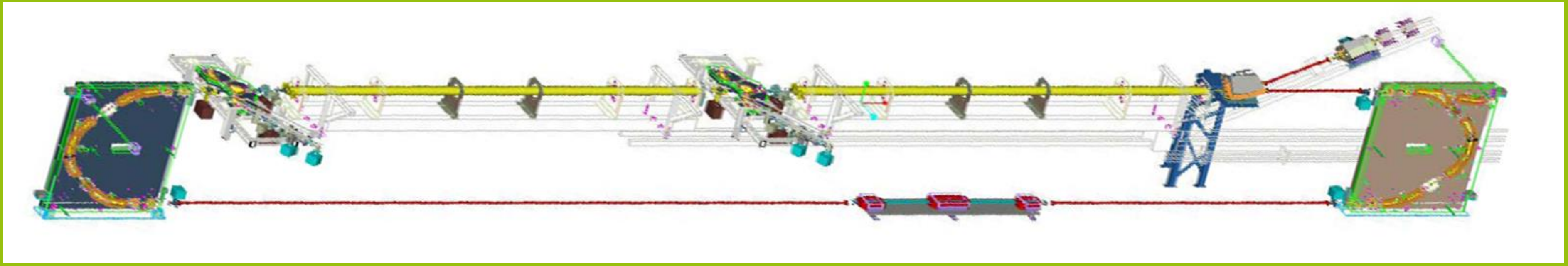
**for the SPF**

- Energy 3 GeV
- Norm RMS emittance 1 mm mrad
- RMS Energy spread 0.4%
- Charge 0.1 nC
- Repetition rate 100 Hz
- RMS pulse-to pulse energy stability 0.05%
- RMS pulse to pulse positional stability 4 μm (H&V)
- RMS angular stability 4 μrad
- FWHM bunch length 100 fs
- RMS time jitter <0.5 ps
- Drift (minutes-days timescale) 1 ps
- Background 1% charge outside 1 ps.

# Why was projected in this way? Why S-band?

2. For historical reasons: we had a long experience in the construction, improvement and use of the S-band Linac from the old MAX-lab
   - SLED technology
   - Take special care to the quality of the cooling and temperature-controlled water.
   - Avoid using vulnerable materials in the radiation field etc.



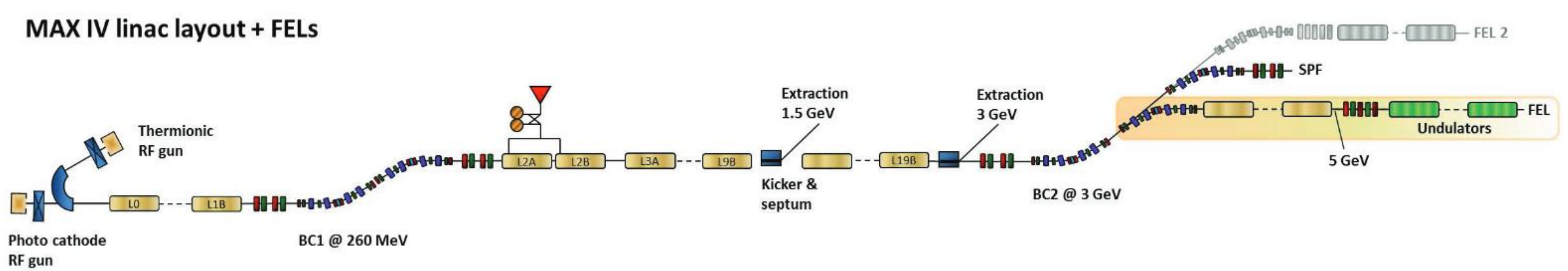
# Why was projected in this way?

3. It was taken into account what techniques can be applied approaching us at the time and several years in the future

4. Modularity was one of our priority on this project, it help on easily and inexpensive installation and maintenance.

5. As simply as possible, but complicated enough to perform the task was charged

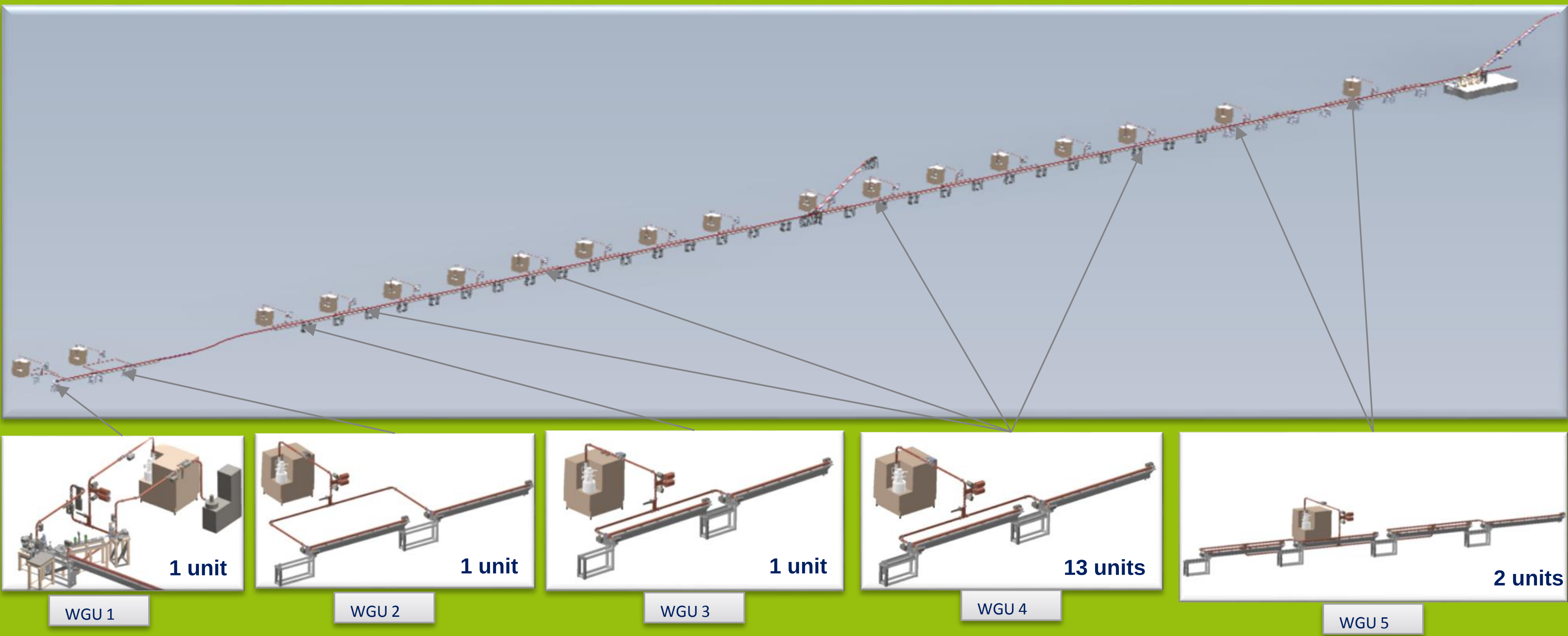
- Master, please tell me the secret how do you paint so beautifully this elephant:
Da Vinci: simple, not paint the parts that do not belong to elephant



# What is its composition?

**LINAC is build on modules: 5 different model for 18 modules**

- 18 pcs: RF power units (37MW peak, 4,5usec, 100Hz), ScandiNova mod & Toshiba klystron
- 1 pc: RF power unit (8MW peak, 3usec, 10Hz), ScandiNova mod & Toshiba klystron
- 18 pcs: SLED (Q=100000, 4,5usec in, 0,7usec out), RI
- 2 pcs: RF guns (a therminioc, second photocathode), MAX IV Laboratory
- 39 pcs: Linac structer (max gradient of acceleration 25MV/M, 5m long), RI

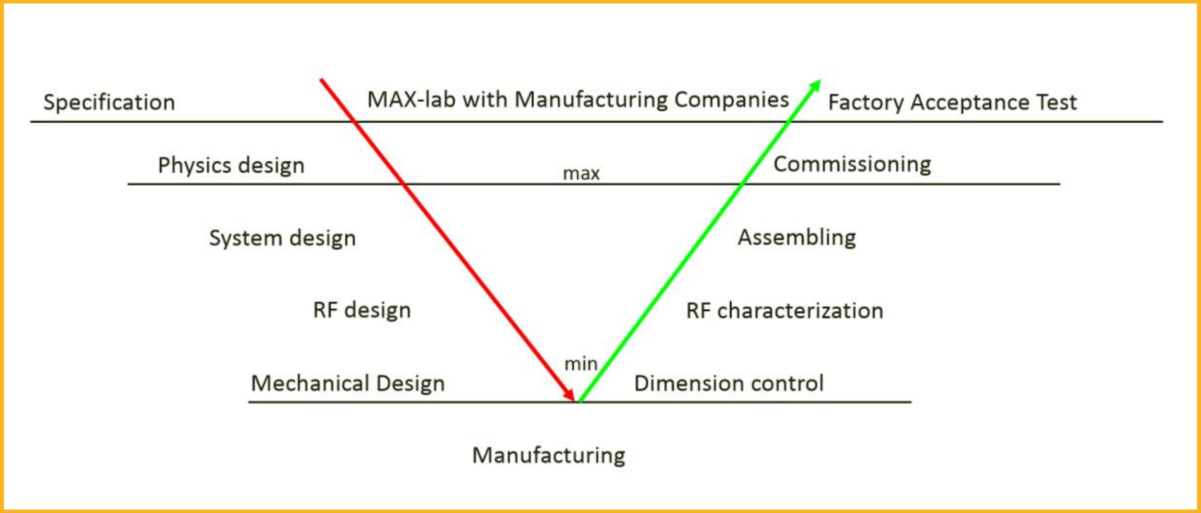


# What is its composition? – Manufacturing Companies

- The philosophy in relations with the companies, cooperate and work together, keep focus to reach the goal.
- As happened to have problems with production or delivery time, follow them near by until we get solution.

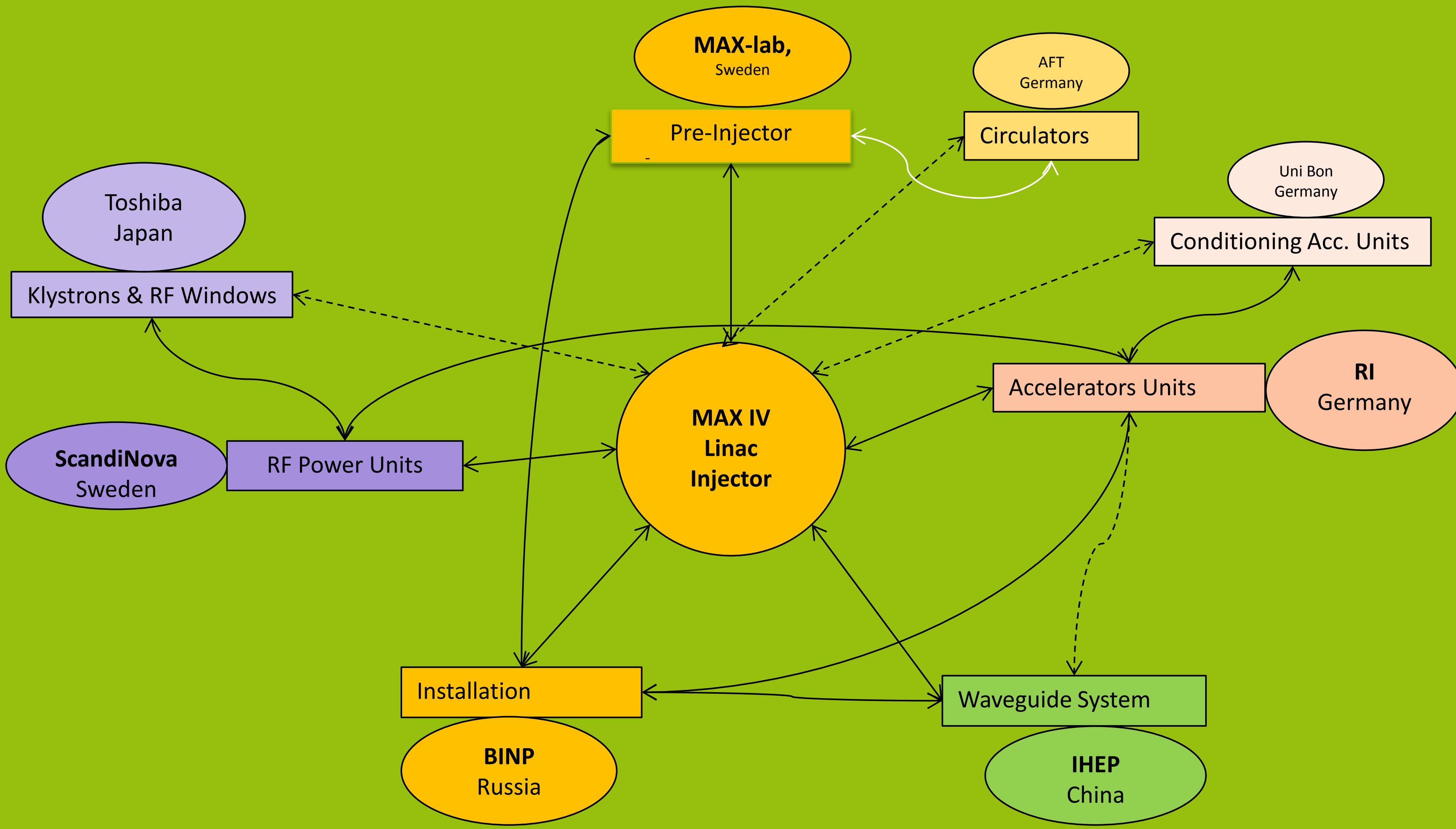
(keep in mind that this will be a long-term relationship)

- The method of cooperation with manufacture companies has been the very familiar "V" form of cooperation and implementation. The cooperation has been somewhat different for different companies. Our moto Trust and Control.



# What is its composition?

- Despite our efforts, we fail to do simpler than this diagram below.

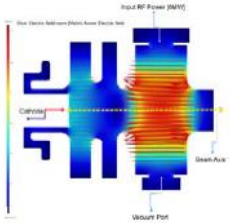





MAX IV

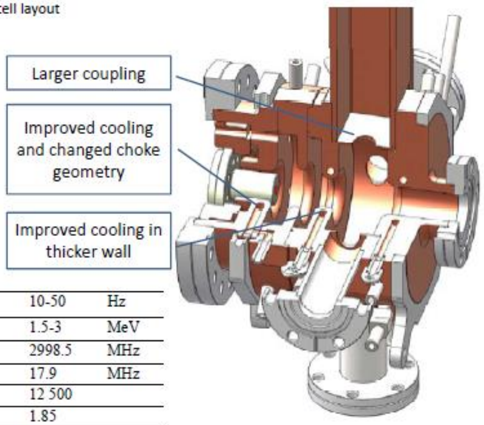
# What is its composition? – RF Guns (Thermionic)

## Thermionic RF gun

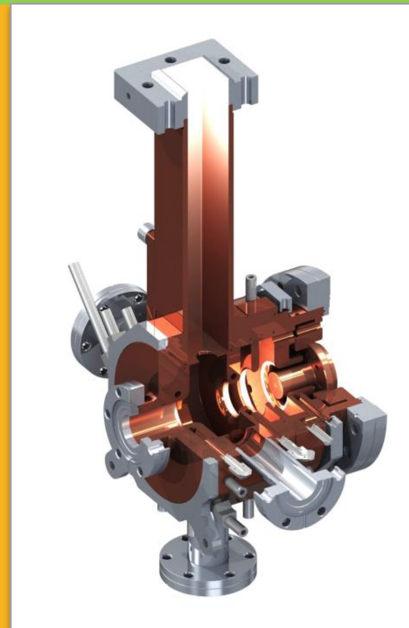


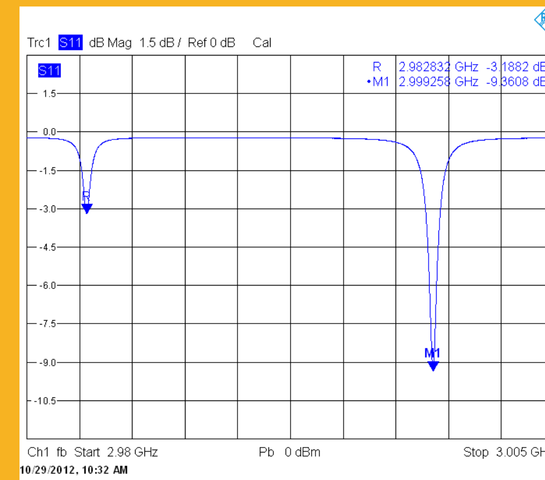
Field and cell layout

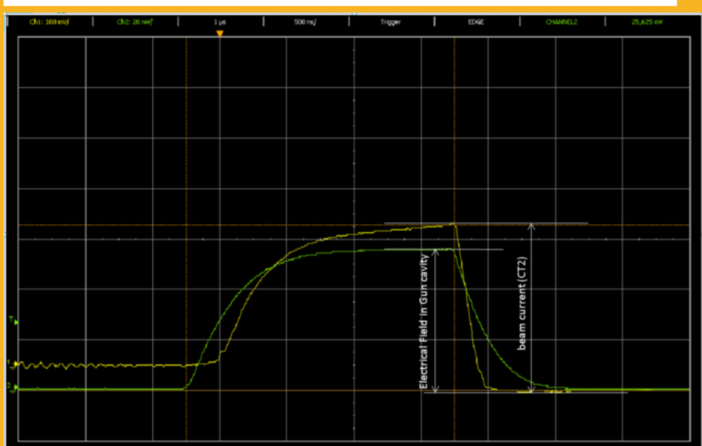
This gun builds on the existing thermionic RF gun in operation at MAX-lab. It is improved for higher coupling, better cooling and lower surface field densities (increased radia on apertures).
The improved structure is in production.
The cathode is standard BaO.

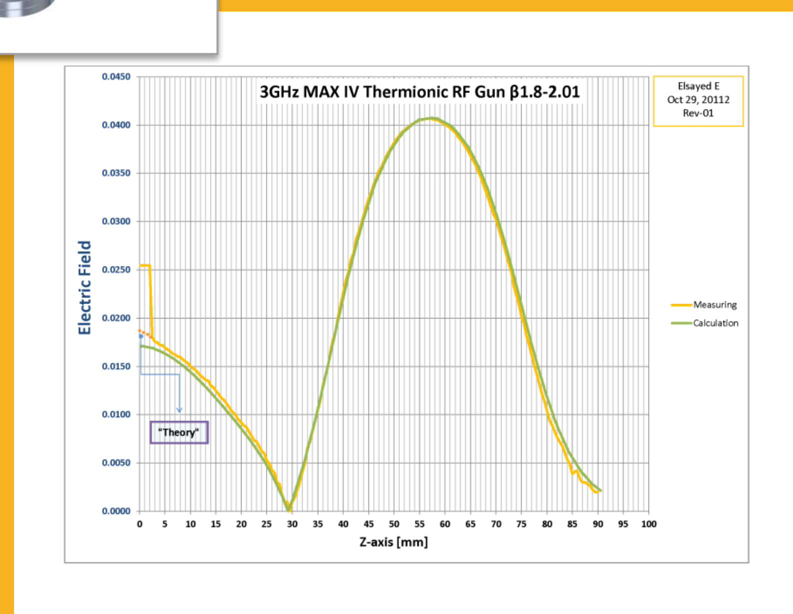



| | | |
|---|---|---|
| Rep rate | 10-50 | Hz |
| Energy | 1.5-3 | MeV |
| Frequency | 2998.5 | MHz |
| Mode separation | 17.9 | MHz |
| Q | 12 500 | |
| Coupling | 1.85 | |



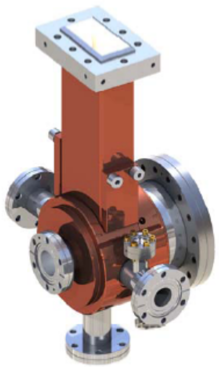


# What is its composition? – RF Guns (Photocathode)

## Photo cathode RF gun

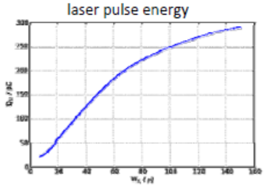


The photo cathode RF guns are built with the experience of the Fermi@ELETTRA gun previously tested at MAX-lab. A first structure has been operated up to 3.3 MeV electron energy (kinetic).

A quantum efficiency of 1.5 $10^{-5}$ for the Cu cathode has been measured. Saturation of the emitted charge (see fig) was seen already above 50 mJ laser energy, which is partly due to the small laser spot size (0.4 mm RMS).

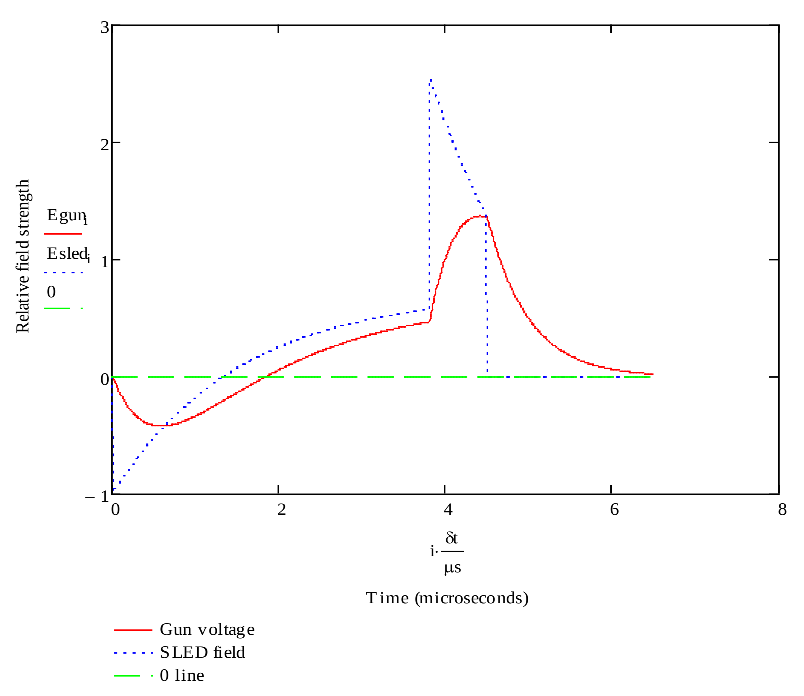
The coupling of the tested structure was 1.45 which is not enough for the short pulses from the SLED system. Thus a gun with coupling >1.85 is in production.

Charge as a function of laser pulse energy



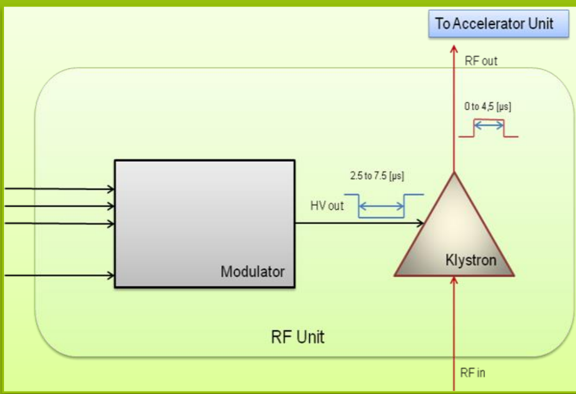
| | | |
|---|---|---|
| Rep rate | 10-100 | Hz (design) |
| Energy | ~4 | MeV (design) |
| Frequency | 2998.5 | MHz |
| Mode separation | 14.3 | MHz |
| Q | 12 150 | |
| Coupling | 1.76 | |

- Using SLED RF pulse on photocathode RF Gun, is released 4,6 times less heating compared to a 3 μs rectangular pulse for a given gun field



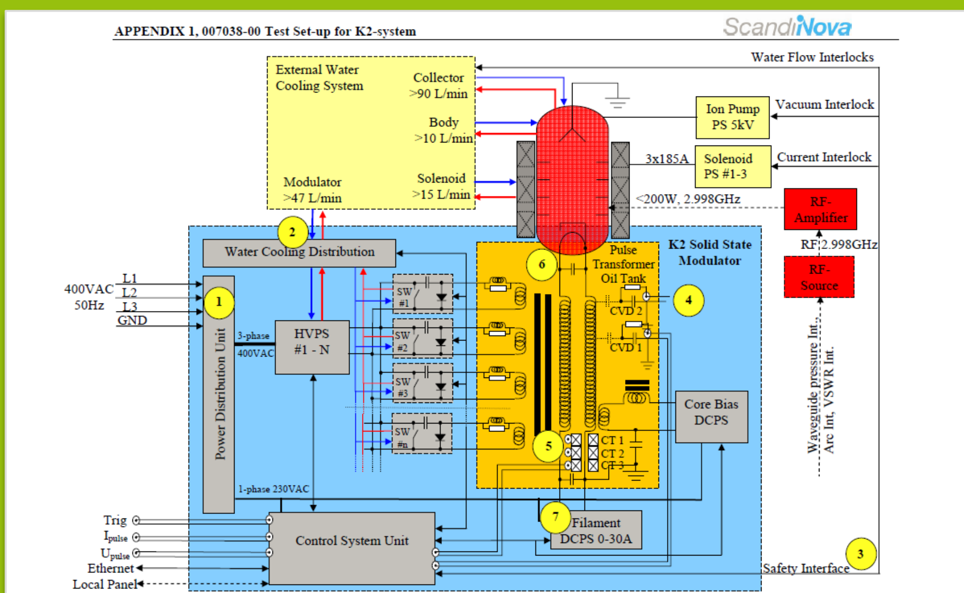
# What is its composition? - RF Units (Modulator)

¤ 18 pcs SCN modulator K2, Toshiba klystrons model E37310,
¤ 1pc SCN modulator K1, Toshiba klystron E37326




- Three principal concepts:
1. Spit Core
2. Parallel Switching
3. Pulse to Pulse Control

- Our K2 modulators have three HVPS and seven parallel switching units.



# What is its composition? – RF Units (Klystron)

## RF Unit parameters

| Nr | Parameter | Unit | Value |
|---|---|---|---|
| 1 | RF frequency | MHz | 2998,5 |
| 2 | Max. Peak RF Output Power | MW | 35 - 37 |
| 3 | Max. Klystron Average RF Power | kW | 16 -18 |
| 4 | RF flat top pulse width variable | μs | 0 to 4.5 |
| 5 | Voltage Pulse width variable (80%) | μs | 2.5 to 7 |
| 6 | Pulse Repetition Frequency variable | Hz | 0 to 100 |
| 7 | Flat top ripple or droop | % | ± 1,5 |
| 8 | Pulse to pulse voltage stability | % | ± 0.01 |
| 9 | Voltage pulse to pulse jitter | ns | ≤ 6 |
| 10 | Modulator Electric efficiency | % | >80 |
| 11 | Klystron efficiency | % | >40 |
| 12 | RF output flange | | LIL |

**PULSED KLYSTRON AMPLIFIER E37310**

TOSHIBA E37310, S-band high-power pulsed amplifier klystron, is designed for linear accelerators. The E37310 delivers 37 Mw peak output power with a power gain of more than 48.5 dB and with an efficiency of more than 40%. (*1)

The electron beam is focused with the electromagnet VT-68922.

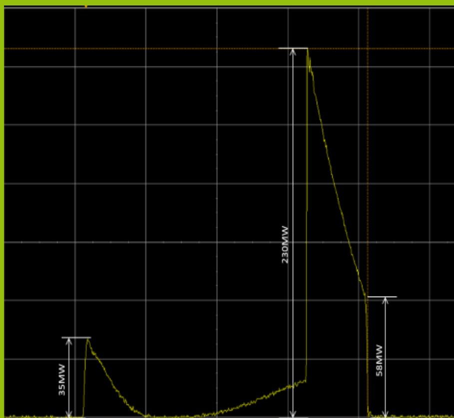
An "M"-type dispenser cathode with high reliability promises long tube life.

## Klystron parameters

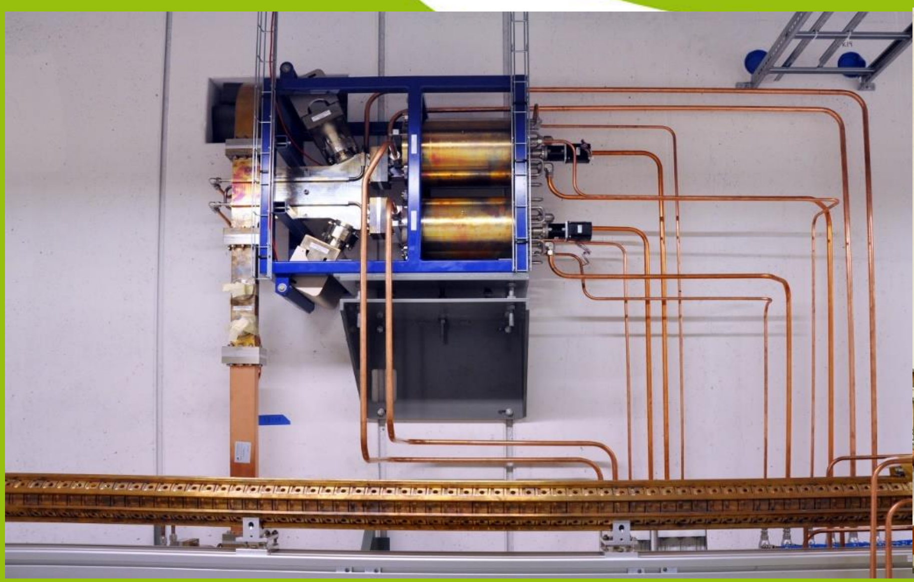
| Parameters | Symbol | Unit | Min. | Max. | Note(s) |
|---|---|---|---|---|---|
| Frequency | f | MHz | 2995.5 | 3001.5 | |
| Heater Voltage | Ef | V | --- | 20 | 3&4 |
| Heater Current | If | A | --- | 18 | 3 |
| Heater Current (surge) | If (surge) | A | --- | 20 | |
| Heater Warm-up Time | th | minutes | --- | 5 | |
| Cathode Warm-up Time | tk | minutes | 25 | --- | 3 |
| Peak Forward Beam Voltage | epy | kV | --- | 165 | 5&6 |
| Peak Inverse Beam Voltage | epx | kV | --- | 50 | 7 |
| Peak Cathode Current | ik | A | -10 | 120 | 8&8A |
| Peak Drive Power | pd | W | --- | 120 | 9 |
| Peak RF Output Power | po | MW | --- | 8.5 | |
| Average RF Output Power | Po | kW | --- | 10 | |
| Collector Dissipation | Pcol | kW | --- | 20 | |
| Pulse Width (duration) (epy) | tp(epy) | μs | --- | 7.5 | 10 |
| Pulse Width (duration) (rf ) | tp(rf) | μs | --- | 5.0 | 11 |
| Pulse Repetition Rate | prr | pps | --- | 300 | |
| Ion Pump Voltage | V ip | kV | 3.2 | 3.8 | 15 |
| Load VSWR | σL | VSWR | --- | 1.4 | 11A |
| Coolant Flow | | | | | |
| Collector | Qw,c | L/min | 25 | --- | 14&14A |
| Body | Qw,b | L/min | 10 | --- | 14 |
| Inlet Coolant Temperature | Tw,i | centigrade | 5 | 40 | 12 |
| Coolant Pressure | Pw,c | MPa | --- | 0.78 | 12 |
| | | (kgf/cm$^2$ | --- | 8.0) | |
| Waveguide Pressure | | | | | |
| Gauge Pressure | PW/G | MPa<br>(kgf/cm$^2$ | 0.098<br>1.0 | 0.294<br>3.0) | 13&13A |

# What is its composition? – SLED Cavities

-RI product, based on MAX-lab uppdated drawings




| | |
|---|---|
| Operating frequency [MHz] | 2998.5 +/- 0.5 |
| Resonant mode | TE015 |
| Q, unloaded | 98000 +/- 5000 |
| Coupling value β | 6 |
| Flange type | LIL |
| Frequency tuning design | end cap deformation by stepping motor |
| Frequency tuning range [MHz] | +/- 1 |
| Frequency tuning speed [min] | max. 1 for full range |
| Operating temperature [°C] | 40 +/- 2 |
| Max. cooling water difference pressure [bar] | 6 |



# What is its composition? – Accelerator structure

| | |
|---|---|
| Operating frequency [MHz] | 2998.5 +/- 0.5 |
| Accelerating structure type | traveling wave, constant gradient |
| Resonant mode | $2\pi/3$ |
| Max. input power (peak) [MW] | 100 |
| Max. input pulse duration [μs] | 0.75 |
| Max. repetition rate [Hz] | 100 |
| Max. input VSWR at full power | 1.10 |
| Bandwidth [MHz] | 4.0 @ VSWR 1.2 |
| Q | 12500 |
| Fill time [μs] | 0.69 |
| Shunt impedance ($U^2/P$) [MΩ] | 250 |
| Accelerating gradient [MV/m] | 20 |
| Energy gain [MeV] | 100 |
| Input coupler type | symmetric with short at one arm |
| Flange type (RF) | LIL |
| Flange type (beam port) | CF 40 |
| Max. leak rate [l mBar/s] | 1e-9 |
| Operating temperature [°C] | 40 +/- 2 |
| Max. cooling water difference pressure [bar] | 6 |
| Required water flow rate per structure [l/min] | 76 |
| Number of cells | 156 |
| Pickup (load cell) connection type | SMA |
| Dimensions (length x width x height) [mm] (including support structure) | 5276x188x389 |

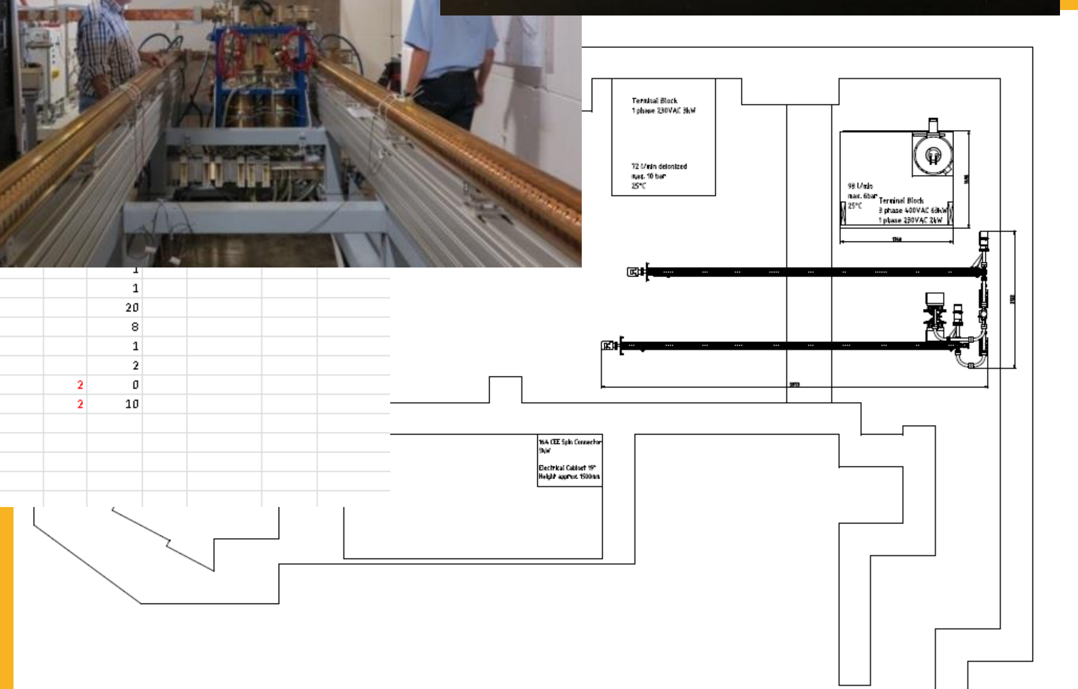
¤ Linear accelerator structures are protected from outside magnet field, by using u-metal protections

¤ Linear accelerator structures and SLED cavities are thermo – isolated.

# What is its composition? – Pre-conditioning

- Conditioning of Accelerator Units have been done by the manufactory, RI

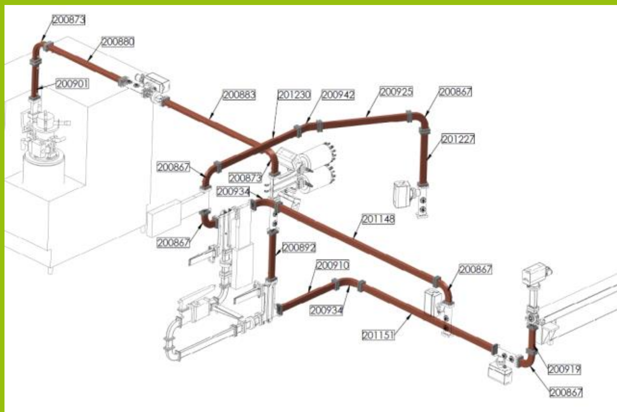
| | E | F | G | H | AF | AG | AH | AI | AJ | AK | AL | AM | AN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | RI Project: 3223-0100 | 19-November 2012 | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | |
| 6 | Delivery Maxlab | | Parts to be de by Maxlab fo unit | | | | | | | | | | |
| 7 | | | | | | | | | | | | | |
| 8 | Device for the units arrangement | Type | amount /unit | RI | | | | | | | | | |
| 9 | Directional Coupler 50dB with CF | MaxLab | 2 | | | | | | | | | | |
| 10 | Directional Coupler 50dB without CF | MaxLab | 1 | | | | | | | | | | |
| 11 | Ion Pump CF63 75l/min | Pfeiffer | 6 | | | | | | | | | | |
| 12 | Ion Pump CF100 75l/min | Pfeiffer | 2 | | | | | | | | | | |
| 13 | ~~Vacuum Cold Cathode Gauges~~ | ~~Pfeiffer IKR270~~ | ~~2~~ | | | | | | | | | | |
| 14 | Full Metal Angle Valves | VAT+MaxLab | 1 | | | | | | | | | | |
| 15 | LIL Spacers | MaxLab | 17 | | | | | | | | | | |
| 16 | CF Reducing Tpiece CF40/CF40/CF63 | for linac end | 2 | | | | | | | | | | |
| 17 | Waveguide 90deg E bend L=200x242 | | 2 | | | | | | | | | | |
| 18 | Waveguide 90deg E bend L=200x266.8 | | 2 | | | | | | | | | | |
| 19 | RF Vacuum window | Toshiba | 1 | | | | | | | | | | |
| 20 | ~~Tpiece CF40~~ | ~~for linac beginnin~~ | ~~2~~ | | | | | | | | | | |
| 21 | Blind flange CF4 | | | | | | | | | | | | |
| 22 | LIL CU Gasket | | | | | | | | | | | | |
| 23 | support for ion | | | | | | | | | | | | |
| 24 | support for ion | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | | |
| 26 | ot | | | | | | | | | | | | |
| 27 | Ion Pump CF100 | | | | | | | | | | | | |
| 28 | adaptor LIL7CPR | | | | | | | | 1 | | | | |
| 29 | Waveguide Pie | | | | | | | | 1 | | | | |
| 30 | Ion pump contr | | | | | | | | 20 | | | | |
| 31 | cables for Ion p | | | | | | | | 8 | | | | |
| 32 | cold cathode 6 | | | | | | | | 1 | | | | |
| 33 | cables for CCG; 3 | | | | | | | | 2 | | | | |
| 34 | connector for io | | | | | | | 2 | 0 | | | | |
| 35 | coax feedthroug | | | | | | | 2 | 10 | | | | |
| 36 | Flowmeter 3x20 | | | | | | | | | | | | |
| 37 | Mini-Circuits NF | | | | | | | | | | | | |
| 38 | pumstand | | | | | | | | | | | | |
| 39 | fiducials | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | | |

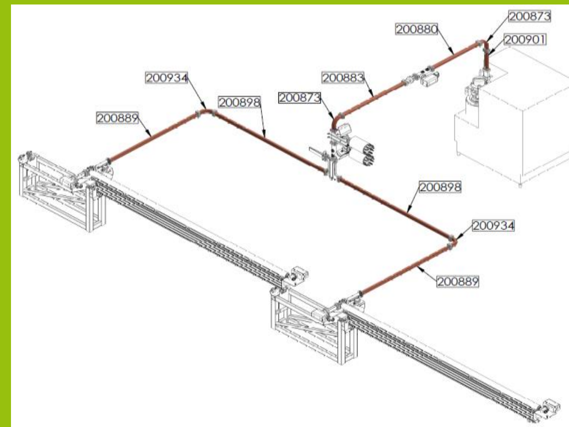


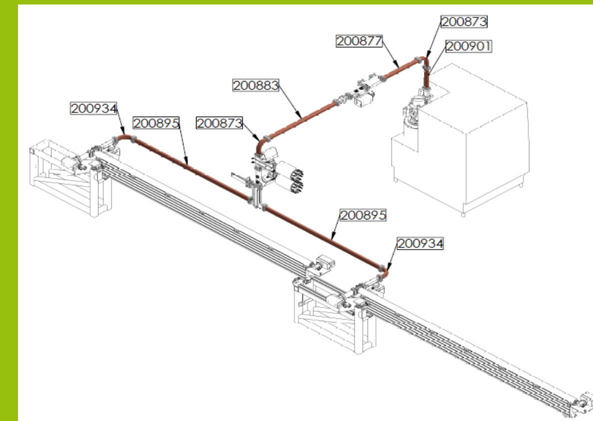


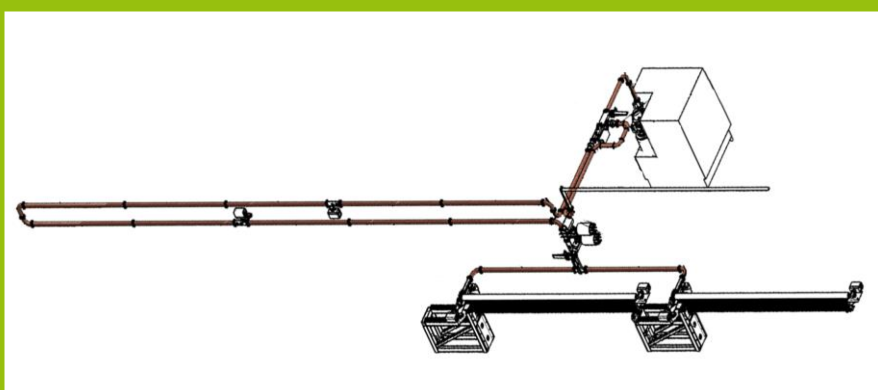

MAX IV

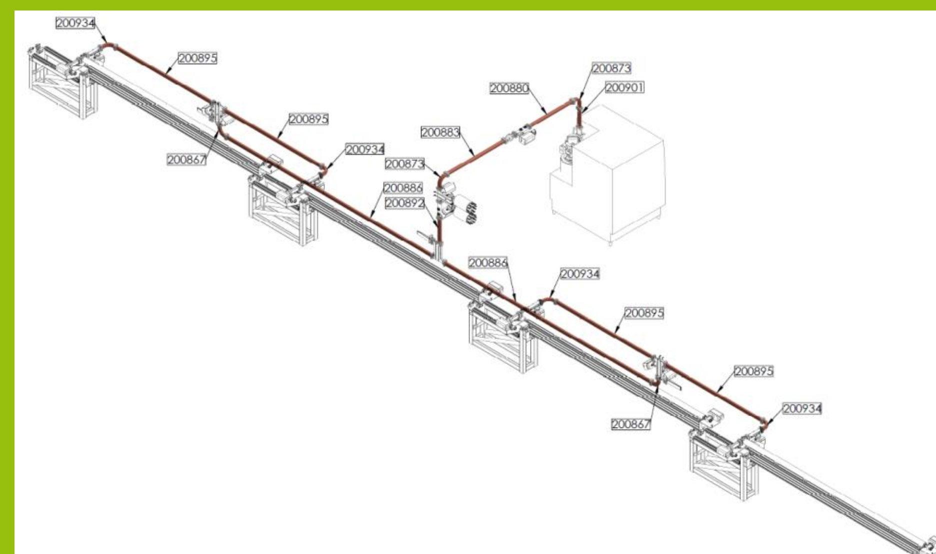
# What is its composition? – Waveguide system



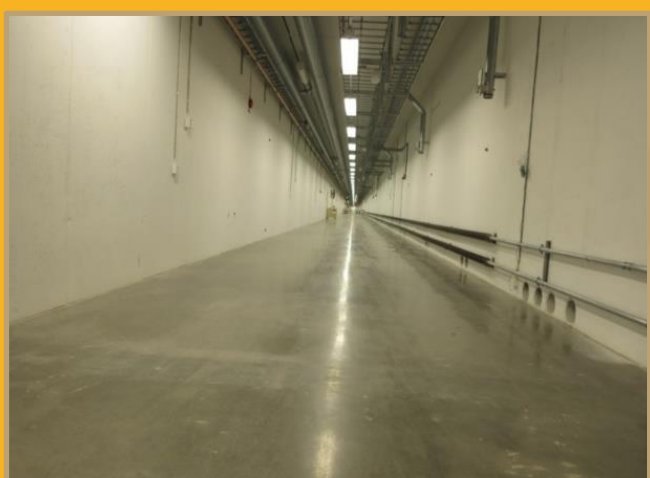





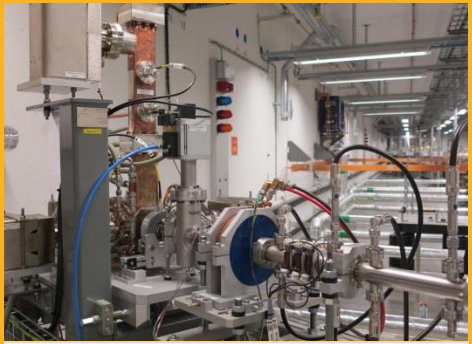
# How it is assembly and it works? – Installation

Klystron gallery
June → September 2013

Linac tunnel
June → September 2013

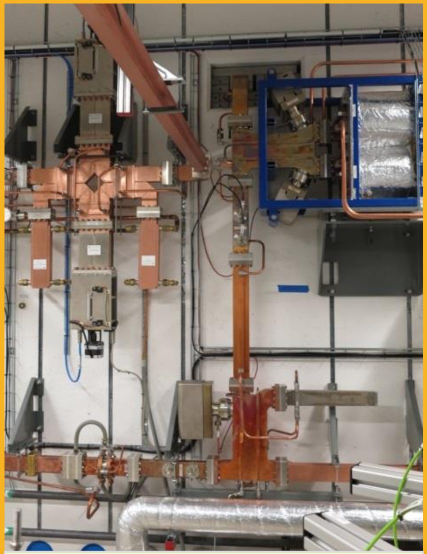
# How it is assembly and it works? – Installation



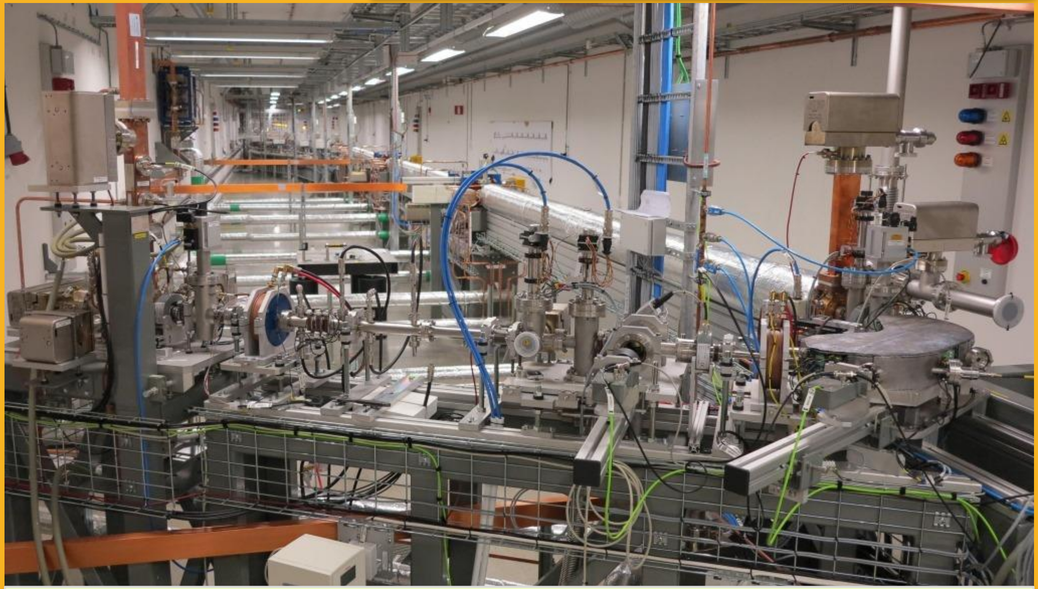
- Thermionic RF Gun

- SLED Cavities

- Linac structure



- Power divider



- Linac tunnel (Pre-injector)

# How it is assembly and it works? – Installation

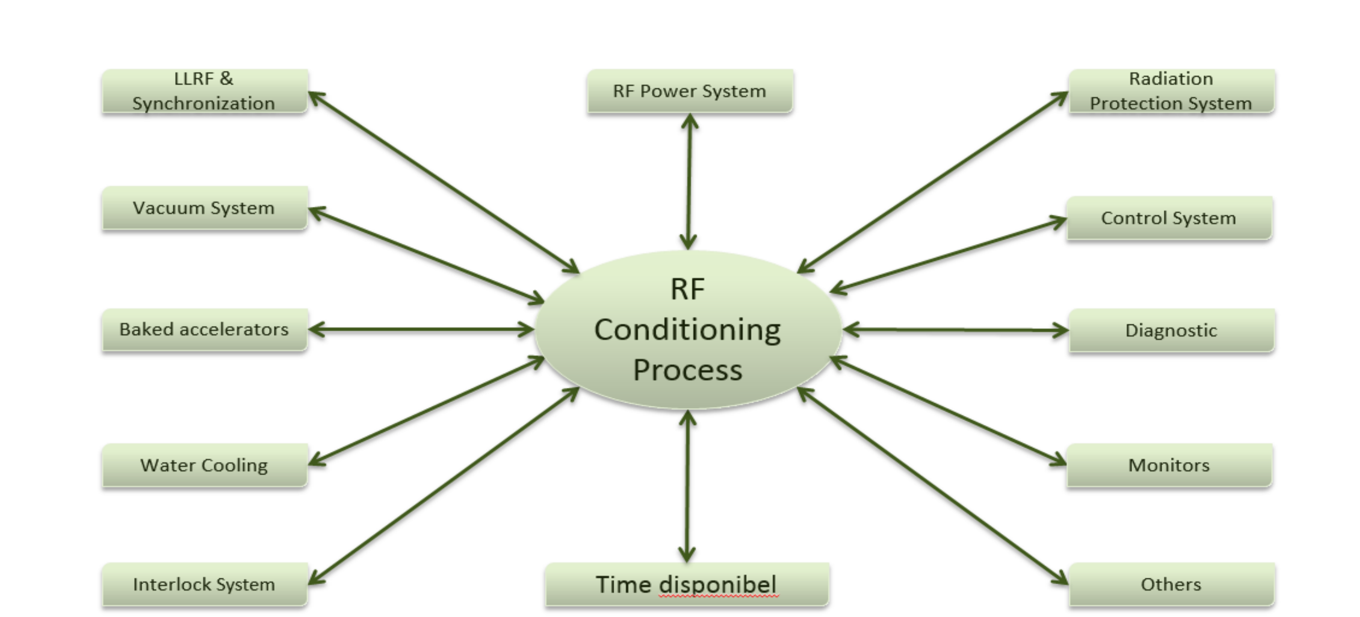
September - 2015


# How it is assembly and it works? – RF conditioning

LINAC conditioning have been done through five phases:

1 - Factory Acceptance Test (FAT) to all linac structures, SLEDs and power dividers , done by RI (Research Instruments)
2 - Pre-conditioning on full RF power to all linac structures, SLEDs and power dividers in radiated protected area in UniBon done by RI, thanks to excellent cooperation RI & MAX-lab & ScandiNova
3 - Factory Acceptance Test (FAT), to RF Units (modulator with Klystron load) done by ScandiNova i Uppsala
4 - Site Acceptance Test (SAT) of RF Units (modulator & Klystron), from SCN in MAX IV Linac klystron galleriet i Lund
5 - Conditioning of complet Linac, by MAX IV personel i Linac tunnels i Lund.

**# Subsystems and conditions** to be fullfilled to have successfully implemented conditioning process




**Parameters achieving the goal**
To achieving the goal, we control and play with following parameters:

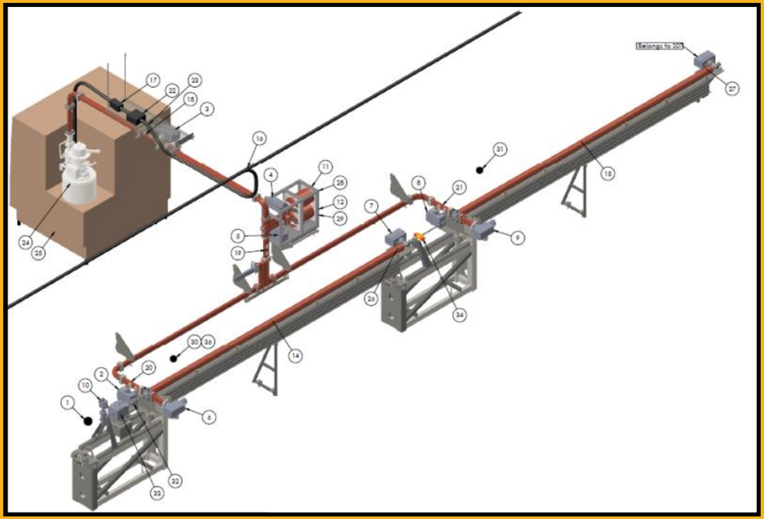
1. Peak RF Power
2. Pulse repetition frequency (PRF)
3. Pulse width
4. 180 degree phase changed

# How it is assembly and it works? – Baking process

¤ **From the beginning** when accelerator units assembling finished, we decided that: units with complicated configuration, as was K00, K01 and K02 to be baked at temperatures of 110 degrees for a week. For others such as K03, K04, etc. that had simple configuration, and very good value vacuum, was decided not to bake them (ironically, to save time)

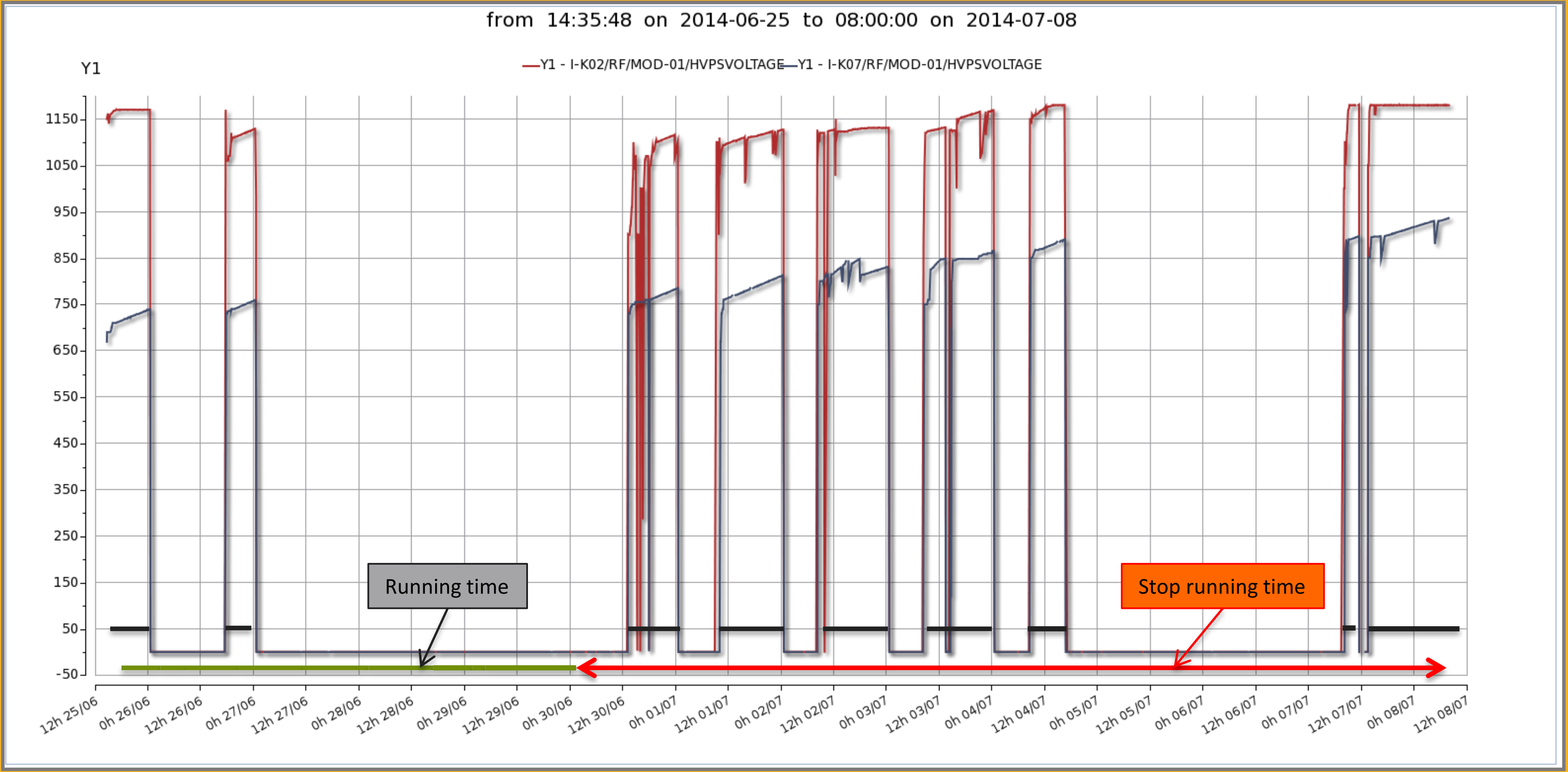
¤ **K02 unit**, even though it was baked, the configuration between Klystron and SLED not allowed us to continue with further conditioning. So we were forced to do the "dry ice blasting" process, after this operation became possible to go beyond med conditioning

¤ **After we made attempts** conditioning units K03, K04 and so on, and have not reached the right result on time, we decided to test baking the worse unit : K06. The result showed that baking had great effect in accelerating this process. So we baked all units, and that help to succeed the RF conditioning on acceptable level..



# How it is assembly and it works? – RF conditioning

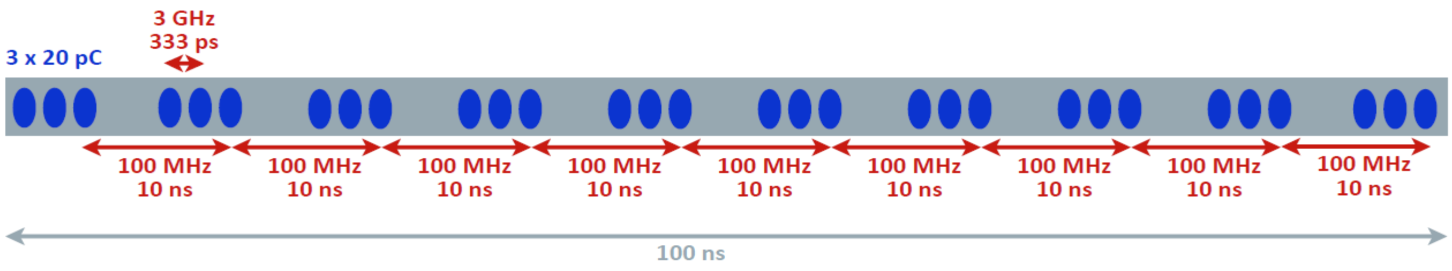
Each pause of conditioning, reduced the conditioning level, and the deterioration was proportional with the length of the time the process have been stopped



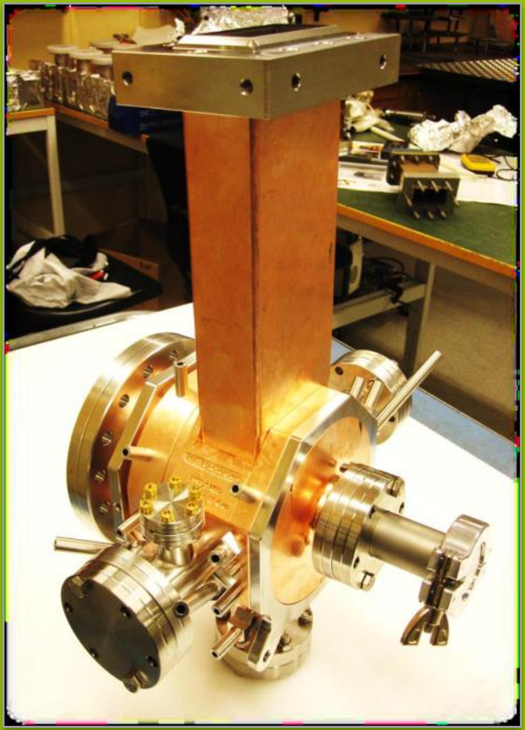

RF conditioning process has been longer than we planned but within reasonable time. Mostly it was the wrong with time planning than conditioning process.
Not all units respond in the same way, had to use different methods depends on the need of each device.

# How it is assembly and it works? – Linac commisioning

- Injector delivers bunches with $\varepsilon_n$ = 10 mm mrad, $\sigma_\delta$ = 0.1%
- Ring injection occurs at 10 Hz (governed by damping time)
- Inject trains of bunches
  - Each train consists of up to 10 bunches (10 x 10 ns)
  - Each bunch can contain up to 60 pC (3 x 20 pC @ 3 GHz)



# Solaris Thermionic RF Gun is delivered

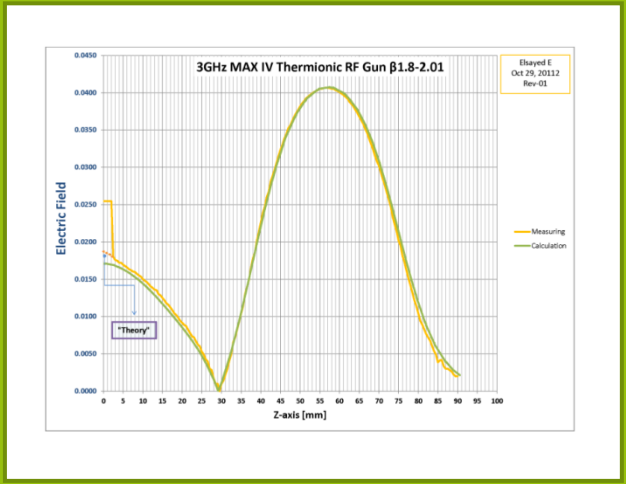


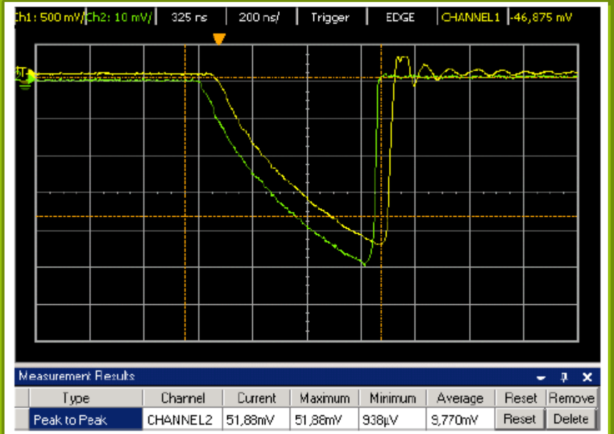
**# Results of Solaris Thermionic RF Gun test running:**

- Current beam: 101 mA before EF,
- Current beam: 40 mA after EF
- EF dipole: 4.3 A => E_kin = 2.3 MeV

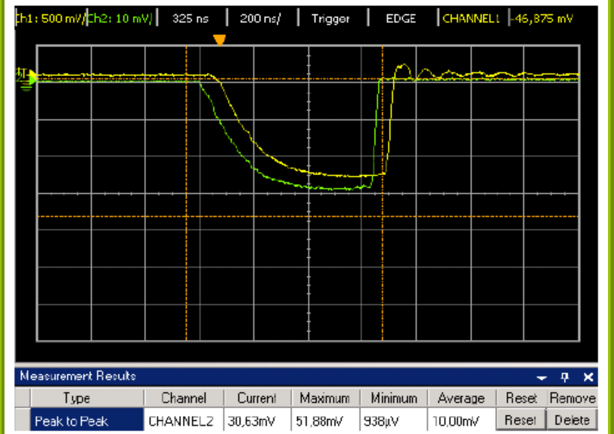
Conditions running:

- Without kicker, 2 mm aperture, 6.8 A filament




HM gun dipole = off, no aperture




HM gun dipole = off, 2mm aperture

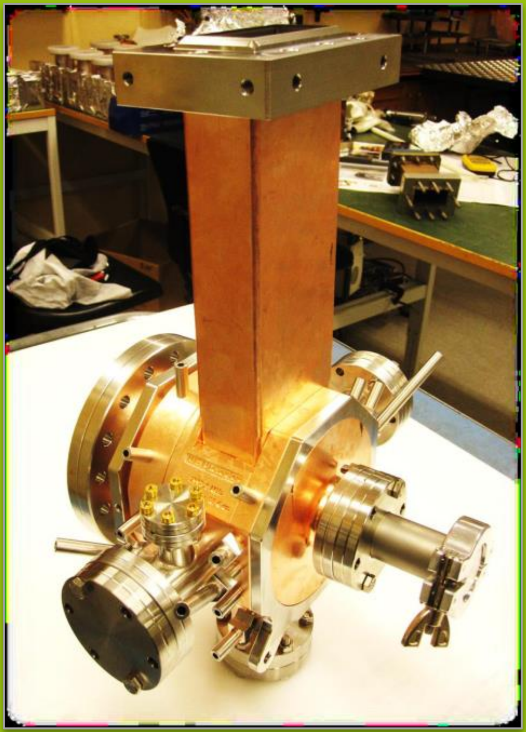
# CLS Thermionic RF Gun is delivered

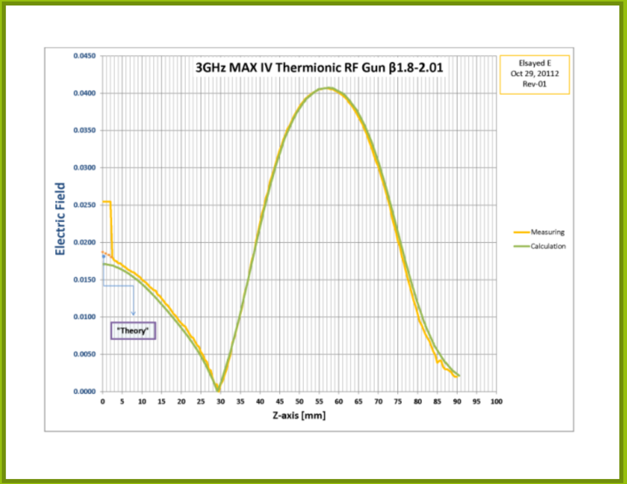
Simulated parameters from COMSOL.

| | |
|---|---|
| Resonance frequency ($\frac{\pi}{2}$-mode) | 2.856 GHz |
| Mode separation | 16.9 MHz |
| $Q_0$ (unloaded) | 13098 |
| Field relation (cathode vs max) | 0.42 |
| Coupling factor ($\beta$) | 1.99 |

Measured parameters in air at 24.3°

| | |
|---|---|
| Resonance frequency ($\frac{\pi}{2}$-mode) | 2.856008 GHz |
| Mode separation | 17.4 MHz |
| $Q_0$ (unloaded) | 12600 |
| Field relation (cathode vs max) | 0.38 |
| Coupling factor ($\beta$) | 1.68 |





# New sub-projects - LINAC

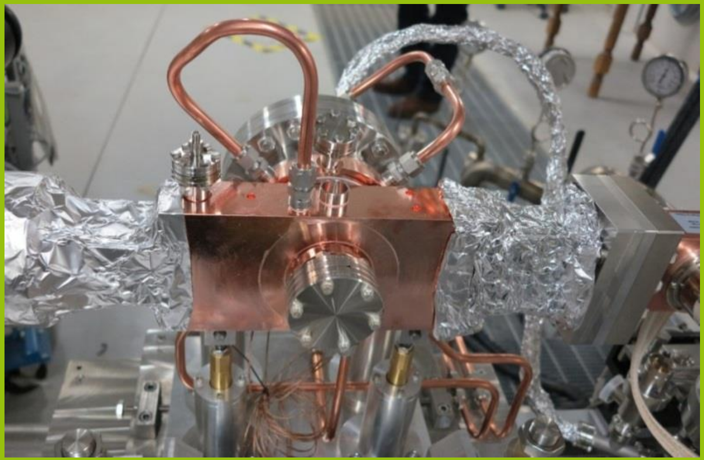
- RF Guns improving and development
- RF power upgrading (to the Linac)
- RF Circulator in vacuum (cooperation with HEIP China)

# The new Photocathode RF Gun

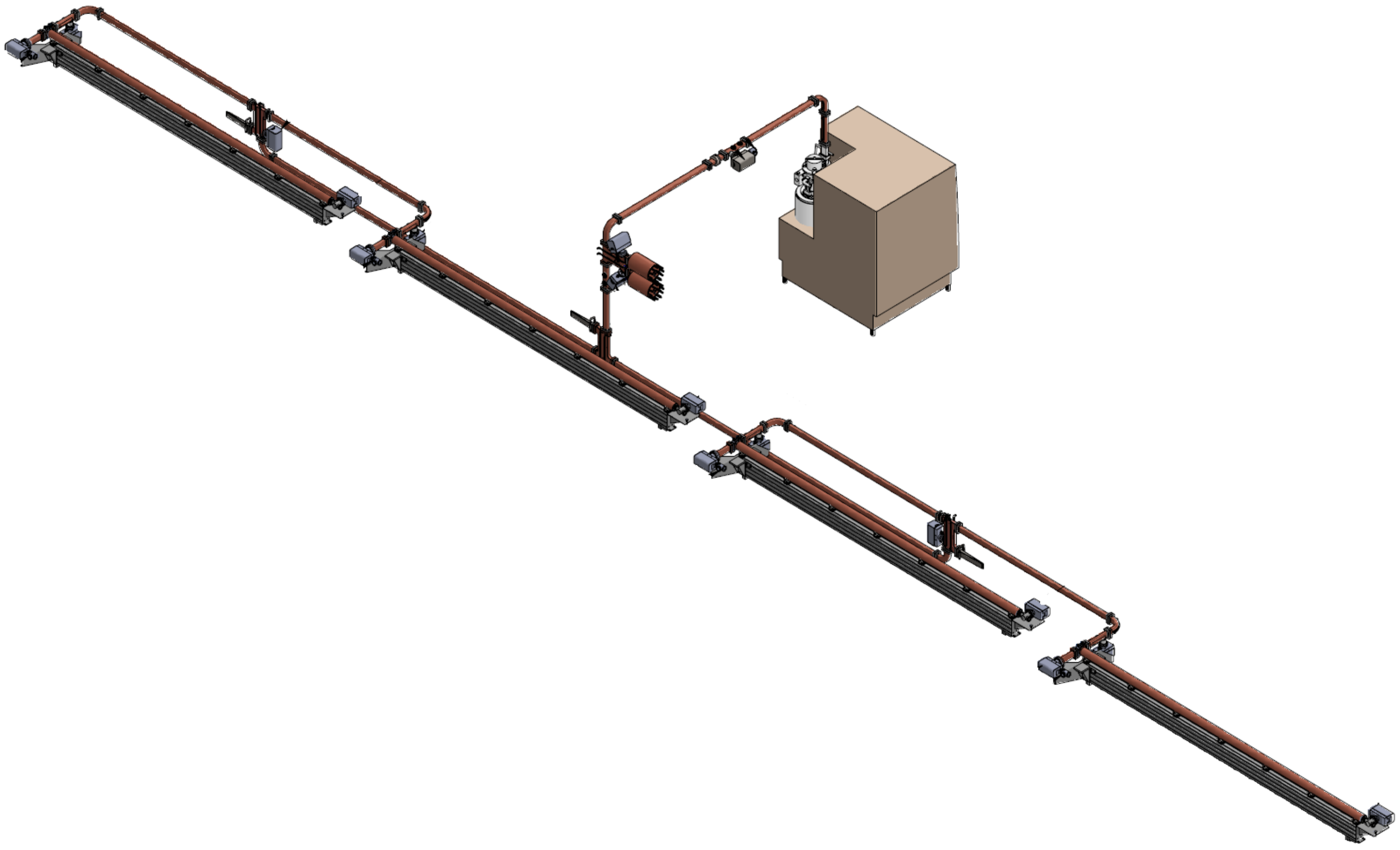
# Next Photocathode RF Gun,  will be build at MAX-lab based on RadiaBeam drawings

# Some of improvements are:

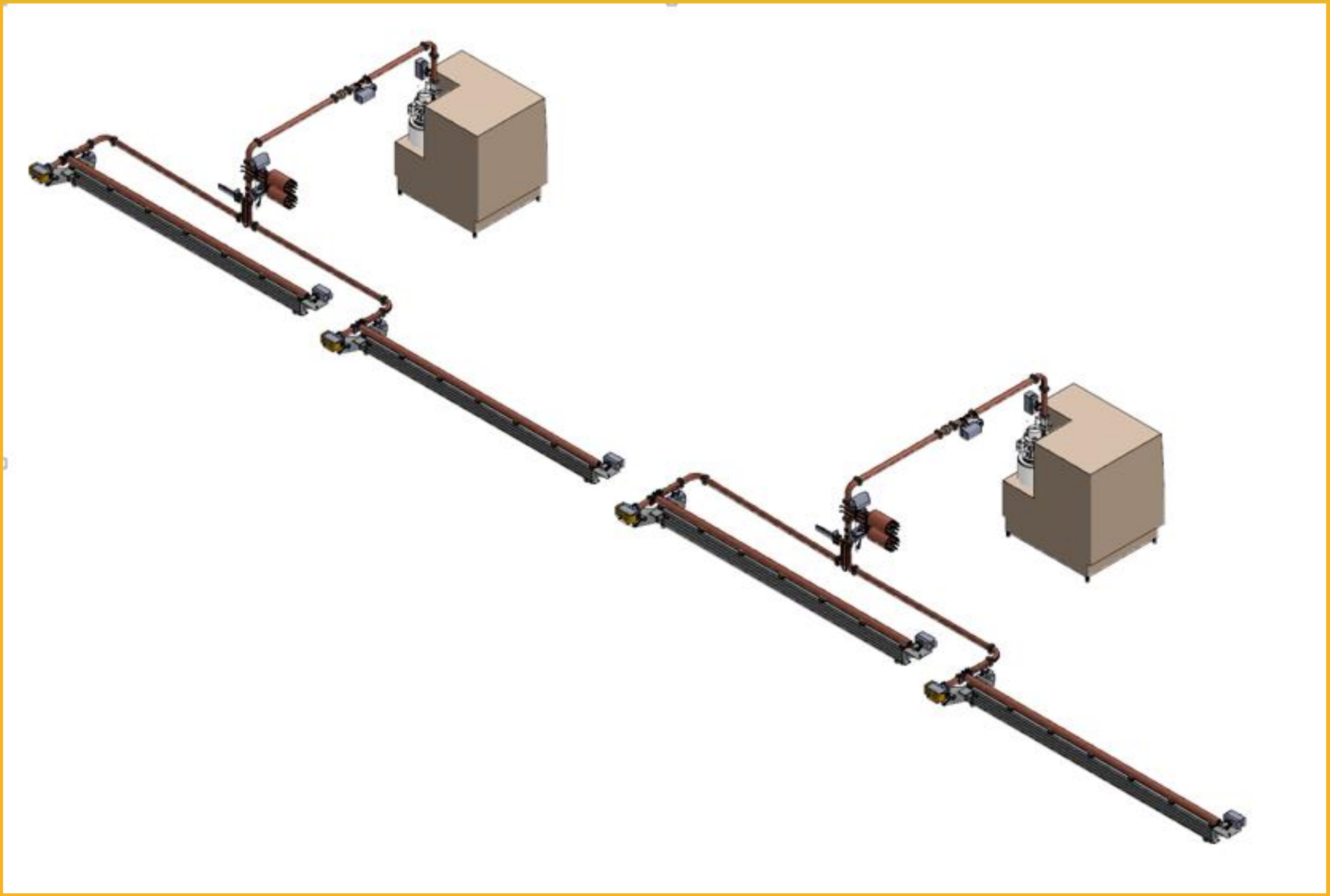
1. Dual RF feed
2. Increased the mode seperation from 3 to 15MHz
3. The iris between two cells was reshaped to reduce its surface field
4. Z-coupling and increasing the radius of the edges
5. Improved cooling channels
6. New cathode mounting



# RF power upgrading (to the Linac)



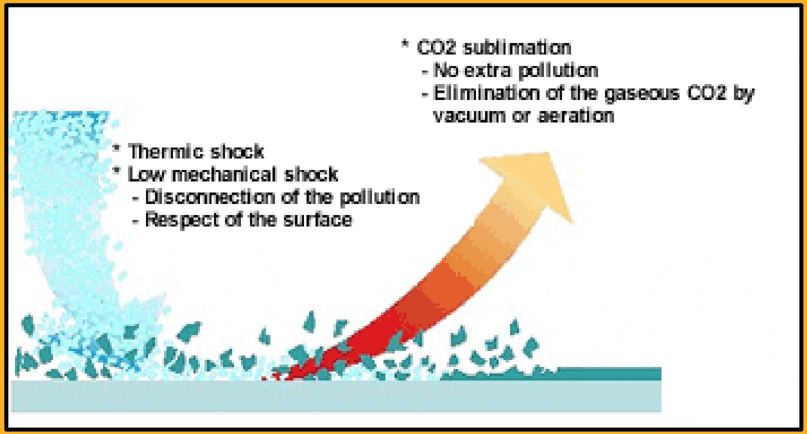
# RF power upgrading (to the Linac)



# Dry Ice Blasting

**Working principles:**
The process consists in throwing particles of dry ice on the surfaces to be cleaned.
The impact of the dry ice particles allows to conjugate three effects:

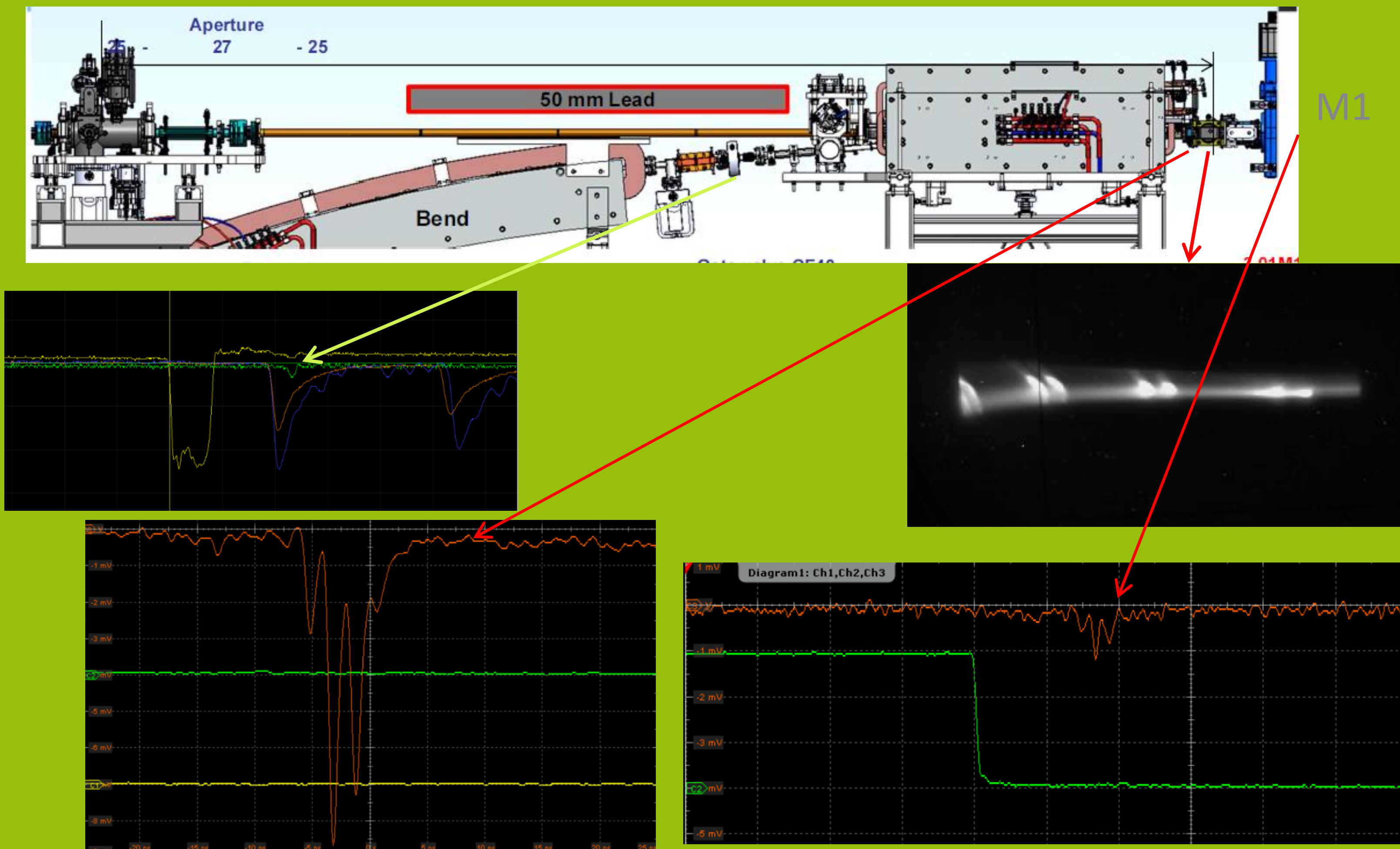
1. A weak mechanical shock with a compression wave disconnecting the pollution of the support
2. A thermic shock, (the dry ice temperature being - 78°C) which is going to weaken the pollution
3. A blowing effect connected to the sublimation of the $CO_2$ is going to eliminate the pollution




# His Majesty the King visiting MAX IV Linac

- Do you know what you are doing here? asked His Majesty Carl XVI Gustaf

# Full answer to the King's question got on week 33– Linac commissioning (week 33)




- Beam observed at the end of TR3 and into the ring !

Many thanks to my RF group colleagues and all collaborators,

Very kind of you to visit us and pay attention to this presentation