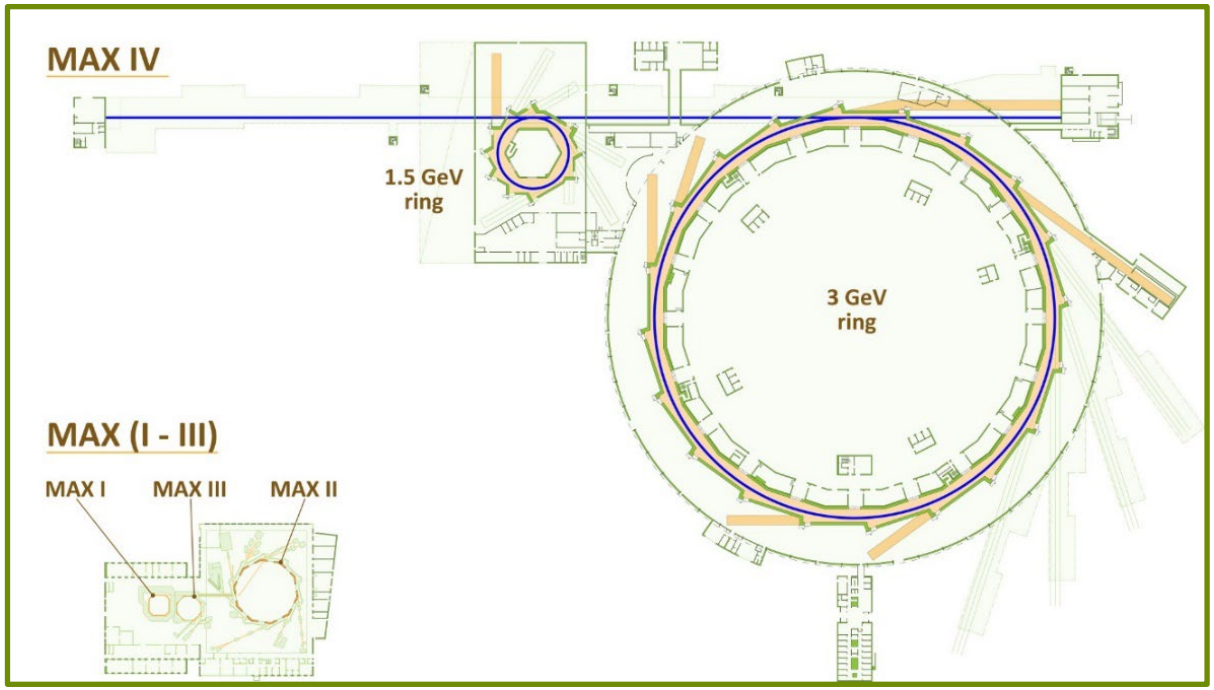
MAX IV Laboratory, Lunds University

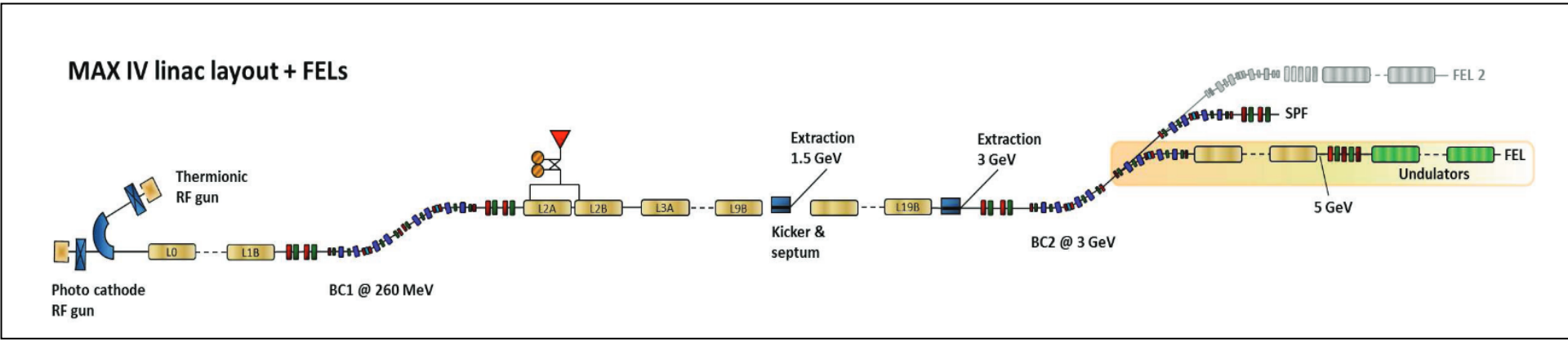
Status of Pulsed RF Powers Units

Content

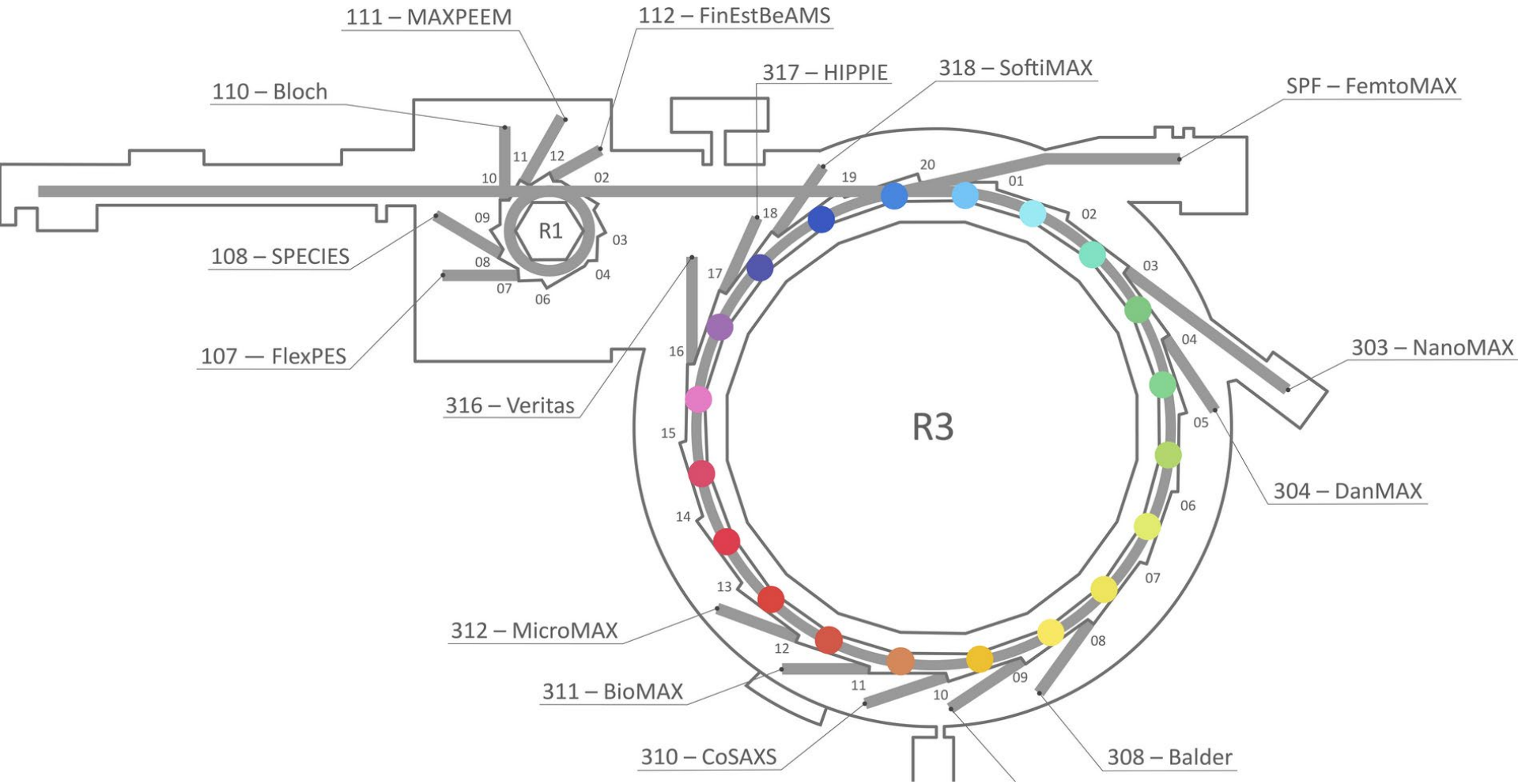
- MAX IV Laboratory, Lund University Sweden
- Pulsed S-band RF powers and Accelerator Units
- The experience of 10 years running
- Conclusions

MAX IV Laboratory





MAX IV Laboratory @ 16 Beamlines

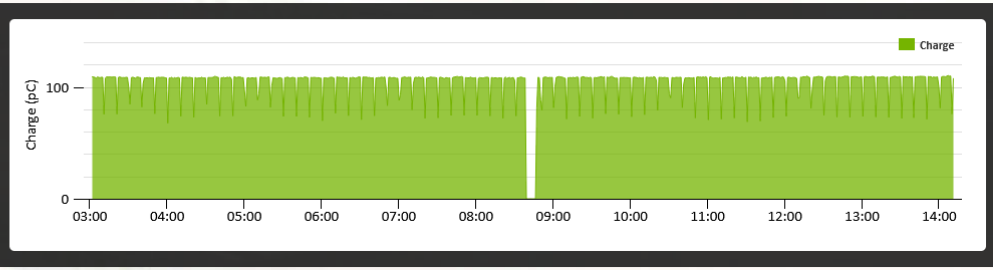


MAX IV Machine Status

Linac

Repetition rate: 9.99 Hz
Accelerated charge: 108.05 pC

Delivery



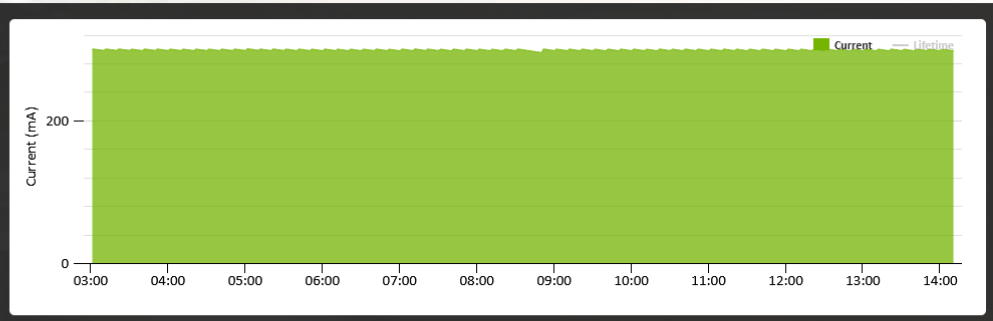
FemtoMAX	4.10	4.14

3 GeV Ring

299.80 mA 18.30 h

Delivery: Top-Up

NEXT INJECTION:
2023-04-05 14:20:00



NanoMAX	5.50
DanMAX	4.60
BALDER	5.00
ForMAX	5.12
CoSAXS	5.77

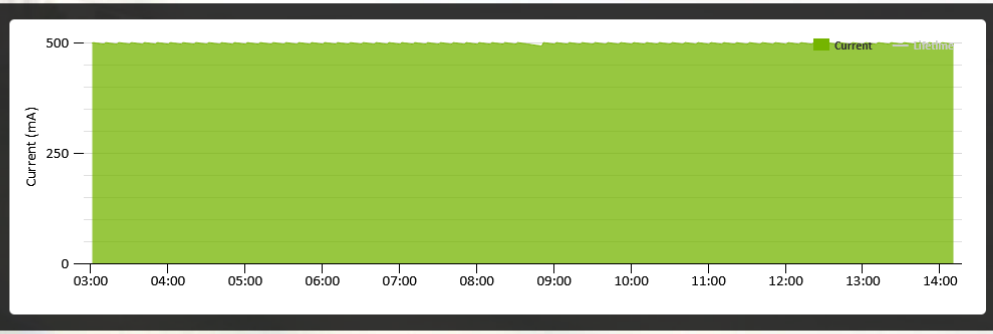
BioMAX	5.04
MicroMAX	48.00
VERITAS	15.02
HIPPIE	25.48
SoftiMAX	18.63

1.5 GeV Ring

499.61 mA 18.75 h

Delivery: Top-Up

NEXT INJECTION:
2023-04-05 14:20:00



FlexPES	30.55
SPECIES	22.23
BLOCH	26.13
MAXPEEM	38.39
FinEst	41.02

Machine Status *2023-04-01 16:03*
R3: Delivery
R1: Delivery
Linac: Delivery

Safety Message

Operator Message

2023-04-05 15:06:57

MAX IV Accelerator Operation 2022

- Exceeded Goal
- Achieved Goal
- Achieved > 80% of Goal
- Achieved less than 80% of Goal

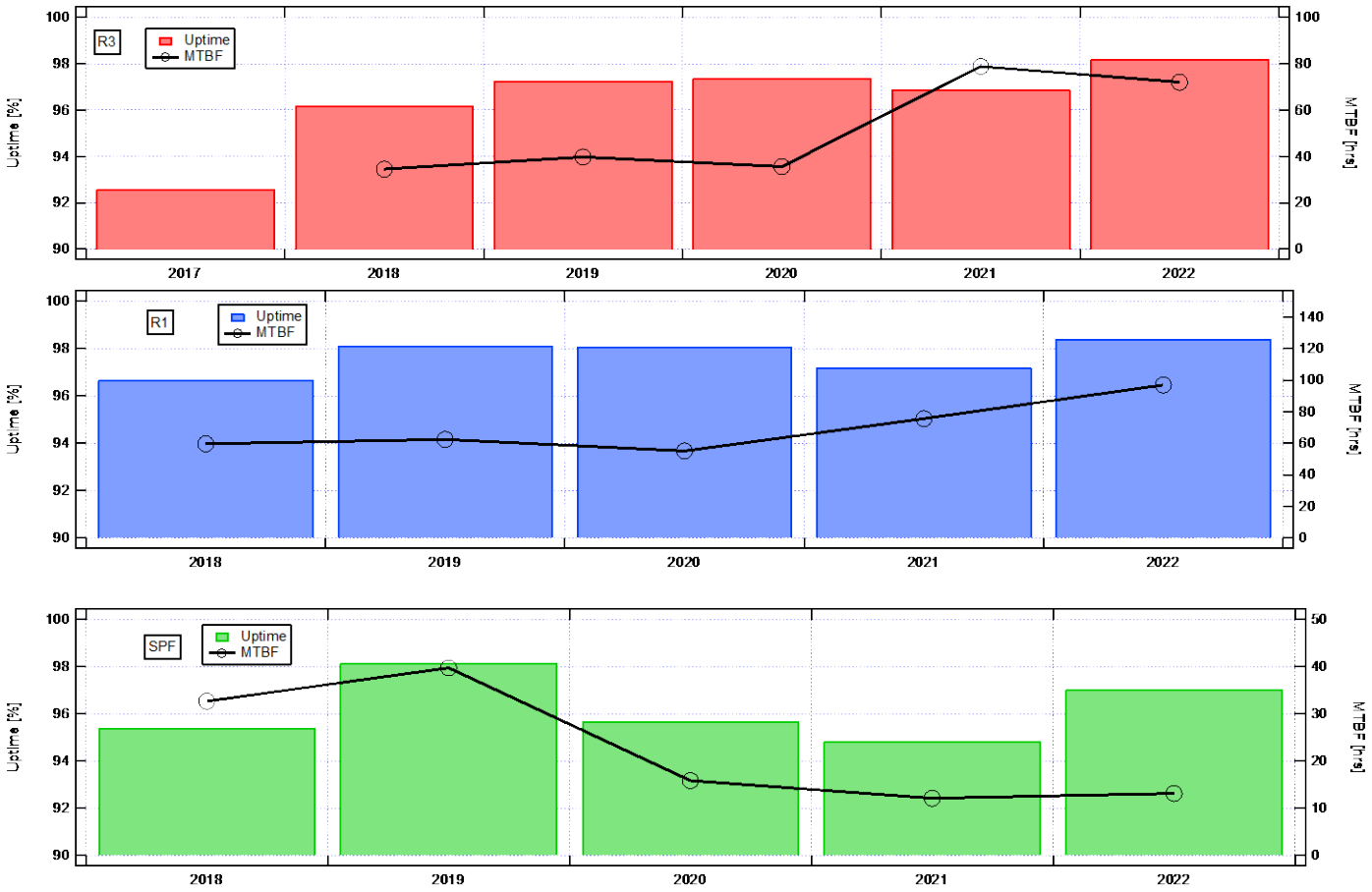
	Goal	Achieved
R3		
BL Scheduled Operation Hours	4500	4464
Availability during BL Operation	97%	98.2%
MTBF [hours]	72	72
Intensity	300 mA	300 mA
R1		
BL Operation Hours	5000	4848
Availability during BL Operation	97%	98.4%
MTBF [hours]	72	97
Intensity	400 mA	400 mA
LINAC		
Operation hours to SPF	4400	4272
Availability during BL Operation	95%	97.0%
MTBF [hours]	24	13
Intensity/Rep rate	100 pC/10 Hz	100 pC/10 Hz

Accelerator Goals 2023

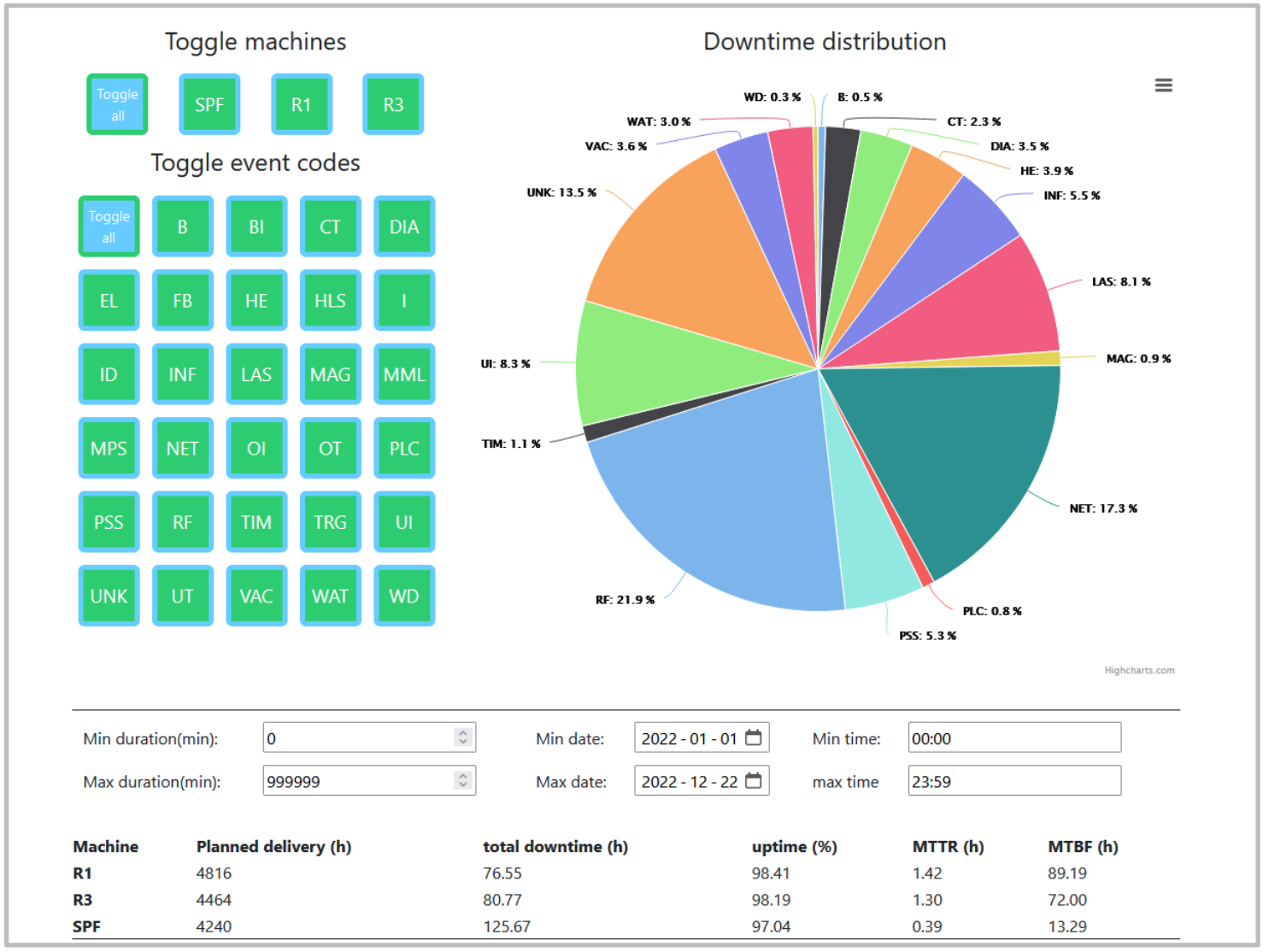
	Goal
R3	
BL Scheduled Operation Hours	4848
Availability during BL Operation	97%
MTBF [hours]	72
Intensity	300 mA
R1	
BL Operation Hours	5136
Availability during BL Operation	97%
MTBF [hours]	72
Intensity	400 mA
LINAC	
Operation hours to SPF	4500
Availability during BL Operation	95%
MTBF [hours] all downtimes	12
MTBF [hours] downtimes> 10 min	24
MTBF [hours] downtimes> 30 min	72
Intensity/Rep rate	100 pC/10 Hz

New goals RF Power Units

Long Term Statistics- Uptime/MTBF



Downtime index



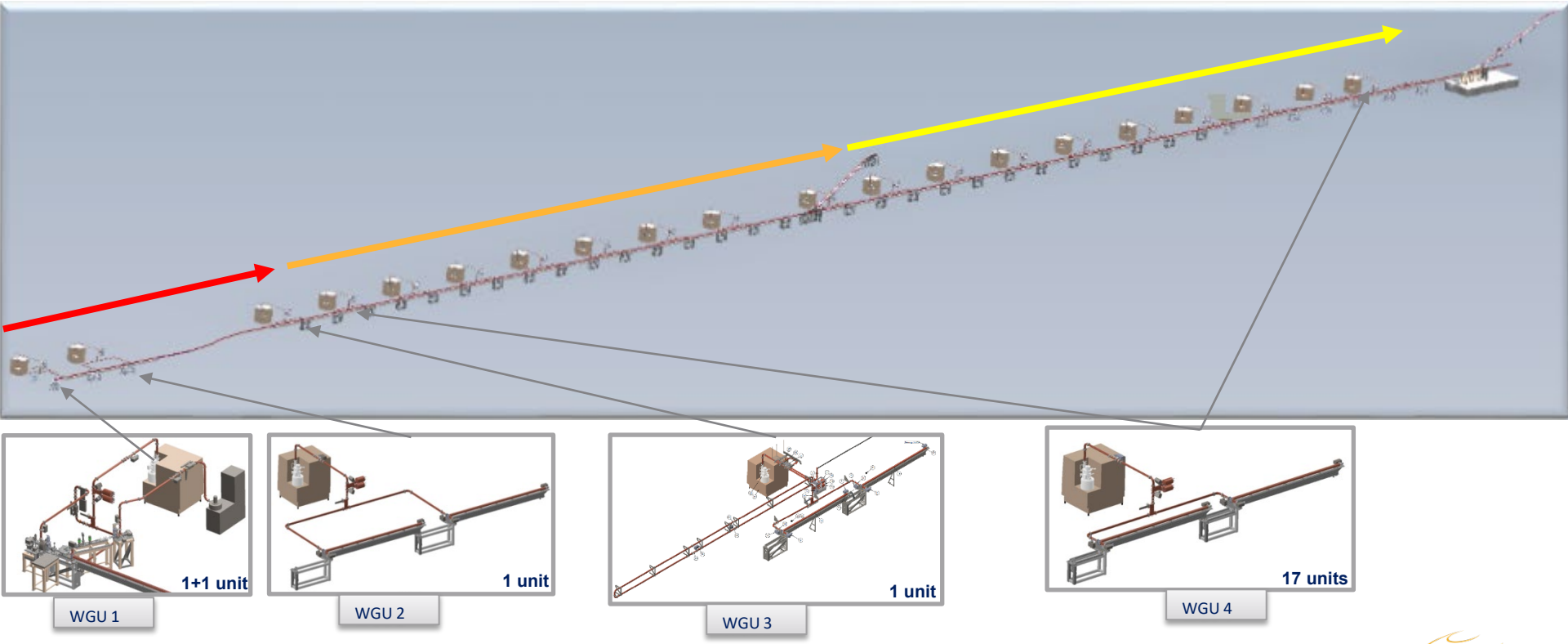
Min duration(min):	0	Min date:	2022 - 01 - 01	Min time:	00:00
Max duration(min):	999999	Max date:	2022 - 12 - 22	max time	23:59

Machine	Planned delivery (h)	total downtime (h)	uptime (%)	MTTR (h)	MTBF (h)
R1	4816	76.55	98.41	1.42	89.19
R3	4464	80.77	98.19	1.30	72.00
SPF	4240	125.67	97.04	0.39	13.29

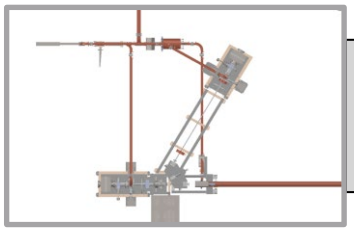
MAX IV Linac

The linear accelerator at MAX IV is constructed for injection top-up two storage rings and as a high brightness driver for the Short Pulse Facility. It is also prepared to be used as an injector for a future Free Electron Laser.

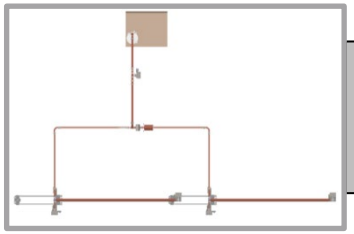
- 20 pcs: Pulsed S-band RF power units (38MW peak, 4,5usec, 100Hz), ScandiNova (Canon)
- 1 pc: Pulsed S-band RF power unit (8MW peak, 3usec, 10Hz), ScandiNova (Canon)
- 20 pcs: S-band RF Power compressor SLED (Q=100000, 4,5usec in, 0,7usec out), RI
- 2 pcs: S-band RF Guns (a thermionic and photo-cathode), MAX IV Laboratory
- 39 pcs: Linac structures (max gradient of acceleration 25MV/M, 5,2m long), RI



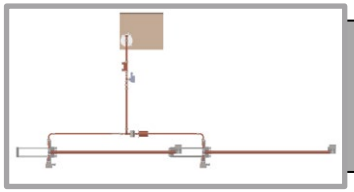
Linac component's overview



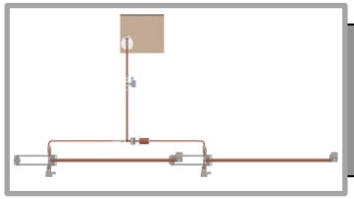
WGU 1



WGU 2



WGU 3



WGU 4

Pre-injector:
- RF Gun Test Stand
- Thermionic RF Gun
- Photocathode RF Gun
- Optic & Energy filter

Home made → MAX-lab, Sweden

RF Power Units:
- High Voltage Modulator
- Klystron
- Long-run test

Purchased by → Scandinova Sweden

Accelerators Units:
- SLED
- Coupler & Power Divider
- Linac structures
- Conditioning

Purchased by → RI Germany

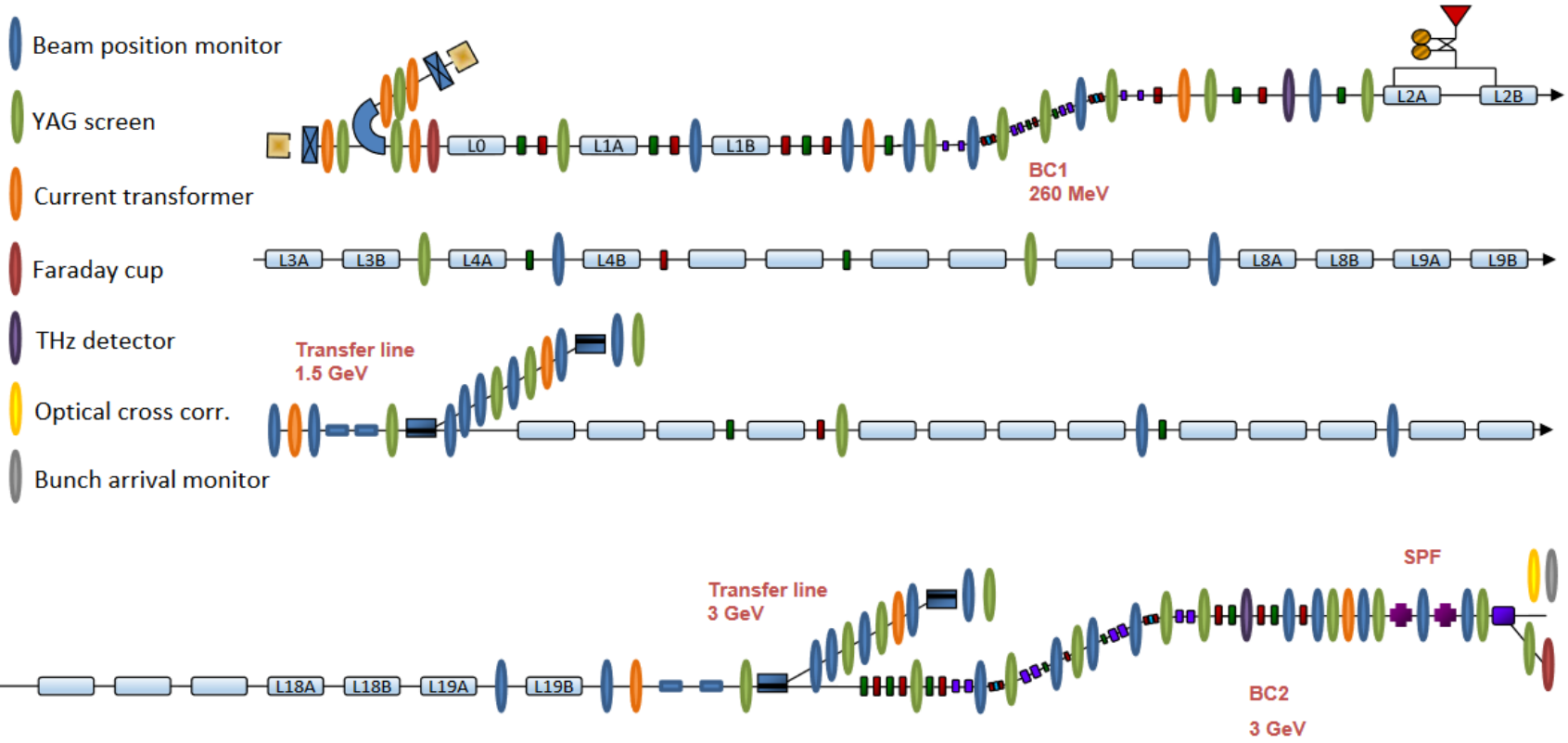
Waveguide System:
- E- band waveguide
- H- band waveguide
- Straight waveguides

Purchased by → IHEP China

Accessories:
- 50 dB direct coupler
- Flanges, gaskets etc.

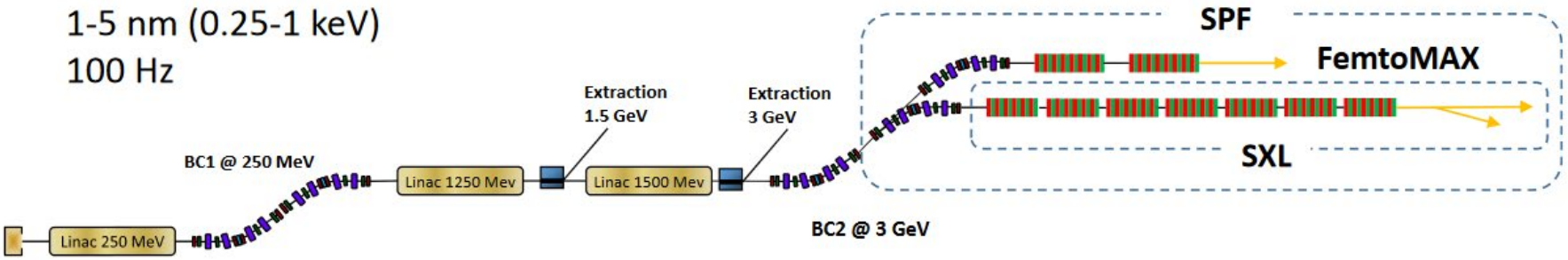
Home made → MAX-lab, Sweden

Linac diagnostic component's overview



SXL in the short pulse facility (SPF)

3 GeV
1-5 nm (0.25-1 keV)
100 Hz



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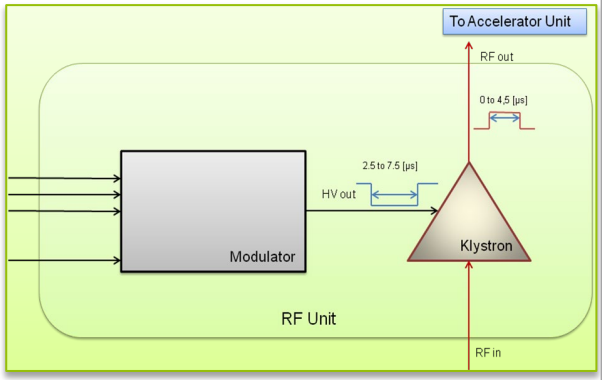
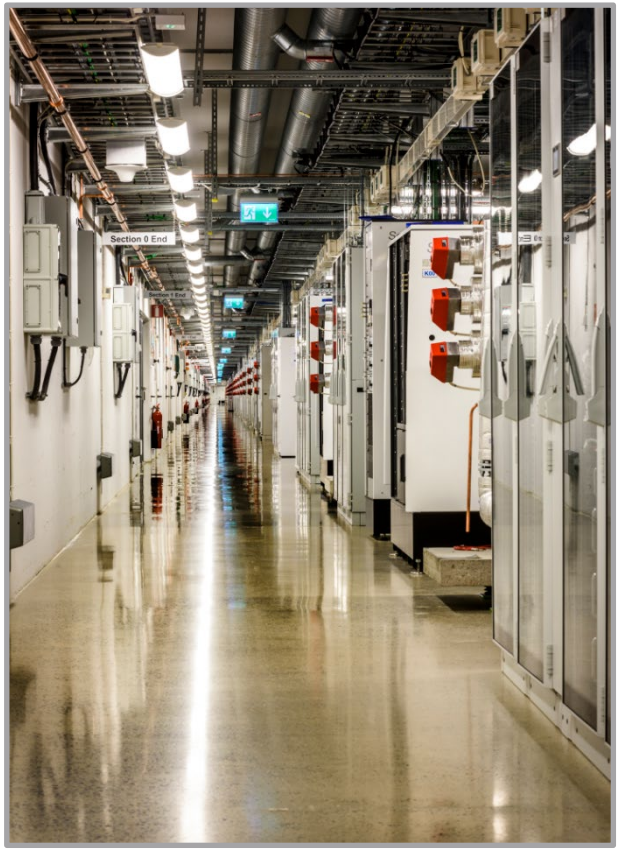
Pulsed RF Power Units (Klystron gallery)

¤ 20 pcs SCN modulator model K200, Canon (Toshiba) klystrons model E37310 (max 38MW)
¤ 1 pc SCN modulator model K100, Canon (Toshiba) klystron E37326 or E3779A (max 8MW)



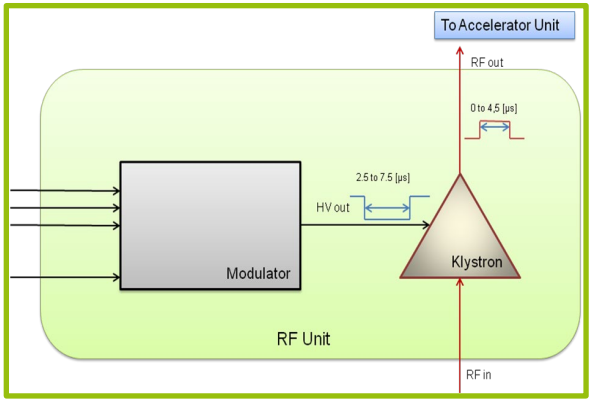


- The modulator K200, have three 25kW High Voltage Power Supplies (DCPS) and seven parallel High Power Switch Units (HPSU).
  (maybe it would be better with four DCPS and eight HPSU)

- The modulator K100, have one 25kW High Voltage Power Supplies (DCPS) and two parallel High Power Switch Units (HPSU).
  (would prefer better position of HPSU in the machine)

Modulator

¤ Total 20+1 pcs SCN modulator K200, Canon klystrons model E37310,
¤ Total 1+1pc SCN modulator K100, Canon klystron E37326



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

Parameters of model K100 and K200 modulators

Parameters	K100	K200
Peak RF power output [MW]	10	38
Klystron Average RF Power [kW]	0.8	18
Klystron voltage range [kV]	170	300
Klystron current range [A]	140	350
Flat top pulse width variable [µs]	0-3	0-4.5
Voltage Pulse width variable [µs]	1-4	2.5-7
PRF variable [Hz]	0-100	0-100
Flat top ripple or droop [%]	± 1.0	± 1.0
Pulse to pulse amplitude stability [%]	±0.01	< ± 0.01
Pulse to pulse to pulse time jitter [ns]	< ±4	< ±6
Pulse length jitter [ns]	< ±8	< ±8
Modulator Electric efficiency [%]	> 80	> 80

In our case:
- K100 modulator has one HVPS and two parallel switching units.
- K200 modulator has three HVPS and seven parallel switching units.

Klystrons

Klystron E37326 and E37310 parameters

Parameters	E37326	E37310
Frequency [MHz]	2998,5	2998,5
Peak forward beam voltage [kV]	165	295
Peak cathode current [A]	120	345
Peak drive RF power [W]	120	800
Peak RF output power [MW]	8,5	38
Average RF output power [kW]	10	20
Klystron efficiency [%]	40	40
Pulse width (epy duration) [µs]	7,5	7,5
Pulse width (RF duration) [µs]	5	4,5
Pulse repetition rate [hz]	300	120
Gain (saturation) [dB]	48,0	48,5
Perveance [µP]	1,8	2,2

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)

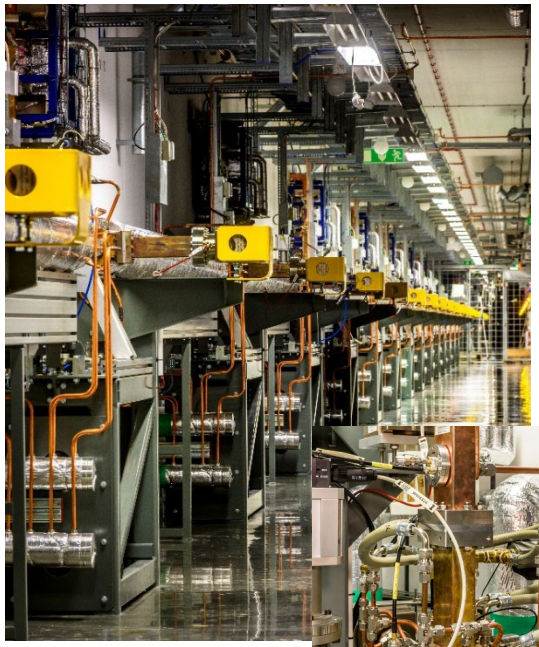
The electron beam is focused with the electromagnet VT-68922.

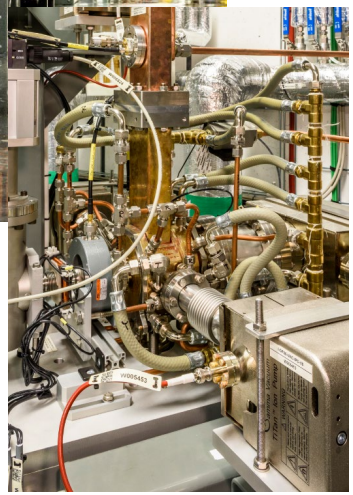
An "M"-type dispenser cathode with high reliability promises long tube life.

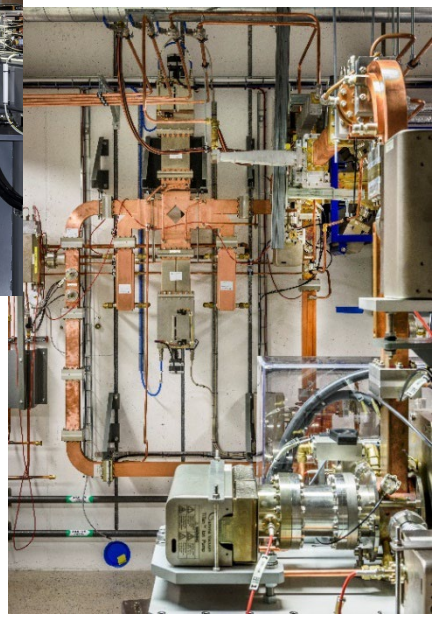
- the warranty lifetime with filament ON is **20 000** hours,
- the average lifetime with filament ON is about **45 000** hours,
- there are individs that can be running much longer …..

Accelerator Units (Linac tunnel)

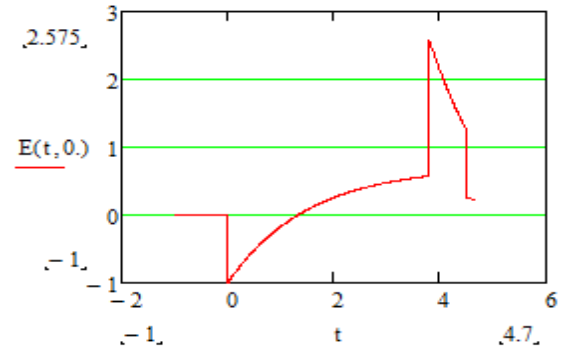
- 39 pcs linear accelerator structures 5.2m (156 cells) from RI,
- 39 pcs RF power compressor (SLED) from RI
- 2 RF Guns





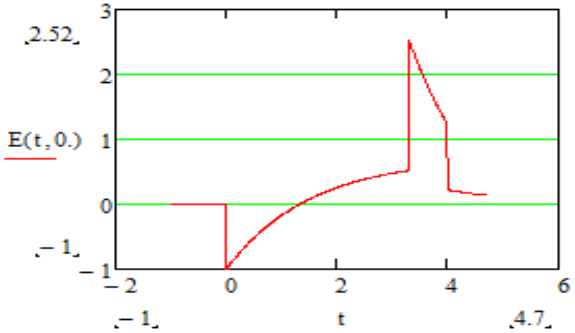


Linac energy adjustment

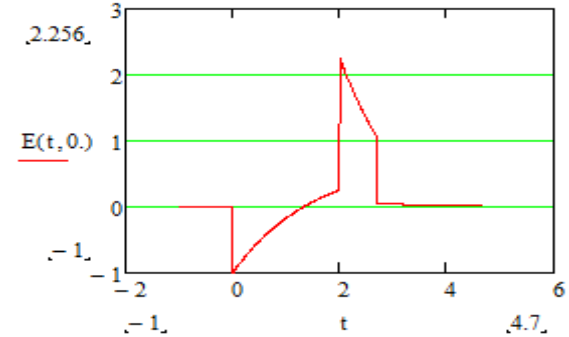


Charging time

3.8 µs



3.3 µs



2.0 µs

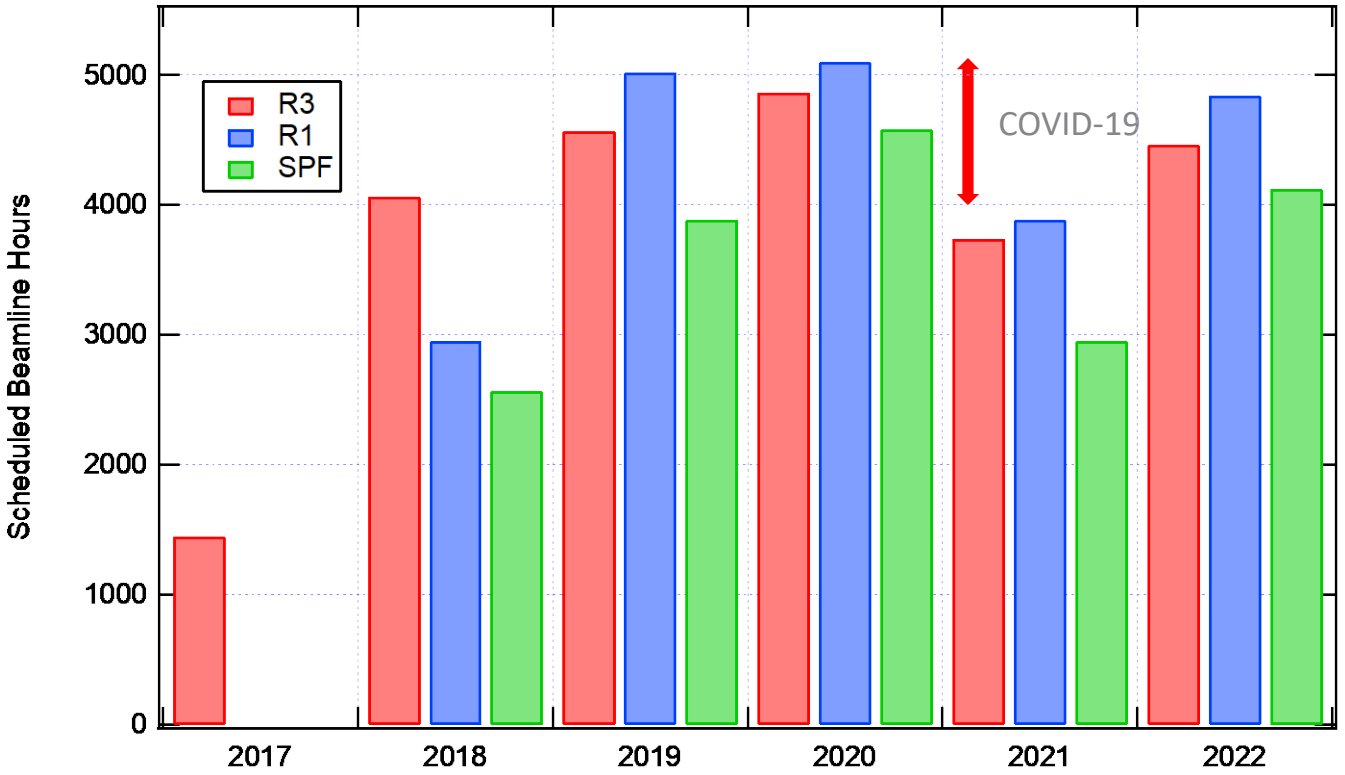
The klystrons are running at konstant voltage to maintain a constant RF phase at the output. In order to reduce klystron output power variations due to variations in the input power they are run in sturation mode.
The output power from SLED is adjusted by varying the charging time.

SLED data
β=6
$Q_o=10^5$

Content

- MAX IV Laboratory, Lund University Sweden
- Pulsed S-band RF Powers and Accelerators Units
- The experience of 10 years running
  - Achievements
  - Problems and Improvements
  - Spare parts
- Conclusions

Achievements (Long Term Statistics- Scheduled Hours)



Problems of Pulsed RF Power Units

The list issues we have encountered from the beginning:

1. Transport damaged klystrons,
2. Insufficient HV conditioning
3. Klystron RF window issues,
4. The electrical motors of the modulator oil filters.
5. Low tolerances of IGBT current protection.
6. Incorrect klystron perveances measurements,
7. Waveguide RF power conditioning
8. Insufficient grounding
9. Damage to the IGBT as a result of secondary radiation and insufficient grounding

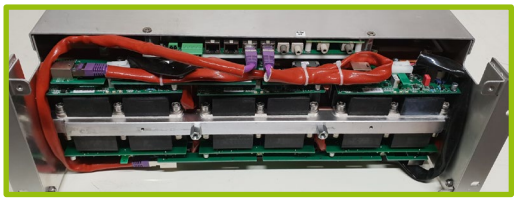
The current list of main problems we face today:

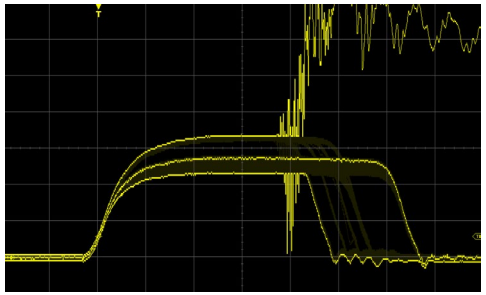
1. Transport damaged klystrons (much less)
2. Lack of klystron conditioning (much less)
3. Klystron RF window issues (much less),
4. The electrical motors of the modulator oil filters (resolved)
5. Low tolerances of IGBT current protection (resolved)
6. Incorrect klystron perveances measurements (still unresolved)
7. Waveguide RF power conditioning
8. Insufficient grounding
9. Damage to the IGBT as a result of secondary radiation and insufficient grounding (much less)
10. The I/O and 24Vdc power supply of Main RF power Unit damaged due to prolonged exposure to high temperature (lack of airflow).
11. Electronics damaged in the Main RF Power Unit and Tank Node.
12. Finally, with the damage in the main electronic circuits, the diagnostics of the modulator does not help in finding the defects.

IGBT damage and improvement

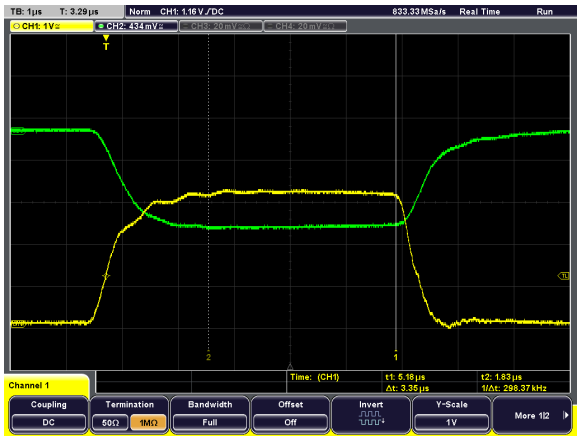
- A factor that increase the MAX IV downtime is still IGBT damage.
- It is worth noting that this time has been reduced a lot, it has not even happened in any modulator with new IGBTs
- This damage mainly came as a result of secondary radiation and sometimes reflection from the discharge in the klystron.

Total **1308** IGBT's





- Replacement of all existing IGBTs with higher working voltage have been done of four modulators.
- In cooperation with SCN, we working to do this replacement of the first 9 modulators.



Other Modulator Unit Improvements

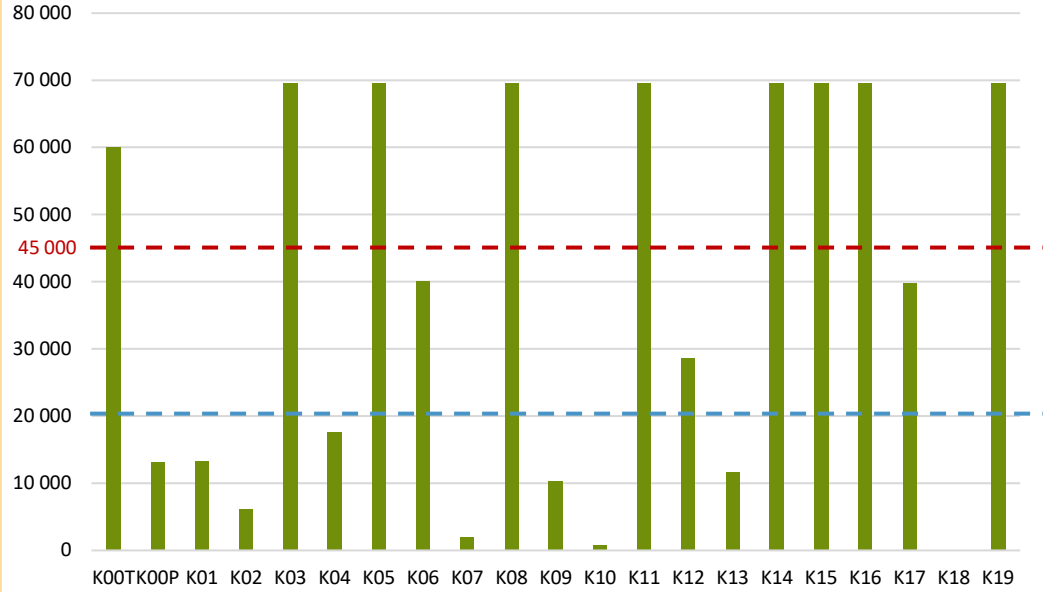
- Replacement of all 24 Volt DC PS and PLC I/O in RF Control Unit in all modulators, in due time. Something that saved many hours of downtime, as well as better ventilation of this unit.

- Improving the diagnosis on the condition of the klystron, through better monitoring of its vacuum.
- Avoid running the klystron without the high voltage cable connected
- Improving air circulation and cooling in the main cabinet of the modulator

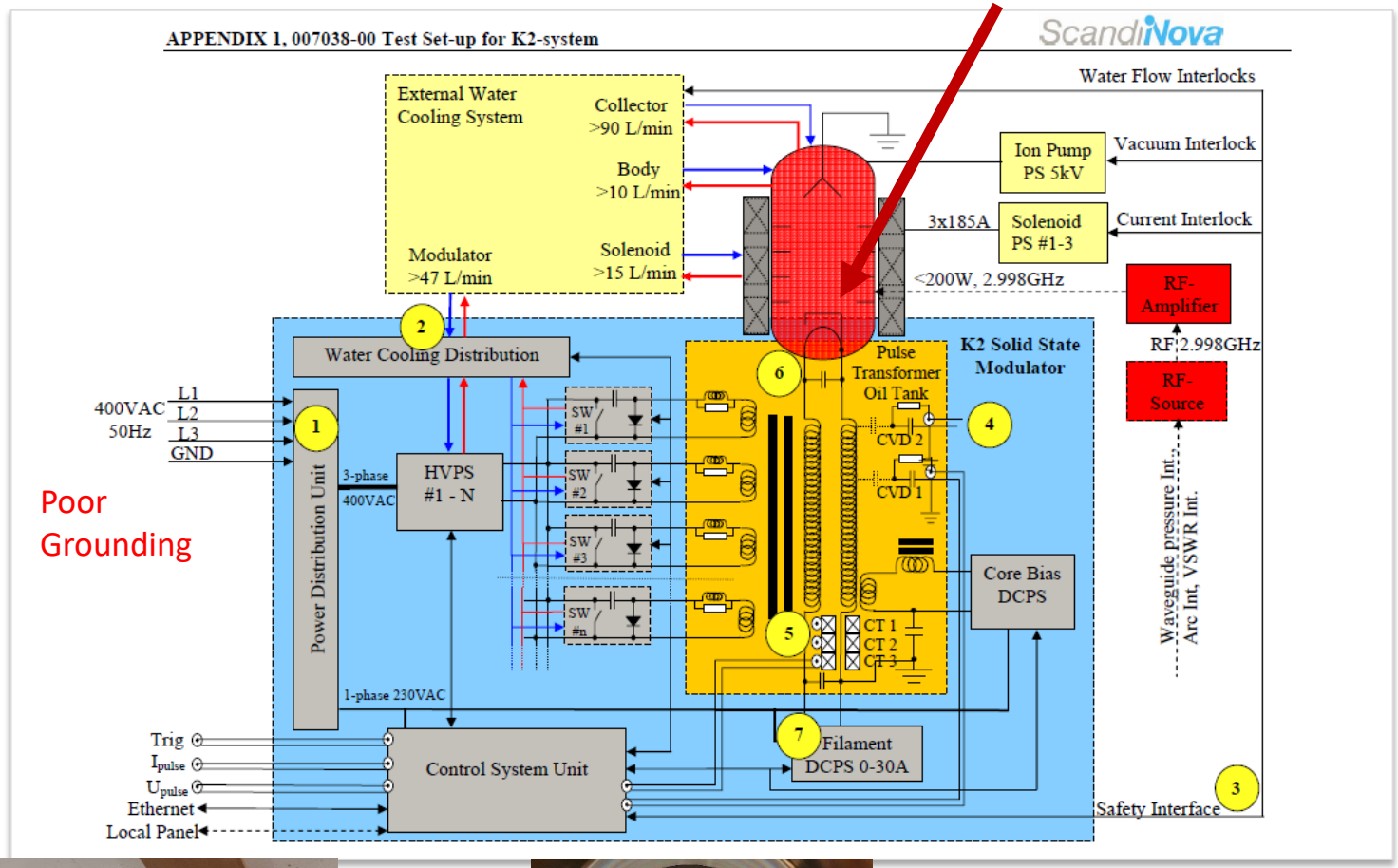
Working hours of MAX IV Klystrons

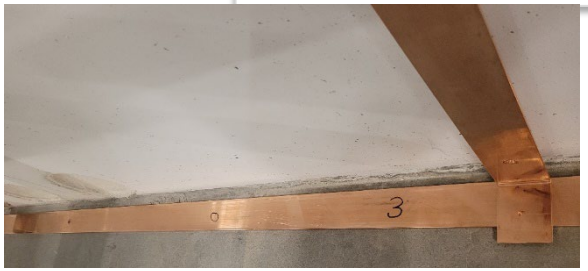
Nr	Mod. Nr	Model	P/P [MW]	S/N	Y/M/D	Working hours
1	K00T	E37326	8	15 C 001	2015.03.10	60 000
2	K00P	E377310	37	20 L 035	2021.07.12	13 100
3	K01	E377310	37	20 L 034	2021.06.10	13 300
4	K02	E377310	37	21 M 040	2022.07.12	6 200
5	K03	E377310	37	12 B 005	2013.01.10	69 600
6	K04	E377310	37	18 G 032	2018.06.15	17 600
7	K05	E377310	37	12 E 009	2013.01.10	69 600
8	K06	E377310	37	16 F 029	2016.10.05	40 100
9	K07	E377310	37	22 D 041	2023.01.23	2 000
10	K08	E377310	37	12 C 007	2013.01.10	69 600
11	K09	E377310	37	21 H 038	2021.12.27	10 400
12	K10	E377310	37	21 F 037	2023.03.10	800
13	K11	E377310	37	11 K 001	2013.01.10	69 600
14	K12	E377310	37	18 H 033	2019.03.04	28 600
15	K13	E377310	37	21 E 036	2021.10.06	11 600
16	K14	E377310	37	11 M 004	2013.01.10	69 600
17	K15	E377310	37	12 J 020	2013.01.10	69 600
18	K16	E377310	37	12 E 010	2013.01.10	69 600
19	K17	E377310	37	16 E 028	2016.07.16	39 800
20	K18	E377310	37	22 D 042	2023.04.05	0
21	K19	E377310	37	12 H 017	2013.01.10	69 600

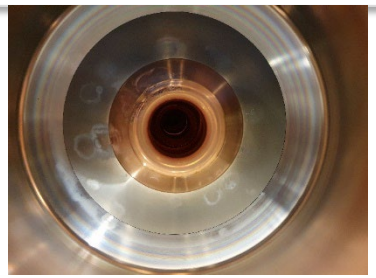
- Acumulated working hours of a klystron in MAX IV Linac on the average is **7 500 hours per year** with filamnet ON.
- For the 21 klystrons model E37310 acumulated on the average are **158 000 hours per year.**
- MAX IV purchased on the average **three klystrons per year** (the average lifetime with filament ON from Canon is about **45 000** hours) of this model, until we have 8pcs spare.
- Two klystrons model E37326 acumulated **15 200 hours per year**, we purchase **one klystron per three years**.



Klystrons discharge







Weak parts of klystrons and unnecessary diagnostics

Measuring the temperature difference of the cooling water at the inlet and outlet

Output window

1. Thermal load
2. High electric field strength

→Window ceramic leak

Electron gun

Large energy of discharge

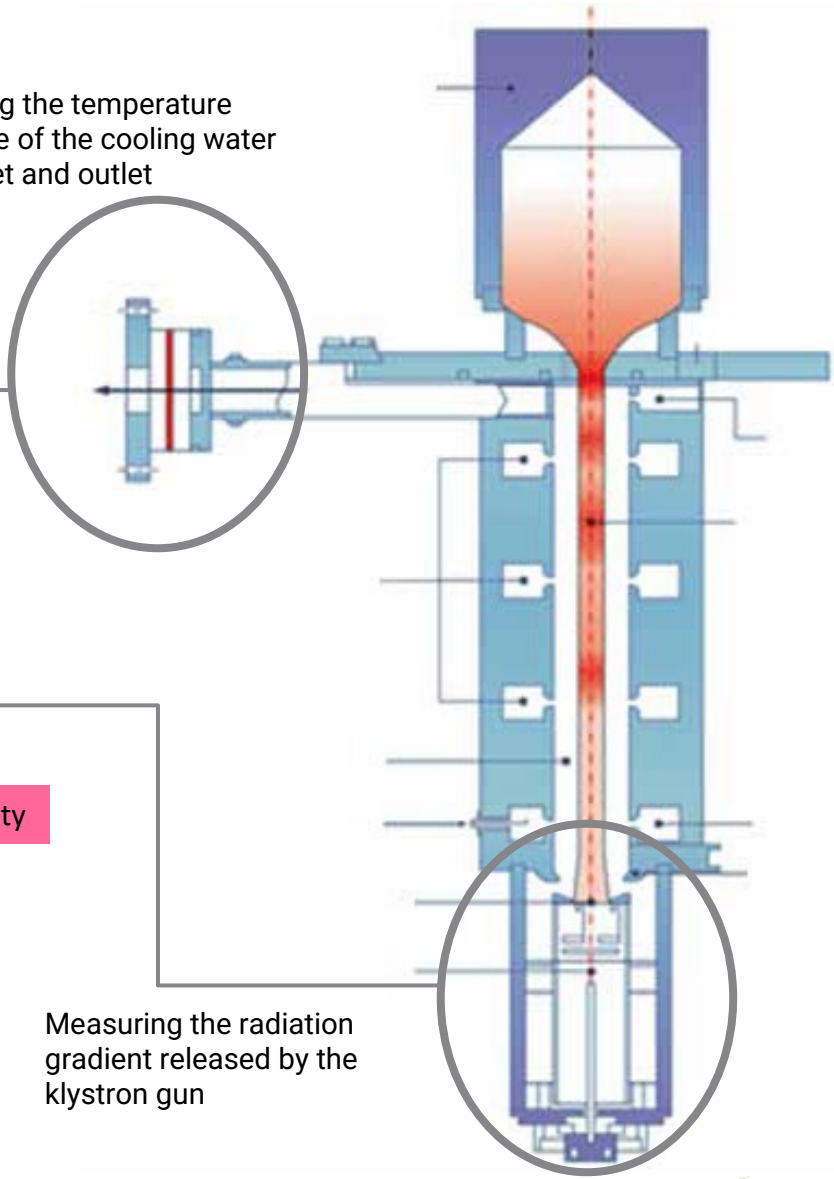
→Degradation of high voltage durability

Gun ceramic

Creeping discharge or partial charging

→Gun ceramic leak

Measuring the radiation gradient released by the klystron gun



The Klystron replacment

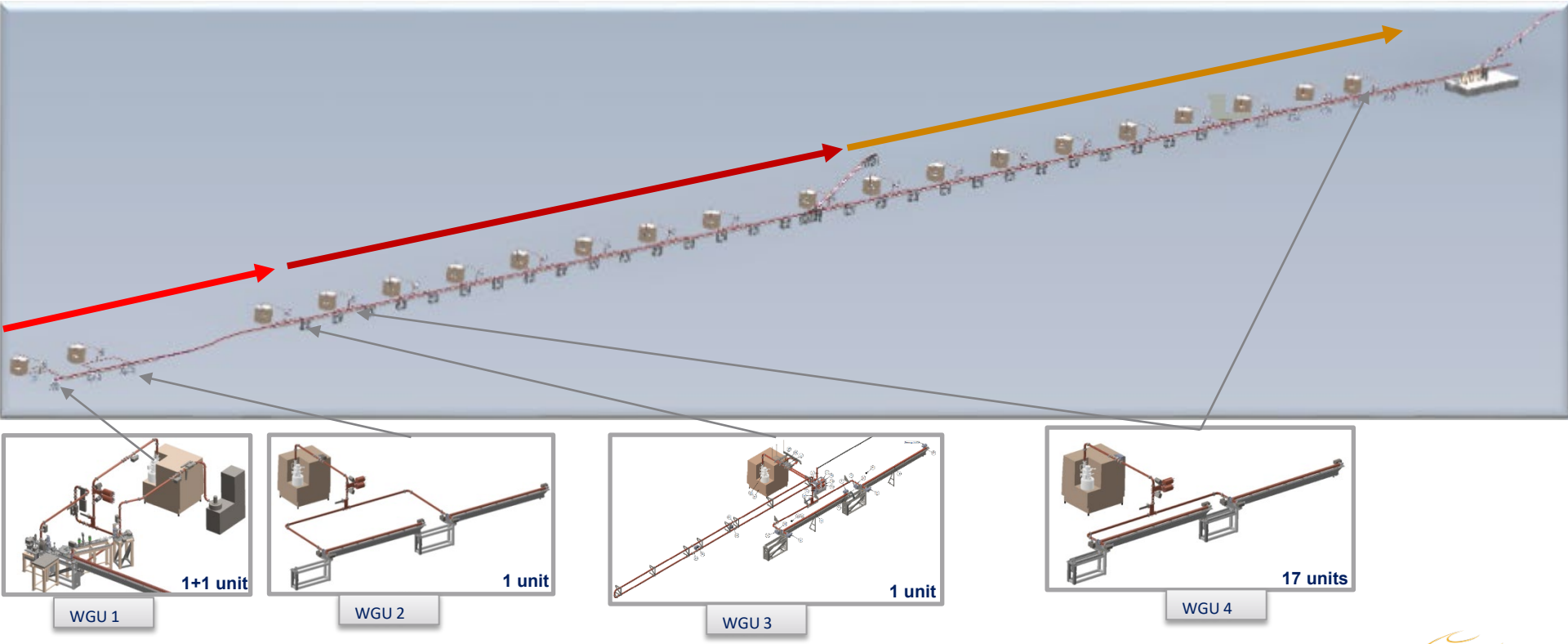
- Group I
- 2 pcs: Mod K200 & Klystron E37310
- 1 pc: Mod K100 & Klystron E37326
- Group II
- 8 pcs: Mod K200 & Klystron E37310
- Group III
- 9 pcs: Mod K200 & Klystron E37310

Klystrons are changed after 45,000 working hours and the changed ones are saved to be used in the third group

When problems are observed, if possible the klystrons are kept in operation under light conditions and replaced at the next shutdown.

When problems are observed and it is not more than one klystron, they are replaced immediately

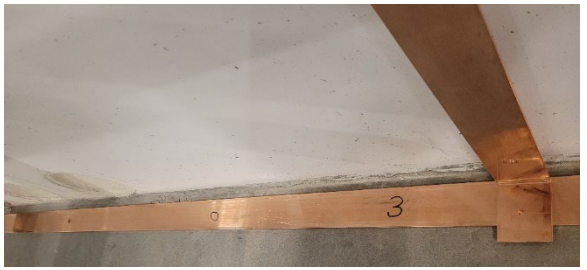
RF conditioning for the unit with new klystron is done simultaneously when the Linac is in normal operation, just delaying the trig signal for the unit to be conditioned.



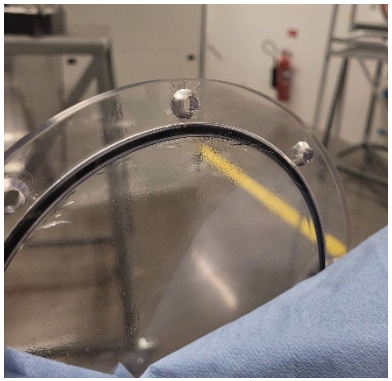
Problems (RF Power Unit downtimes)

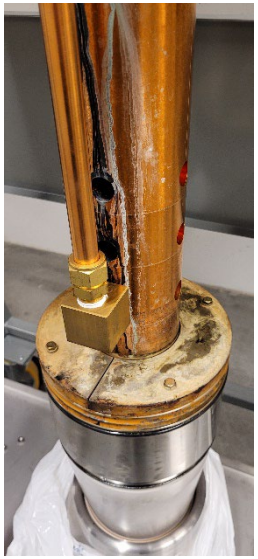
- The age of klystrons has contributed to the significant increase in the time of defects. Moreover, at the end of life, with internal electrical discharges, which in the absence of effective grounding create problems in the electronics of the modulators.

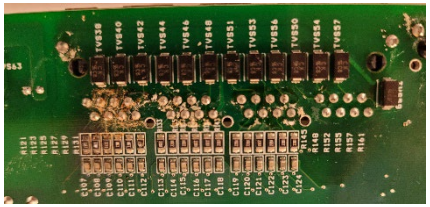
- Assessment of the problem and **replacement of klystrons at the right time**. The unnecessary extension of the time of their use, apart from not having any benefit, creates other problems for us in the modulator

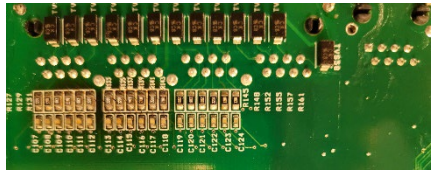


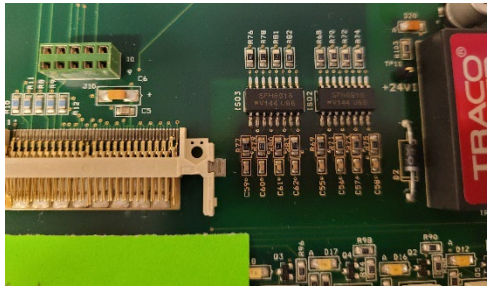
Problems (RF Power Unit downtimes)











Spare Parts

- **Economic and technical stability of our suppliers**

MAX IV is very interested that the companies that contributed and contribute to it (such as SCN, Canon, RI, etc.) to have economic stability, otherwise it will be very difficult for MAX IV to continue working normally.

- **Healthy and fair contracts**

MAX IV have agreed and signed a three-year agreement with SCN and Canon for the most important and unconventional parts. We repeat this contract at the end of three years. So far it has worked very well.

- **Closely following new technology and technical improvement**

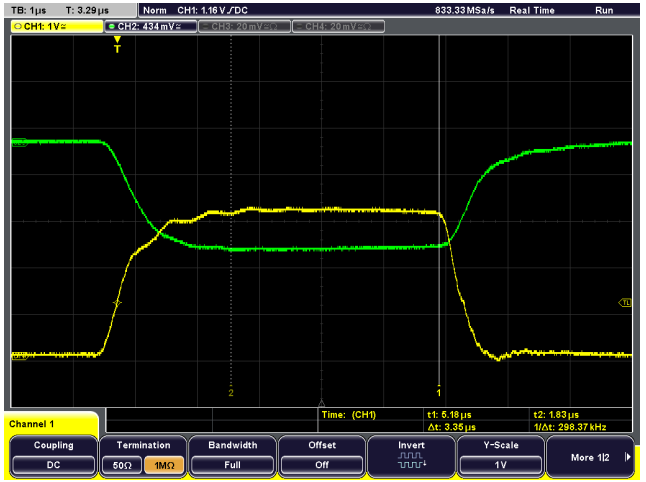
Since the technique used in the MAX IV modulators is outdated (more than 10 year old), it is planned to purchase and install an extra modulator K200, which will serve to test all spare parts for the modulators, as well as further testing and conditioning of the klystrons. If needed.

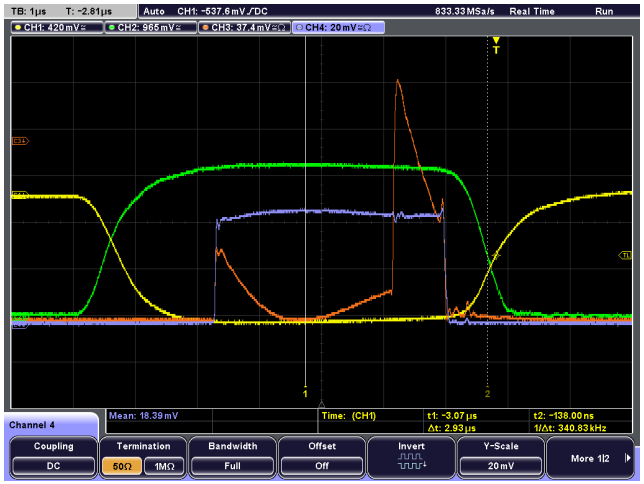
Conclusions

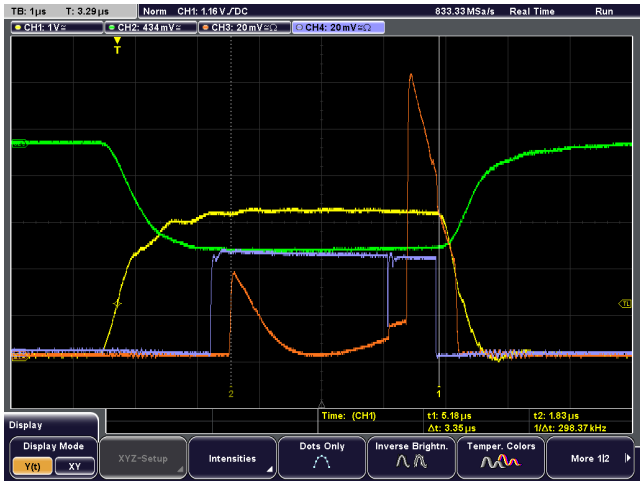
- We can not avoid having technical problems; but we can work with them:
  - **Patiently explaining** as much as possible the other divisions for the work that is done and required to maintain so many devices that work pulsed and with high voltage. Continuous communication should be maintained. That help to avoid as much as we can working under **high psychological pressure**, which has significantly reduced errors and increased the quality of repair.
  - Very important to prepare an intelligent and **efficient list for spare parts**. This list should be adapted to the situation of the machines. All the spare parts are stored in rooms that are housed in the klystron gallery. Very easy to access to them, and we have prepared accessories that facilitate the work of transporting and mounting heavy parts of the modulator.
  - **Sufficient budget** for spare parts and repair assistance. RF units (modulator and klystron) having klystron component as consumable part, our goal is to keep the annual maintenance budget no less than 3% of the initial investment of them. We have all spare parts possible needed for the modulator reparation. It is a potential risk for us to face a critical situation "the ketchup effect" when 18 klystrons are working more than 45 000 hours.
  - Maintaining **close ties with suppliers**, seeing problems as common and working to solve them together
  - **Qualified personal** and ongoing qualification for the maintenance (preventive maintenance and possible repairs). It has become clear in defect and critical situations, who should deal with this problem and what to do. For example, every summer shut-down it's detailed planed the operation of replacing all filters in every modulator, it's made a high voltage test of oil of every modulator etc.)
  - **Improvements.** We follow very carefully what happens over the time with the spare parts coming out of the market. Try in time to provide replacement or upgrade with product that is in the brand.

Thank You!!

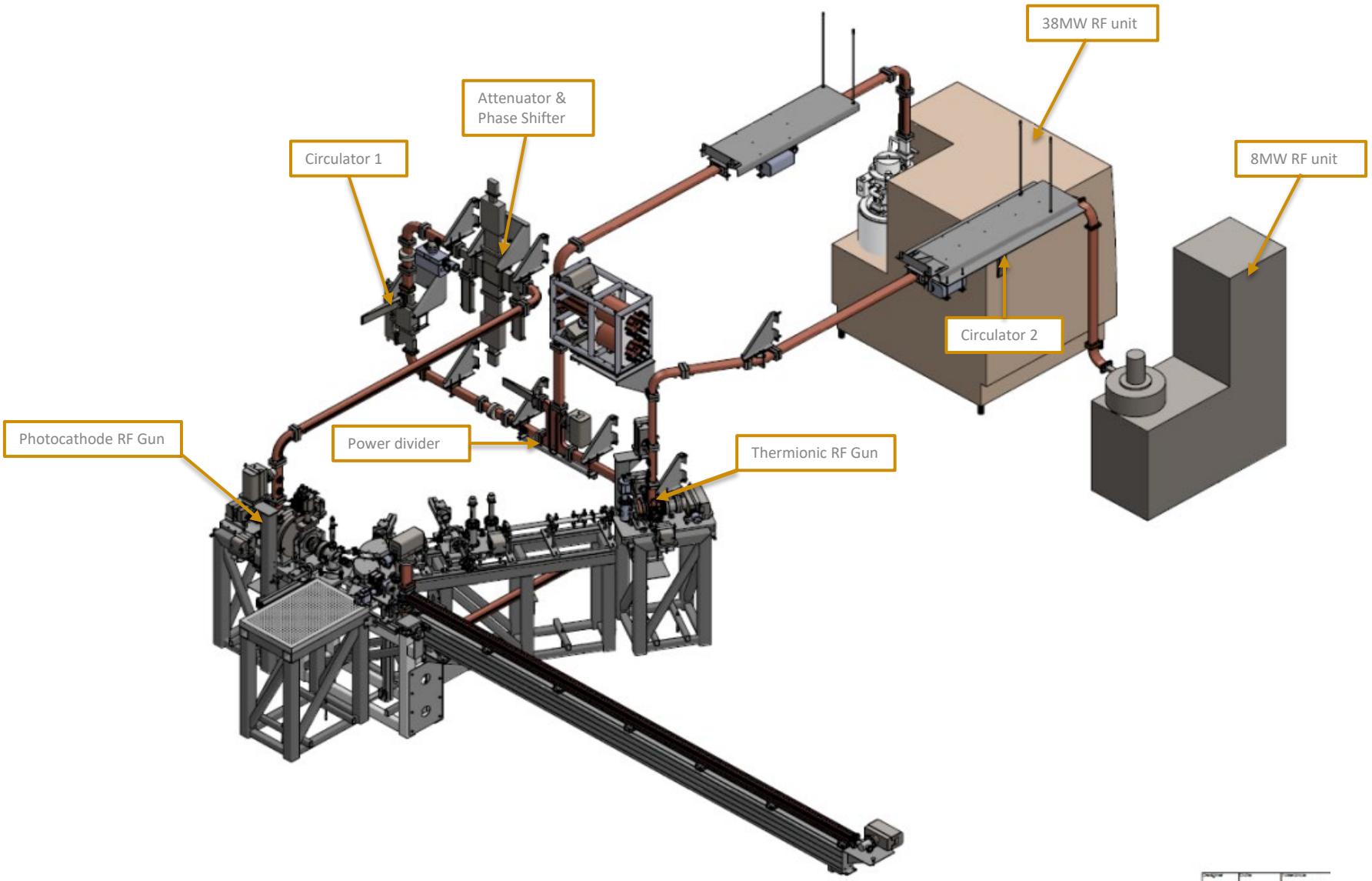
Ikly & Ukly Curves



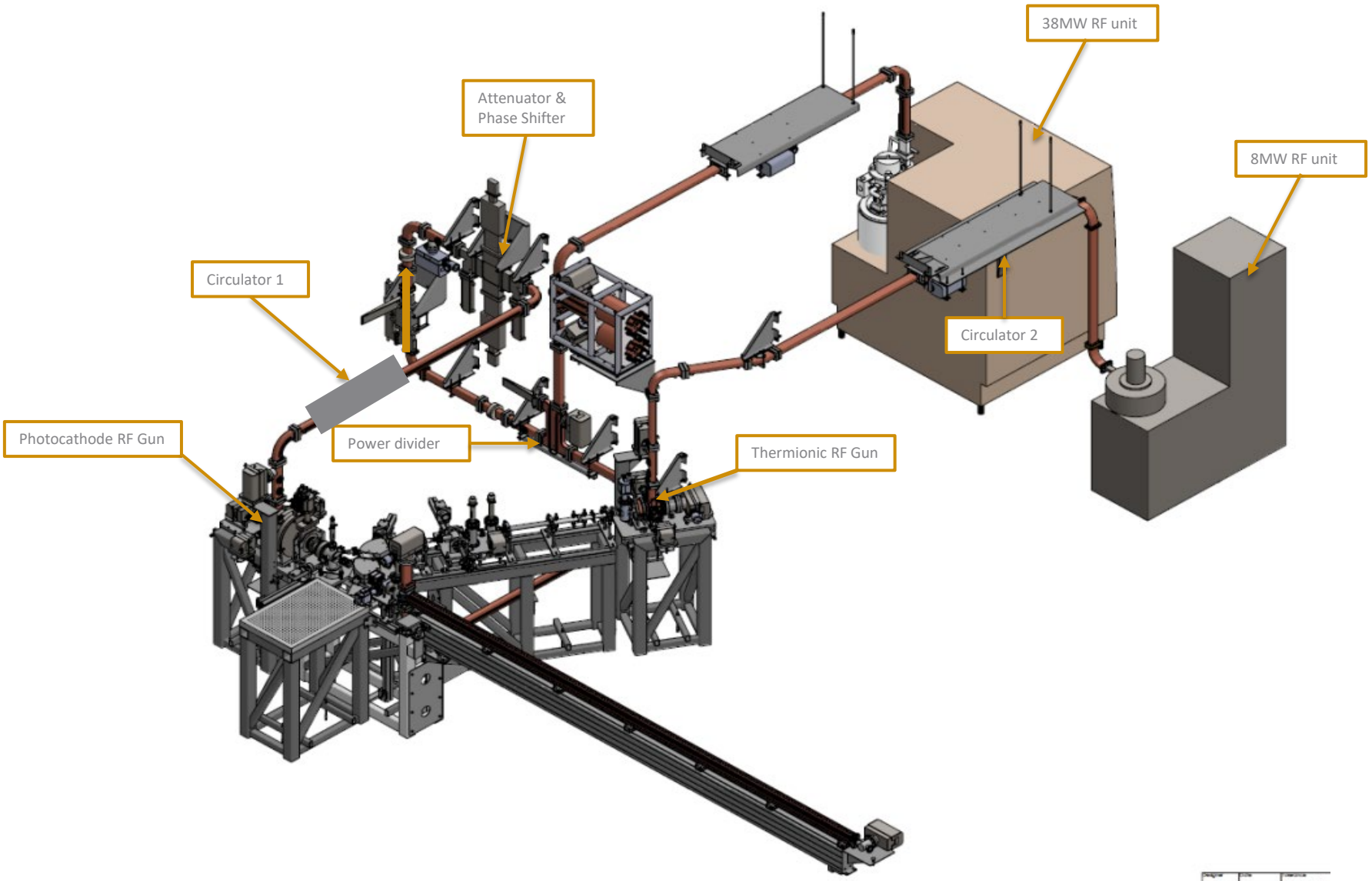




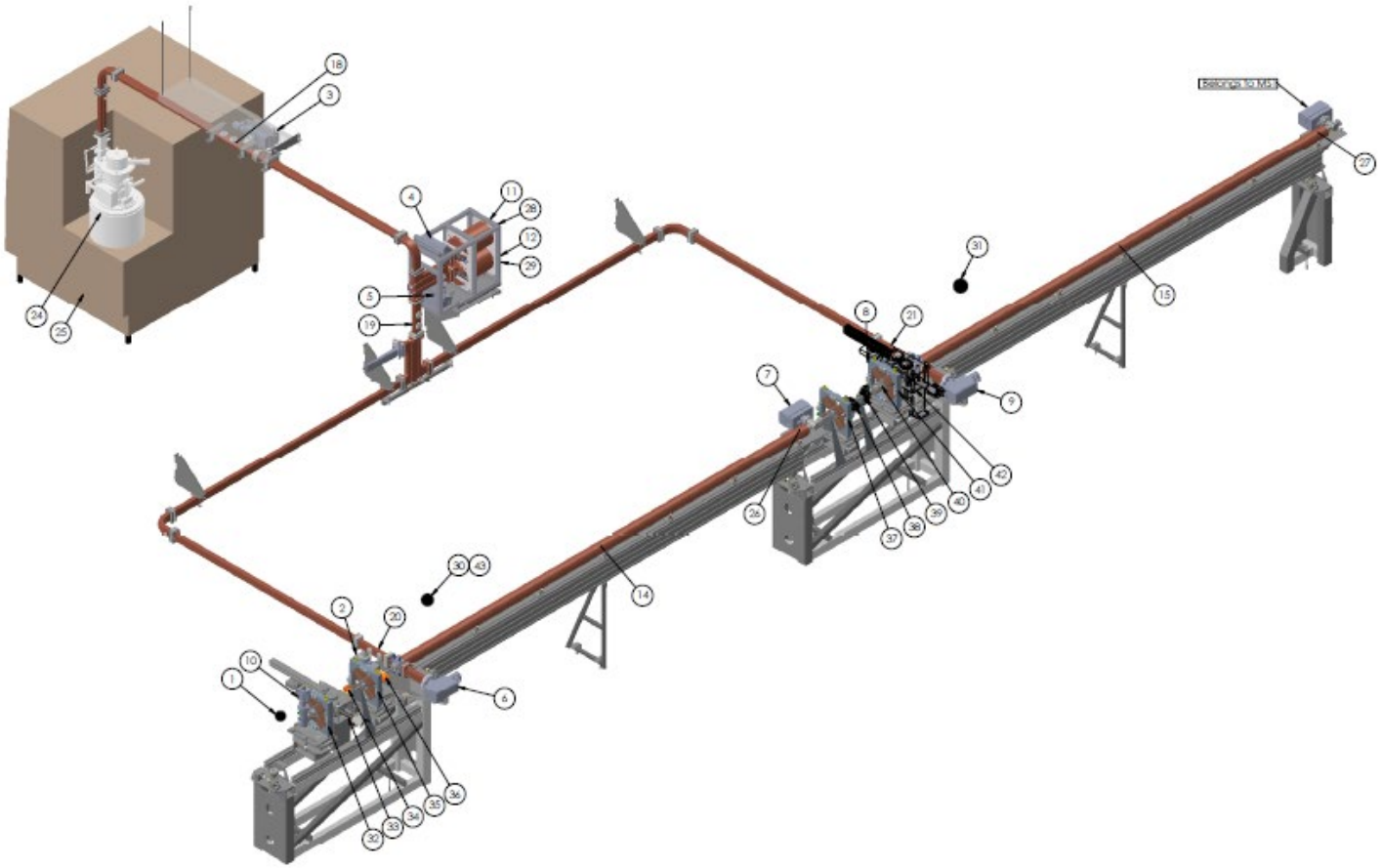
RF Power & Accelerator Unit K00+K00TG



RF Power & Accelerator Unit K00+K00TG

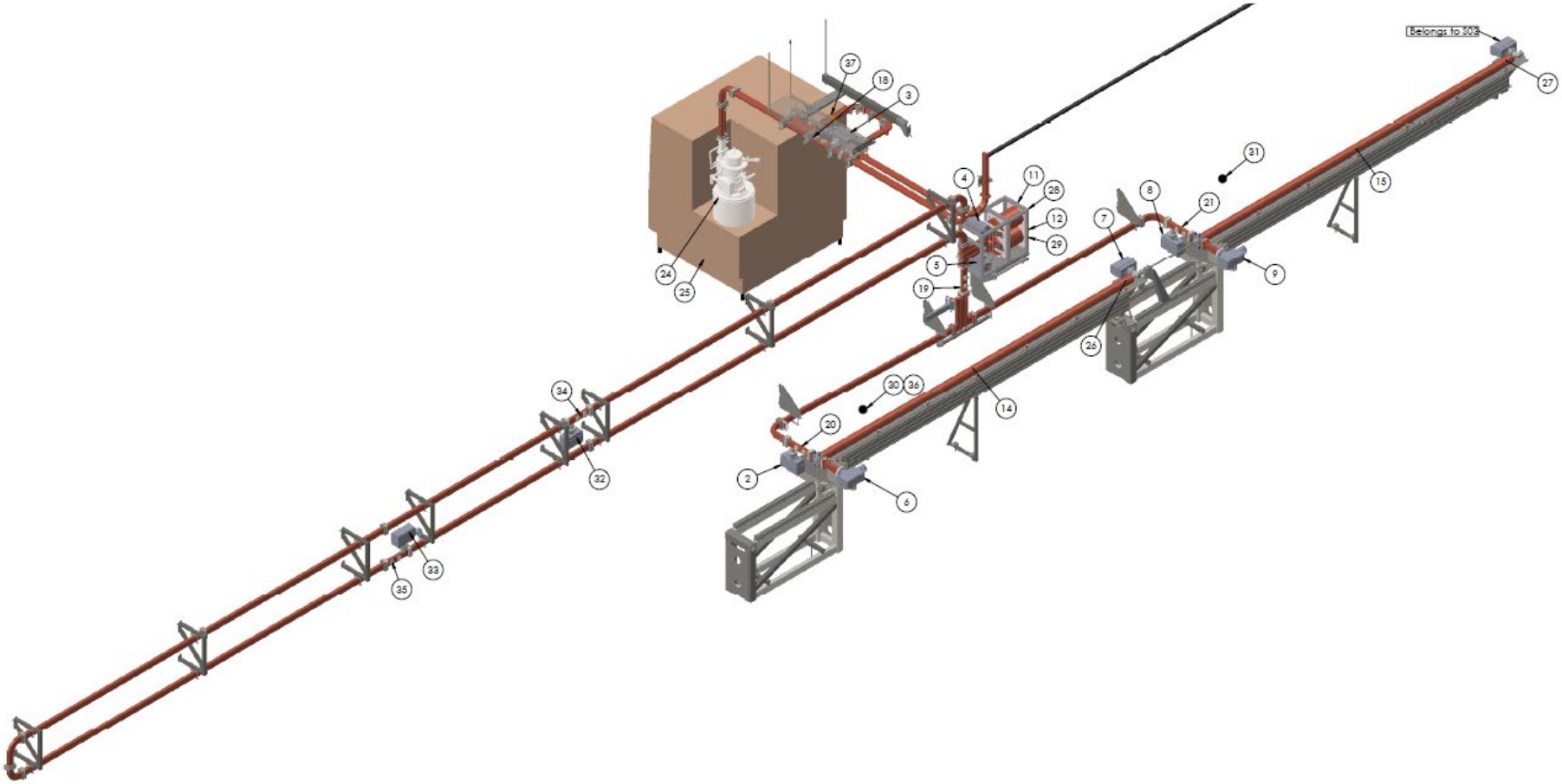


RF Power & Accelerator Unit K01

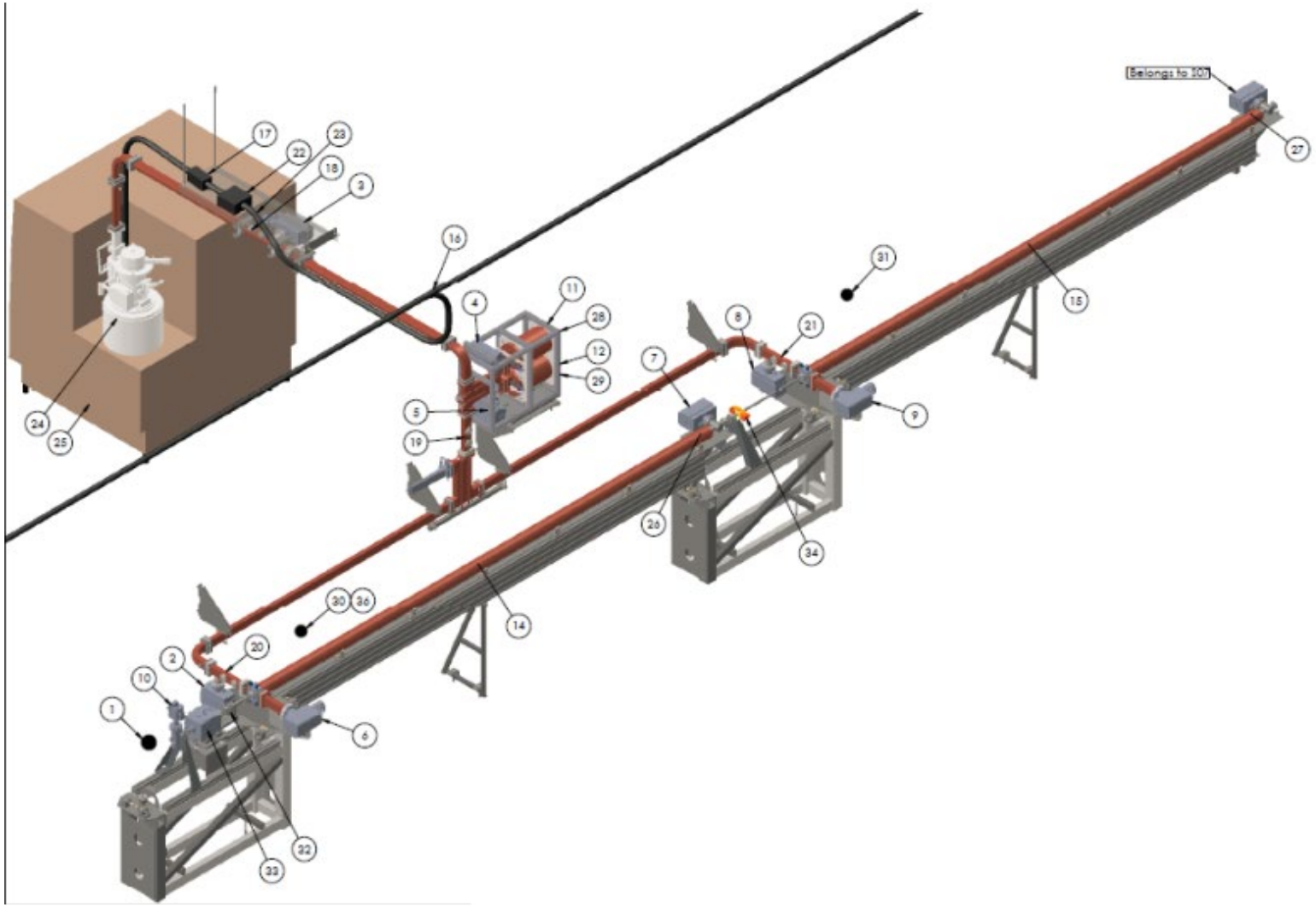


RF Power & Accelerator Unit K02

To utilize the RF power produced by K02 to feed both the accelerator structures and the main driver, the RF effect on the path to the structures will be delayed longer than the time taken for electrons to pass the distance from the first cavity to the last of klystron (the bunch electron time in klystron was circa 120ns, we delayed the RF power pulse with 170 ns)



RF Powers & Accelerator Units K03 – K19

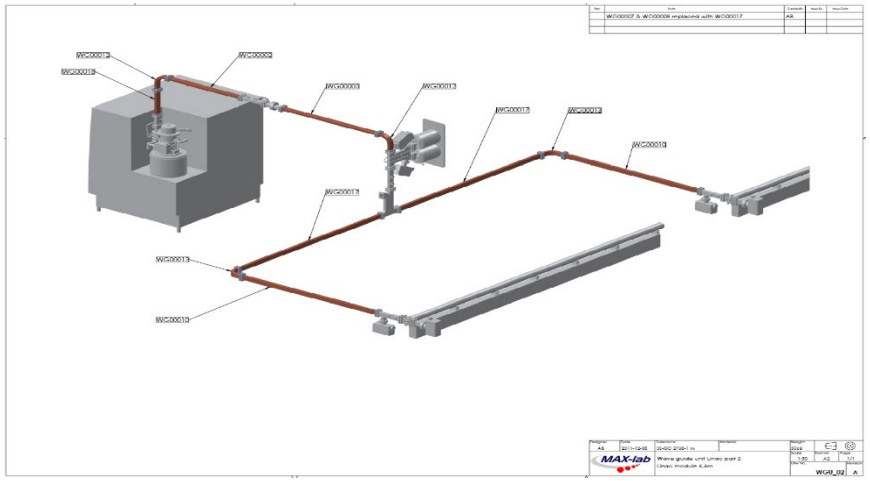


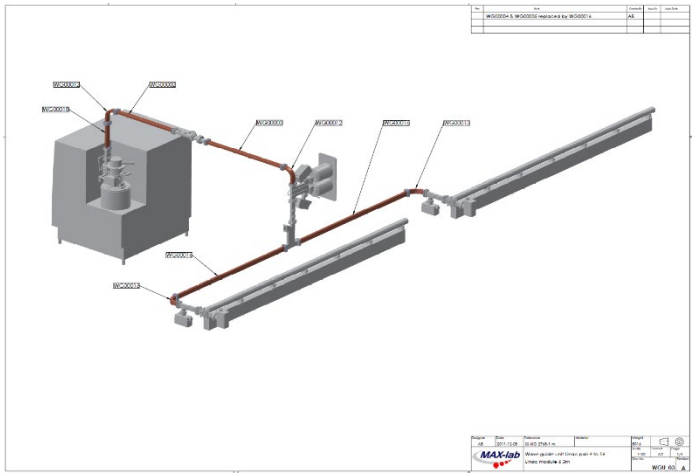
RF specifications Feb. 2012

Interface type	LIL flange
Frequency range	2998 MHz +/- 10 MHz
Peak power handling	35 MW; 4,5us or 200 MW; 0,8us
Pulse Repetition Frequency	100Hz
VSWR	1.10:1 maximum
Insertion loss per meter, max	0.02 dB
Insertion loss per flange	0.005 dB
Section of Waveguide Size WR284	80.54 x 42.44mm/72.14 x 34.04 x4.2mm
Waveguide material	CuOFE oxygen free copper
Tolerance in length	±0.5mm
Waveguide atmosphere	High Vacuum atmosphere
Leakage rate, max	1x10 exp-9 mbar-l/s
Bake able Temperature	150°c
Coolant	Water
Coolant temperature	20 to 40°c
Coolant pressure max	10 bar

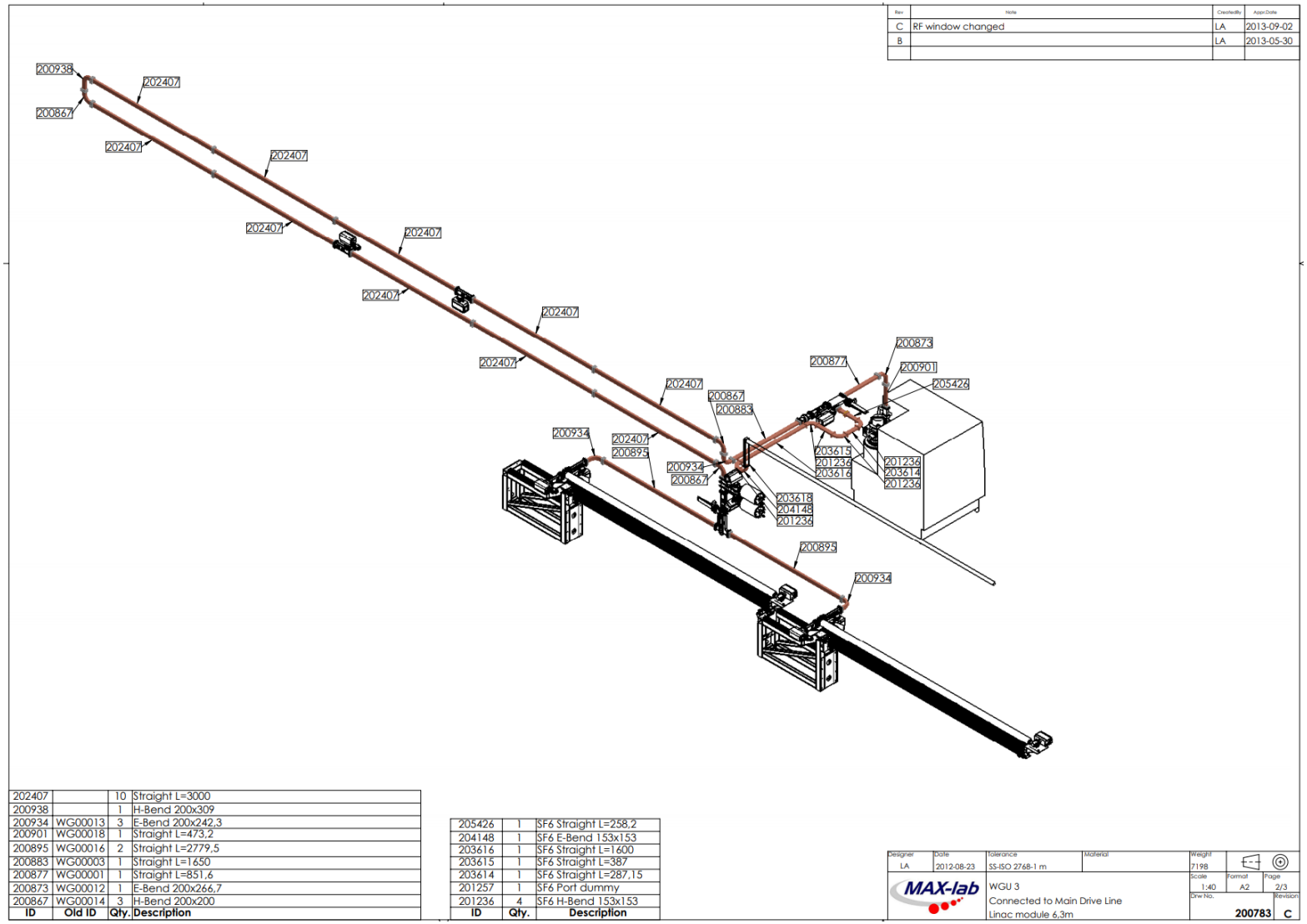
Offers:

1. Mega
2. CECOM
3. Spinner
4. IHEP





Waveguide Unit K02



Rev	Note	Created By	Appr. Date
C	RF window changed	LA	2013-09-02
B		LA	2013-05-30

ID	Old ID	Qty.	Description
202407		10	Straight L=3000
200938		1	H-Bend 200x309
200934	WG00013	3	E-Bend 200x242,3
200901	WG00018	1	Straight L=473,2
200895	WG00016	2	Straight L=2779,5
200883	WG00003	1	Straight L=1650
200877	WG00001	1	Straight L=851,6
200873	WG00012	1	E-Bend 200x266,7
200867	WG00014	3	H-Bend 200x200

ID	Qty.	Description
205426	1	SF6 Straight L=258,2
204148	1	SF6 E-Bend 153x153
203616	1	SF6 Straight L=1600
203615	1	SF6 Straight L=387
203614	1	SF6 Straight L=287,15
201257	1	SF6 Port dummy
201236	4	SF6 H-Bend 153x153

Designer	Date	Tolerance	Material	Weight
LA	2012-08-23	SS-ISO 2768-1 m		7198

MAX-lab

WGU 3
Connected to Main Drive Line
Linac module 6,3m

Scale	Format	Page
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