Markus Schneider :: RF Group :: Paul Scherrer Institut

Status of the High Intensity Cyclotron RF-System at PSI

Ninth CW and High Average Power RF Workshop 21 - 24 June 2016

Agenda

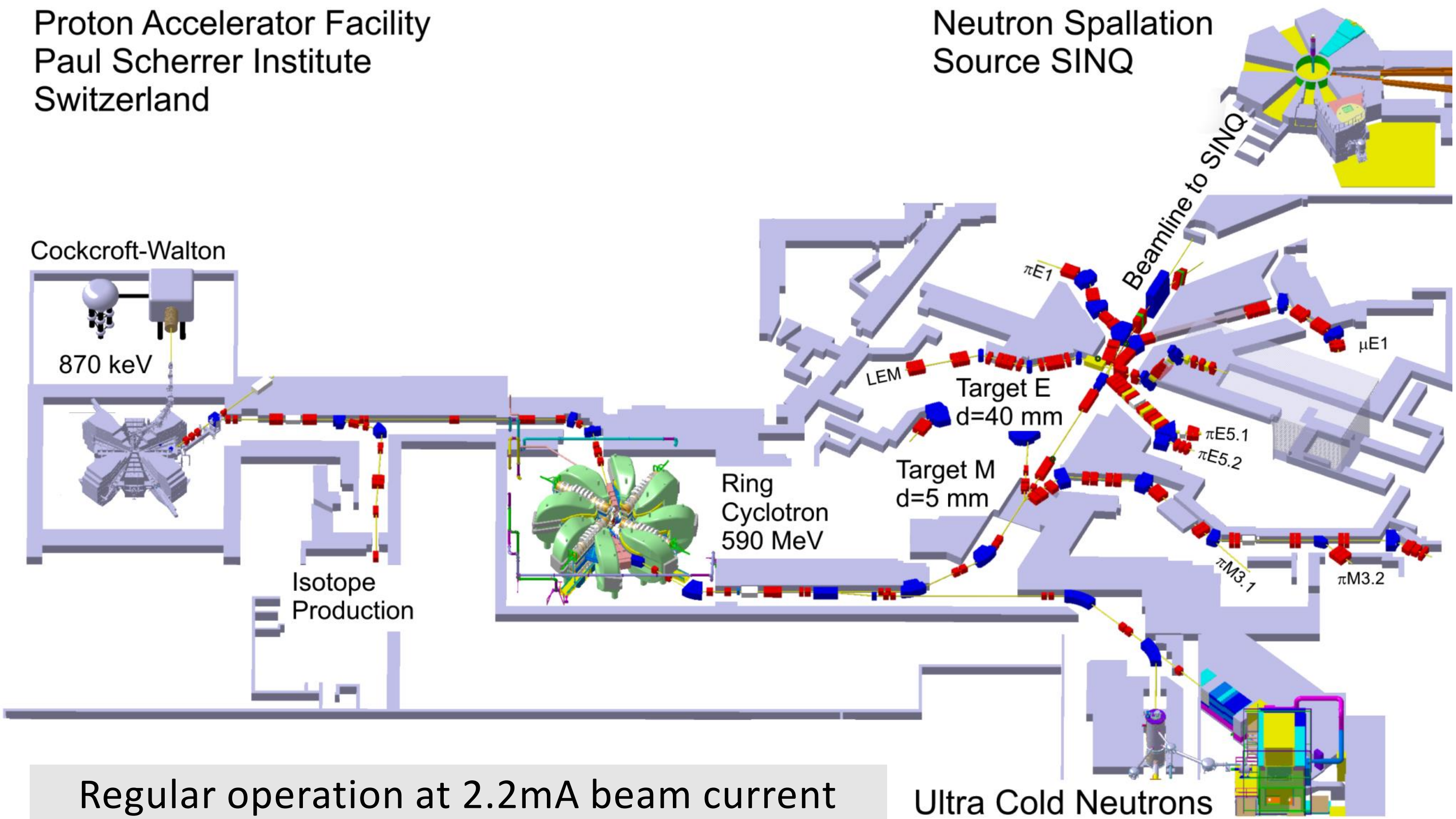
- Overview HIPA (High Intensity Proton Accelerator)

- RF-system for the Injector 2 cyclotron
  - upgrade program

- RF-system for the Ring cyclotron
  - operating experience
  - flattop problems
  - operating parameters

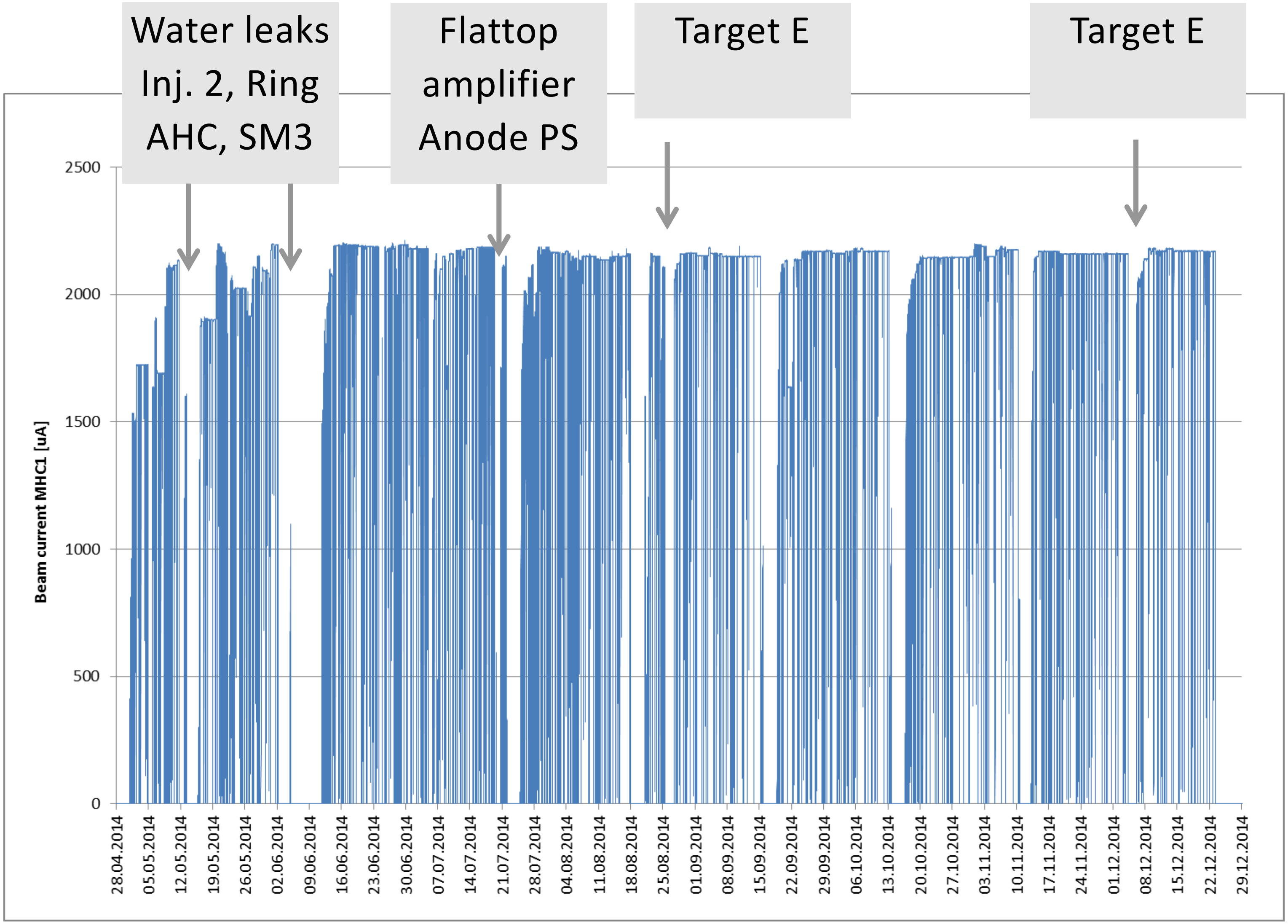
- Tetrodes
  - lifetime and failures

Overview High Intensity Proton Accelerator

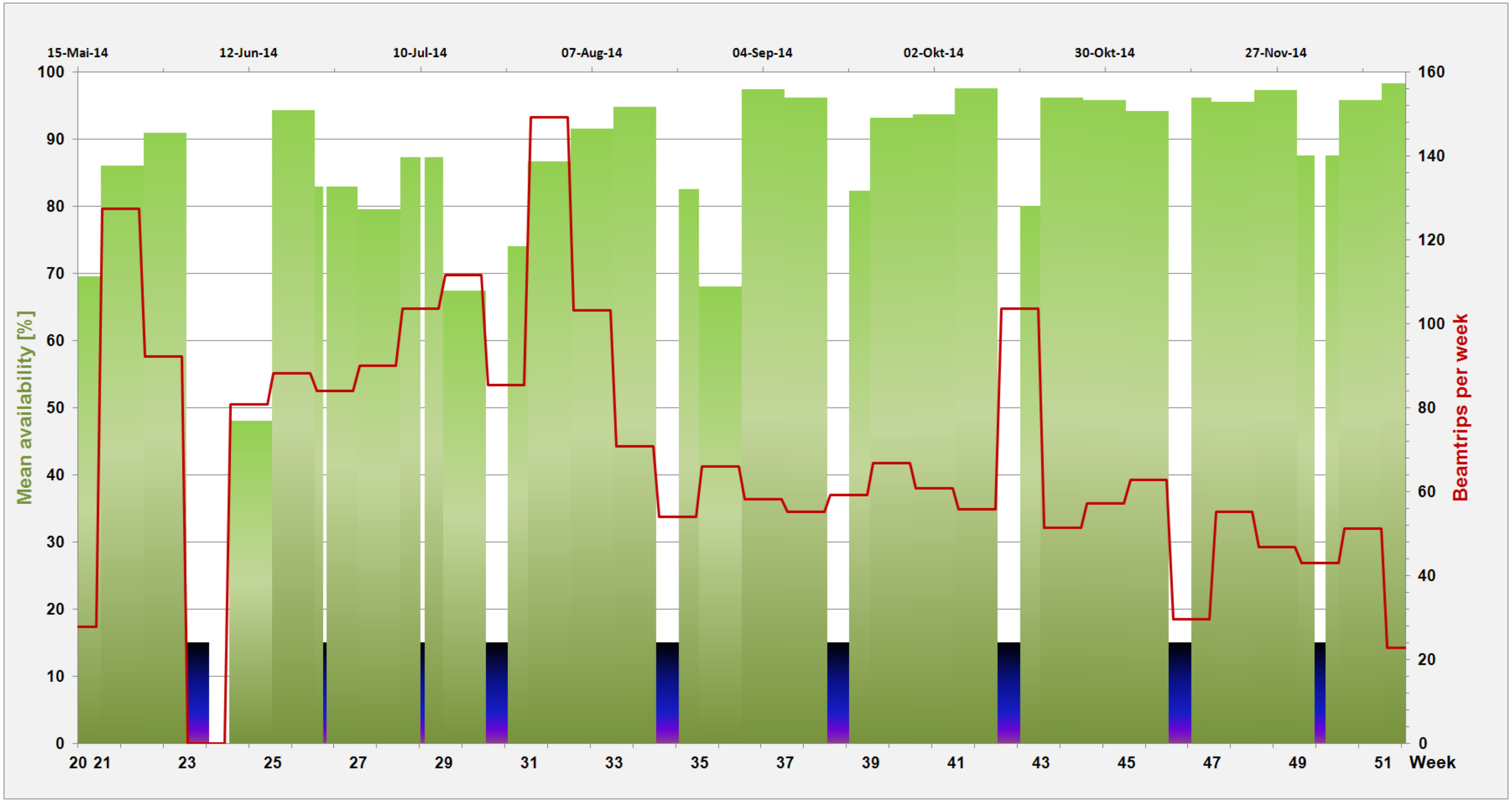


Regular operation at 2.2mA beam current
1.2 MW beam power

Operation HIPA 2014



Operation statistic HIPA 2014



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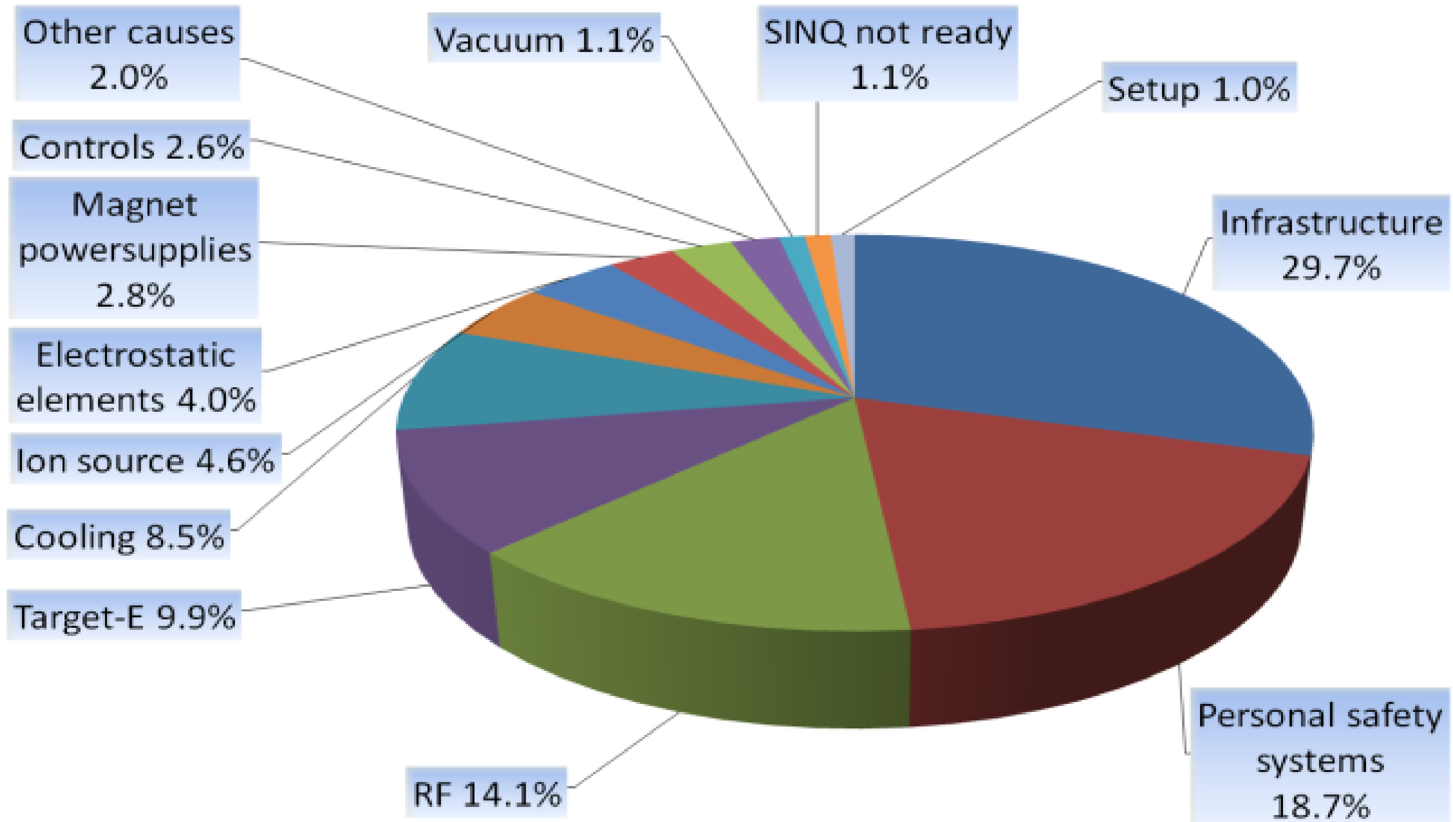
Operation statistic HIPA 2014

Beam-time statistics for HIPA	2014
Total scheduled user beam time	4608 h
Compensated outage time	+84 h
Beam current integral	
To meson production targets	9.1 Ah
To SINQ	6.0 Ah
To UCN	0.02 Ah
To isotope production targets	0.08 Ah
Outages	
Total outages (current < 1 mA, time > 5s) minutes)	520 h
Availability (with compensated outage time)	86.4%

Operation statistic HIPA 2014



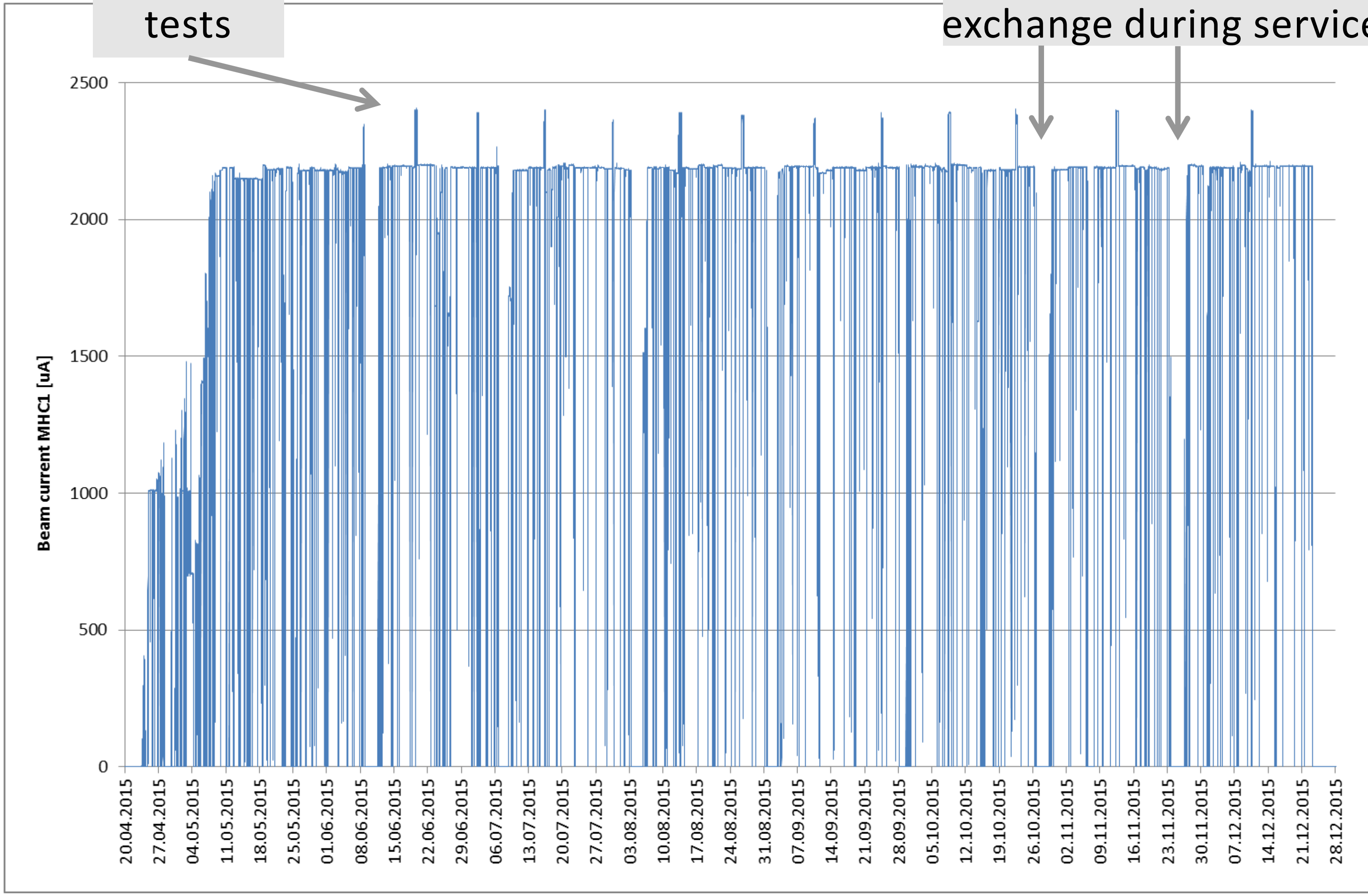
Downtime characterization for HIPA outtages longer then 5 minutes (ca. 520 hours)

Courtsey by Anton C. Mezger
Annual Report 2014, operation of the PSI Accelerator Facilites in 2014

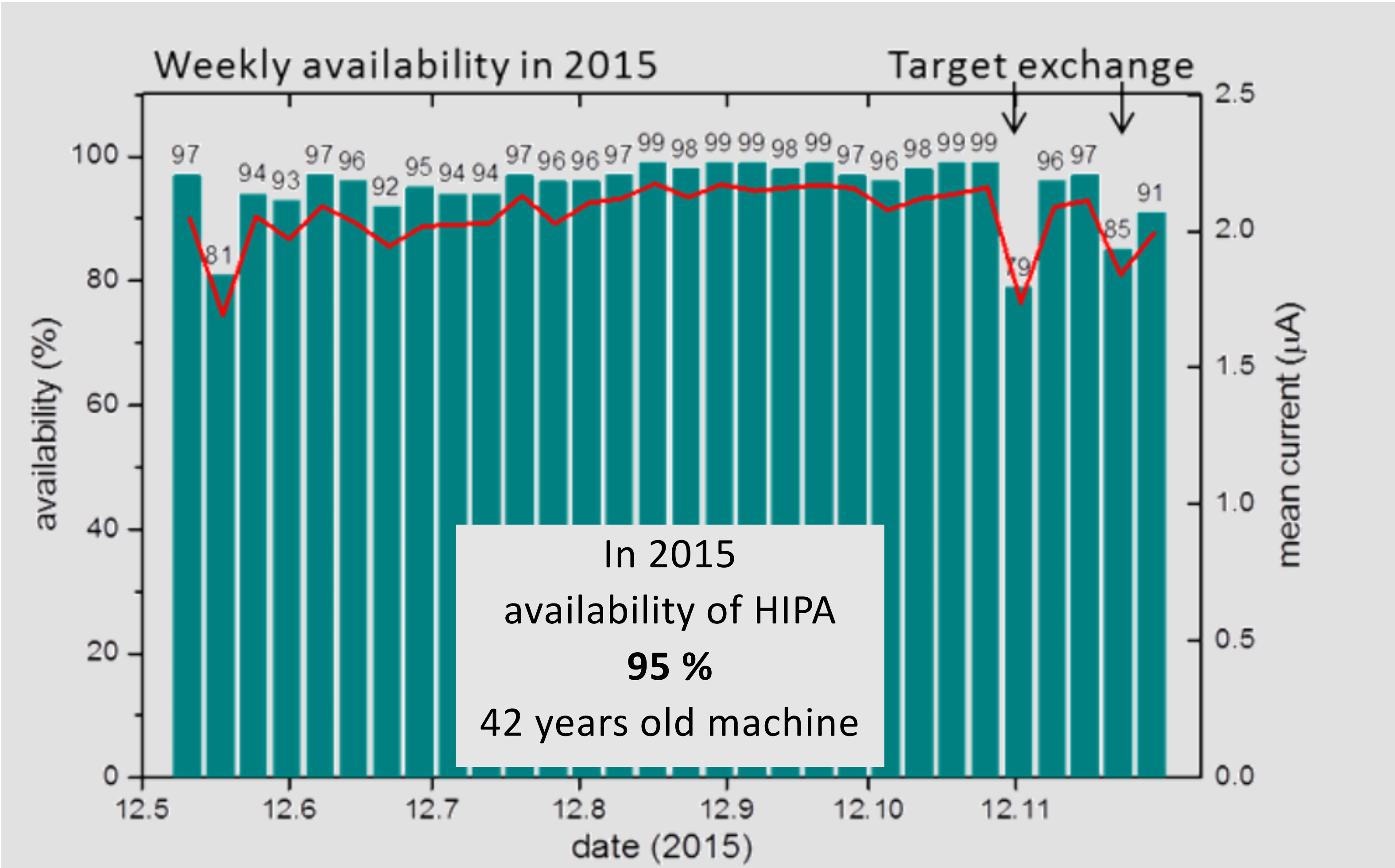
Operation HIPA 2015

High current tests

Flattop coupler vacuum leak exchange during service

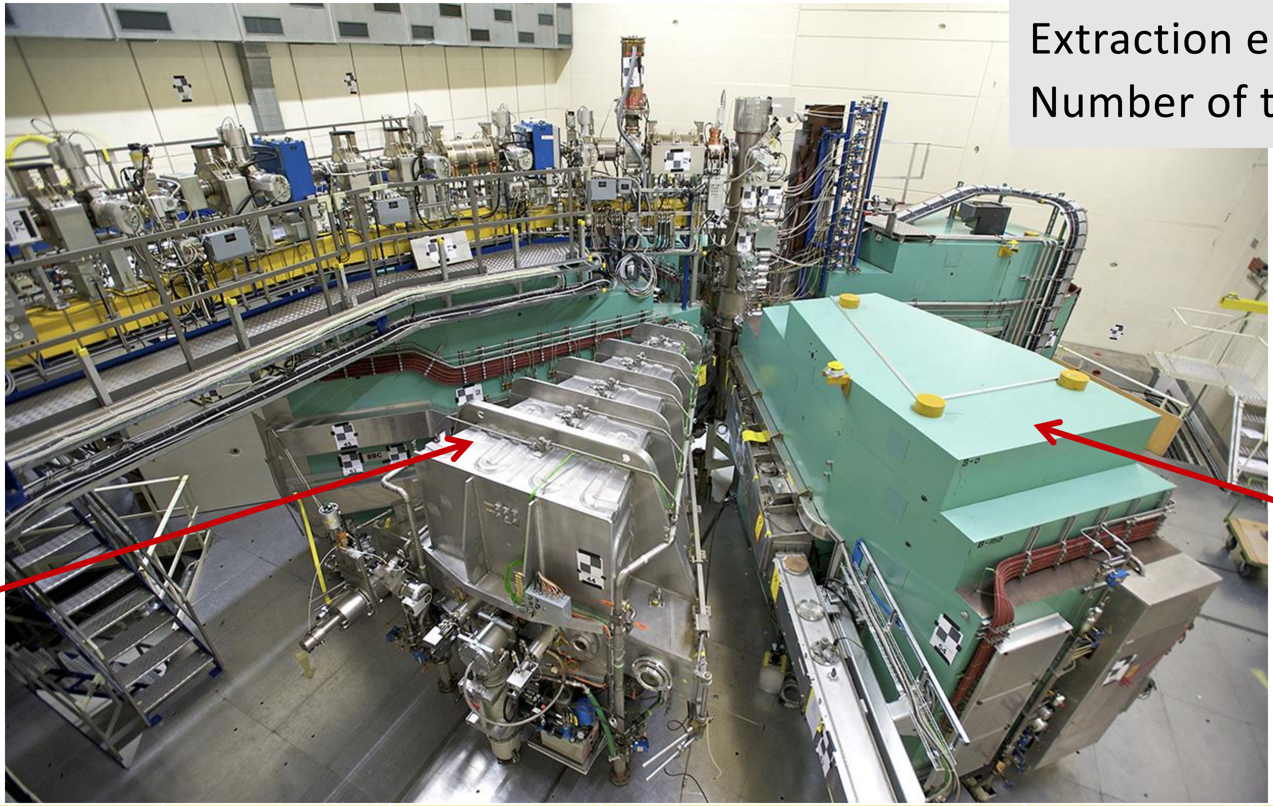


Operation statistic 2015



Injector 2 Cyclotron

Injection energy: 870 keV
Extraction energy: 72 MeV
Number of turns: 83

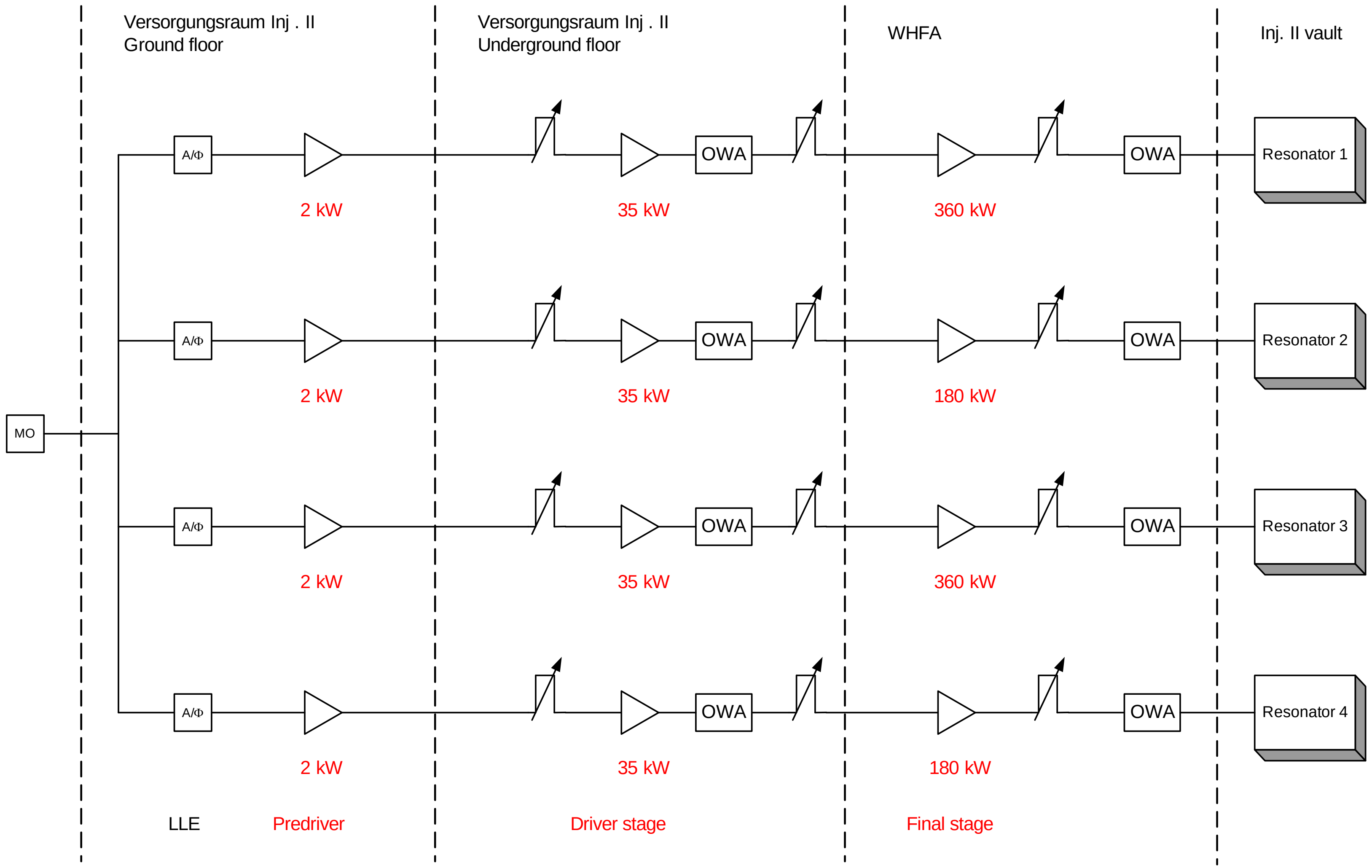


Resonator 1

sector magnet

Resonator	type	material	frequency	gap voltage	Wall losses in cavity	incident power @ 2.4 mA Beam
1 & 3	Double gap cavity	aluminum	50 MHz	~ 420 kVp	~ 150 kW	~ 225 kW
2 & 4	Flattop cavity	aluminum	150 MHz	~ 31 kVp	~ 5 kW	~ 14 kW
2 & 4 new	Single gap cavity	aluminum	50 MHz	~ 400 kVp @ extraction	~ 50 kW	

Overview new rf system for the Injector 2 cyclotron



Status upgrade Injector 2: Resonators

Test bunker had to be moved:
Old systems not any more supported
-> new psys
-> new vacuum system
-> new data acquisition system

Commissioning end of June 2016

Tests of resonator 4:
-> final design tuners
-> bridge between lips (electrodes)
-> calibration of gap voltage

Shutdown 2018:	installation of Resonator 2 as vacuum chamber
Shutdown 2019:	commissioning of new rf – system for resonator 2
	installation of Resonator 4 as vacuum chamber
Shutdown 2020:	commissioning of new rf – system for resonator 2

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Status upgrade Injector 2: Amplifiers

Installation of transmission line
for new final stages

2 x 1MW Amplifiers assembled

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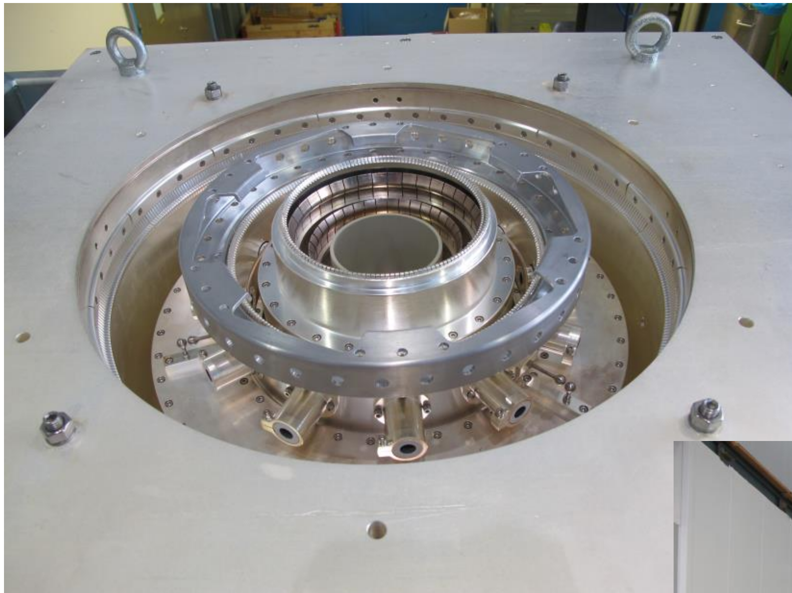
Status upgrade Injector 2: Amplifiers



Tube socket for RS2074HF

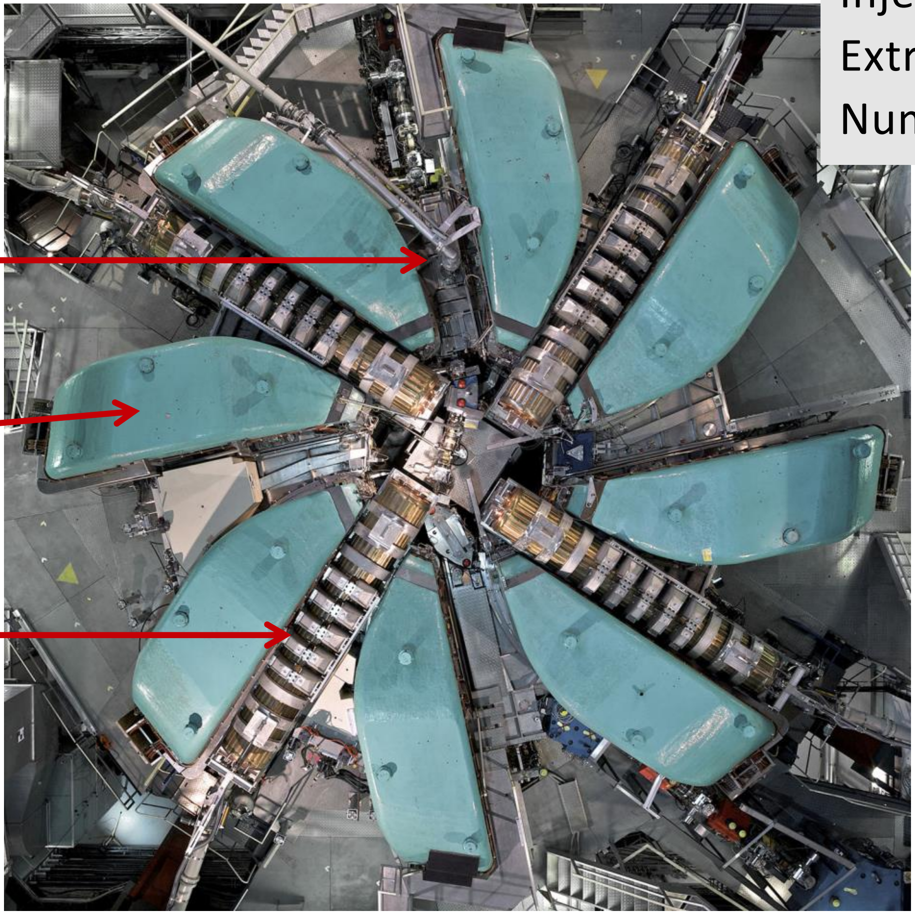
2 x 1MW amplifier
in the machine shop during assembly
finished until end of august

1 final stage tested on load

Test of 4 units until end of 2016

Ring cyclotron

Injection energy: 72 MeV
Extraction energy: 590 MeV
Number of turns: 186



flattop cavity

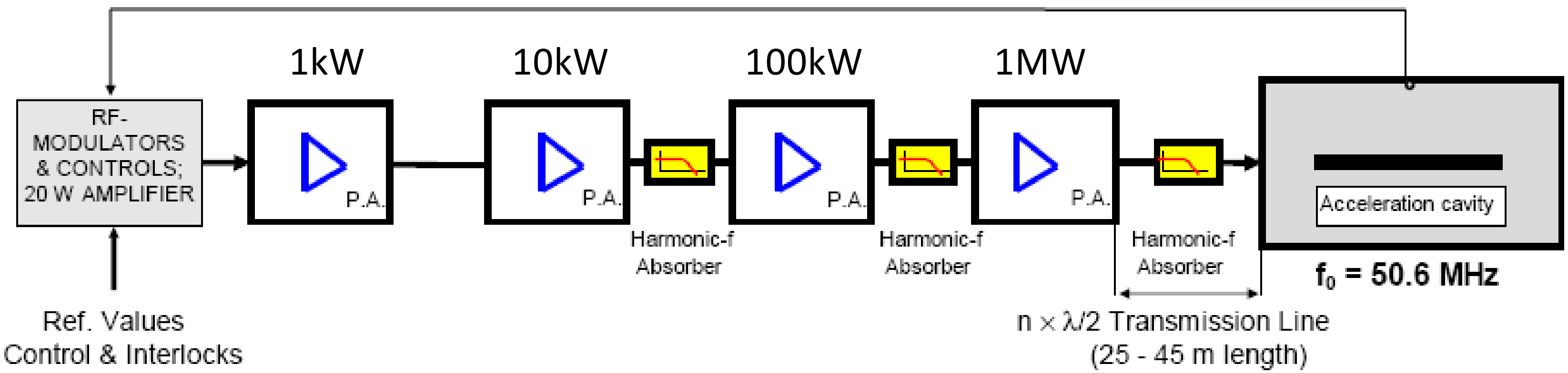
sector magnet

copper cavity

numbers	type	material	frequency	gap voltage	incident power no beam	incident power @ 2.4 mA beam
4	Main cavity	copper	50 MHz	~ 850 kVp	~ 250 kW	~ 600 kW
1	Flattop cavity	aluminum	150 MHz	555 kVp	~ 90 kW	~ - 30 kW

Amplifier chain for one copper cavity in ring cyclotron

4- STAGE POWER AMPLIFIER CHAIN, EMPLOYING POWER TETRODE TUBES



Tube Types:	**YL 1056**	**RS 2022 CL**	**RS 2074 HF**	**RS 2074 HF**
Cooling Method:	forced air	forced air	water	water

Amplifier chains built in early 90s

Some parts were taken over from old rf-system.

Filament hours counter station 3

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Spinnerei (amplifier hall)

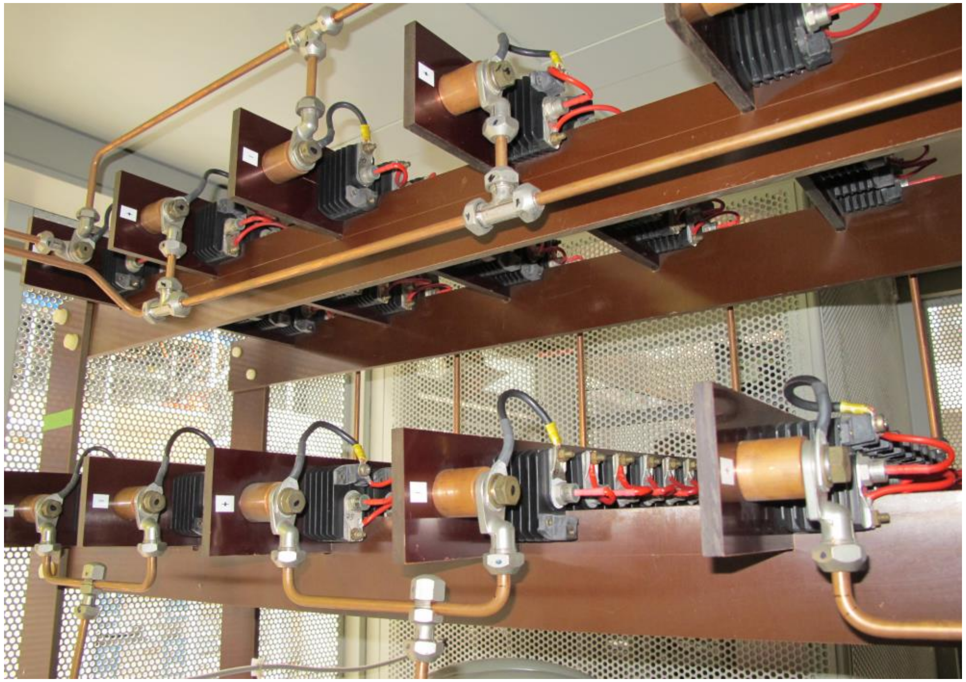
«smaller» amplifiers for the ring cyclotron

1 / 10 kW amplifier @ 50MHz

1 / 10 kW amplifier @ 150MHz

Problems Anode PS Flattop in 2014

- Resistor in filter in Anode PS overheated during failure analysis
- high losses in filter
- Missing branch in 12 pulse rectifier
- 1 Diode was blown up
- 5 Diodes had a short



- Inspection of all diodes in
  100kW Anode PS
  by measuring isolation
- Shutdown 2015
  600 diodes tested.

Unscheduled downtime in 2015 caused by rf

system	component	failure	downtime
Cav. 1	solid state amplifier	fan failure	45’
Cav. 2	100kW amplifier	resistor in Anode PS	45’
Cav. 2	1kW amplifier	tetrode failure (G1-G2 short)	1h
Cav. 4	coupler & all amplifiers	arc on coupler, AC/DC over current in PS, trip of several circuit breakers	3h 51’
Cav. 1	1MW amplifier	fan failure Anode PS	3h
Cav. 1 – 4, FT	HF0	cooling circuit for tetrodes	1h 19’
Cav. 1	1MW amplifier	breakdown in capacitor amplifier replaced	2h 30’
Cav. 1 – 4, FT	HF0	insufficient cooling power, wrong operation mode	24’ + 9’
Cav. 1	1kW amplifier	arc in tetrode	9’
Cav. 2	100kW amplifier	tetrode failure (G1-K short) tube replaced	2h 11’
Cav. 4	100kW amplifier	UG2 PS capacitor	4h

Unscheduled downtime in 2015 caused by rf

Night / Weekend

During working hours

system	component	failure	downtime
Cav. 1	solid state amplifier	fan failure	45’
Cav. 2	100kW amplifier	resistor in Anode PS	45’
Cav. 2	1kW amplifier	tetrode failure (G1-G2 short)	1h
Cav. 4	coupler & all amplifiers	arc on coupler, AC/DC over current in PS, trip of several circuit breakers	3h 51’
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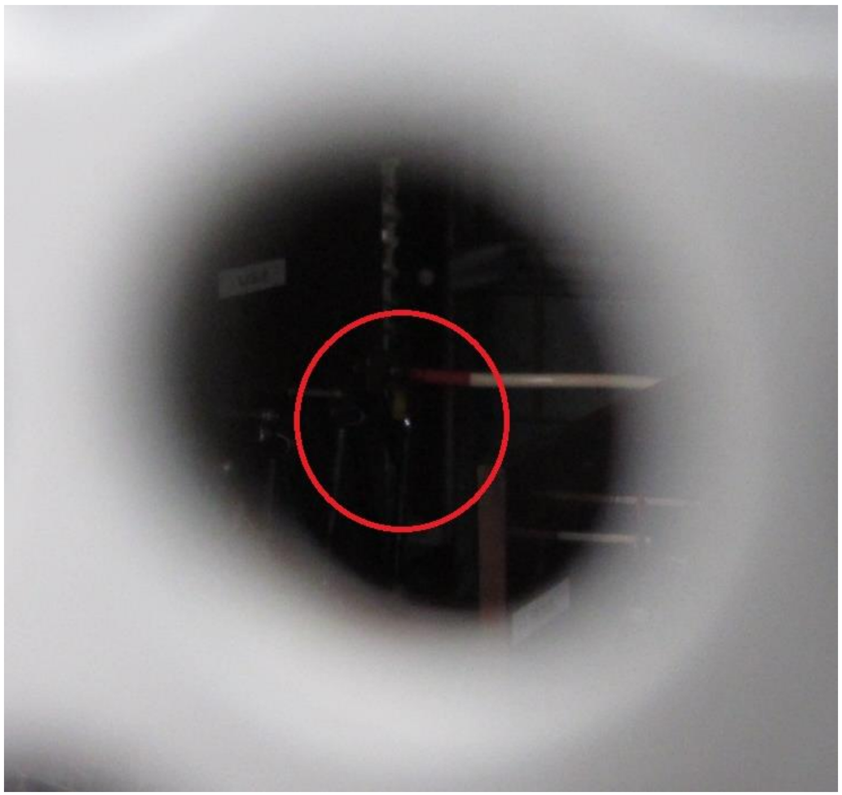
Cav. 4	100kW amplifier	UG2 PS capacitor	4h

Cav. 2 100kW amplifier resistor in Anode PS

Never walk through the amplifier hall on Friday at 18:30……



Spark on HV divider in anode power supply due to broken wire at resistor.
19:15 Beam off, rf off, start of repair

Cav. 2 1kW amplifier tetrode failure

After repair on the same Friday at 20:00……

- tetrode in 1kW amplifier had short between grid and screen
- replaced by new one

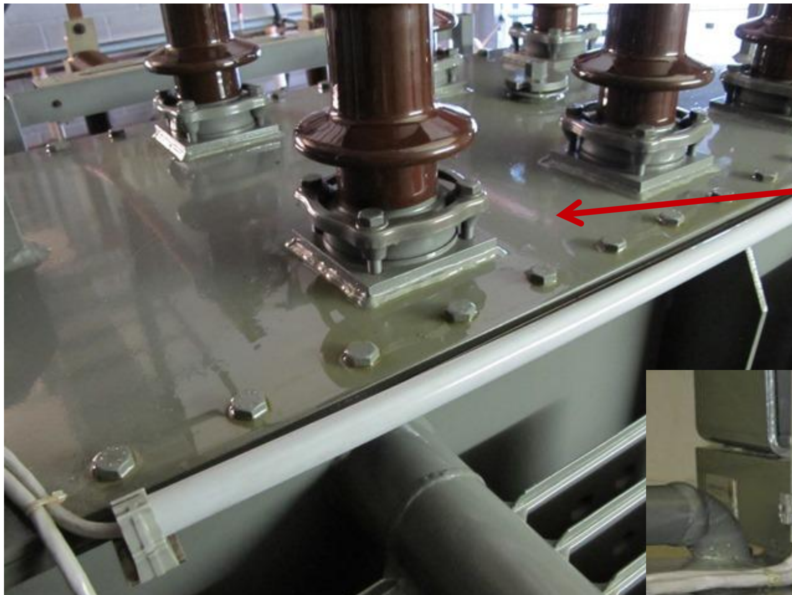
21:00 back on operation with beam

Cav. 1 1MW amplifier fan failure Anode PS

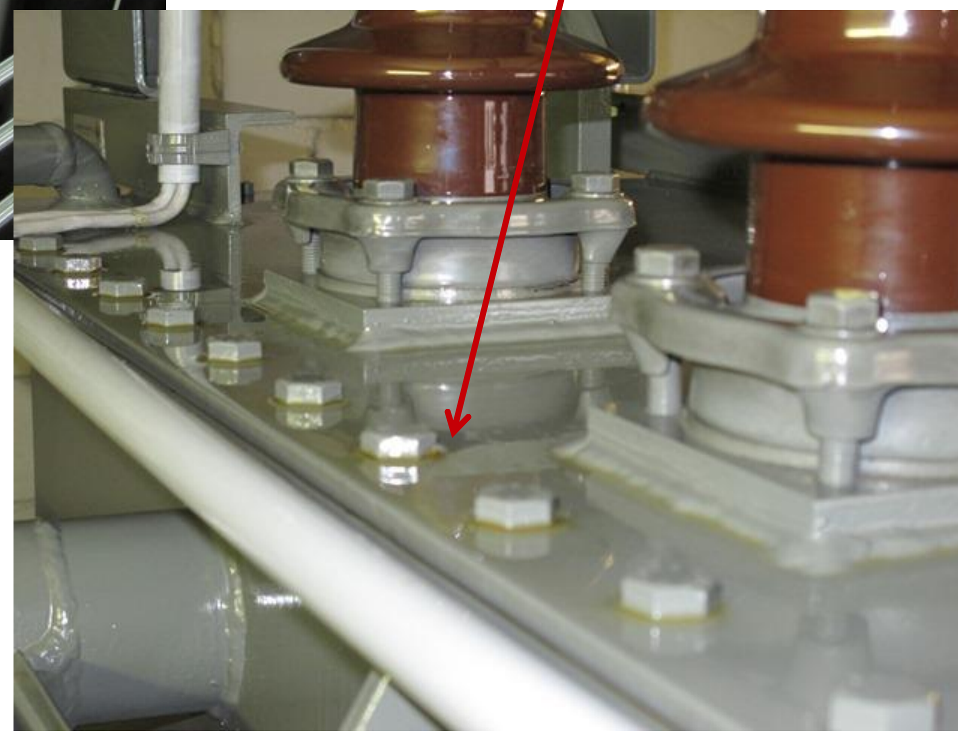
Fan for transformer cabinet was running only on lower speed.
No spare part in house.

Improved cooling by a party tent.

Oil leaking transformer Anode PS



oil film on transformer
leaking isolator

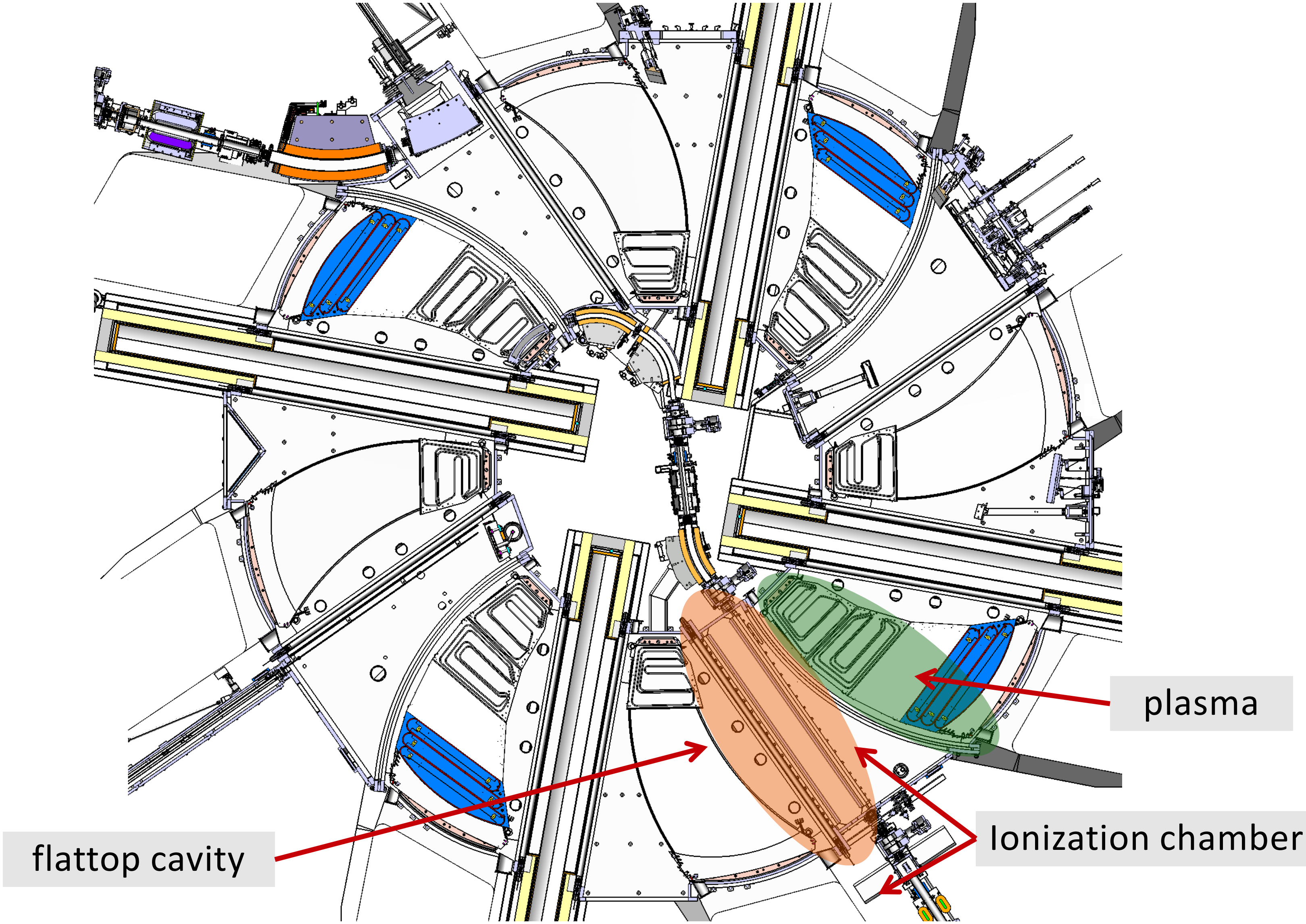


Transformer built in 1984
Replaced shutdown 2016

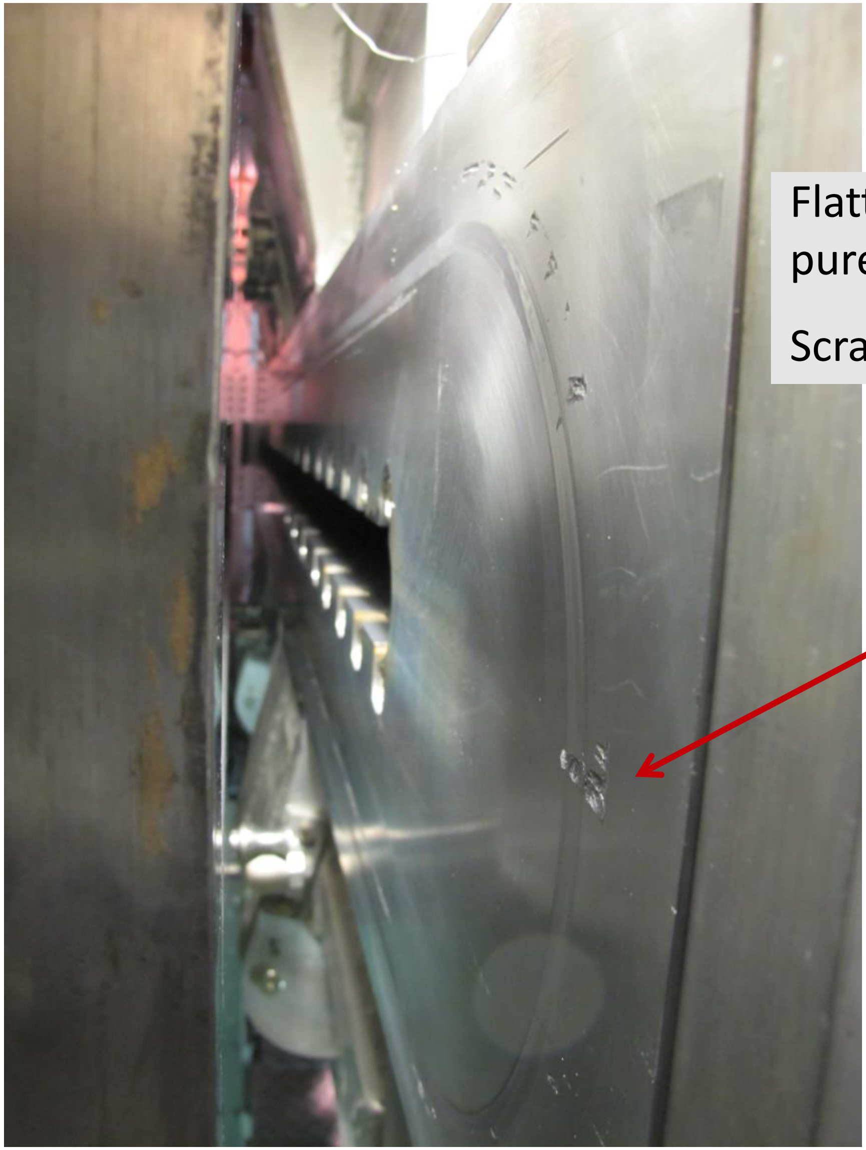
New transformer in Anode PS station 3

Transformer installed during shutdown 2016

Flattop problems



Flattop cavity



Problems to get a good vacuum

Flattop cavity
pure aluminum

Scratches from vacuum sealing

How a vacuum surface should not look like

Machining / smoothing surface in 20?? for good surface for the vacuum o-ring sealing

Flattop cavity

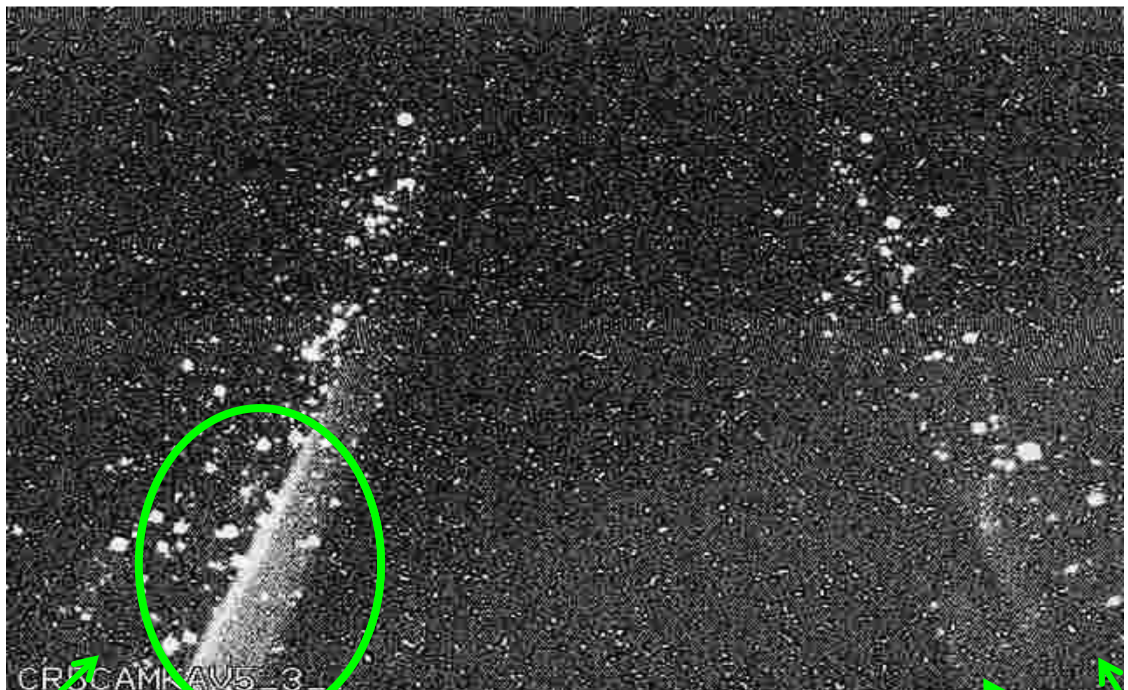
Shutdown 2015

- remove cavity -> necessary preparations for defining machining process
- refurbish hydraulic tuning system
- Improve vacuum (new square sealing)
- painting with Aquadag

Flattop cavity shutdown 2015

- Cavity was reinstalled in cyclotron
- During conditioning for the nominal voltage 15 kW more power needed.
- High losses on ionization chambers

glowing between lips



lips

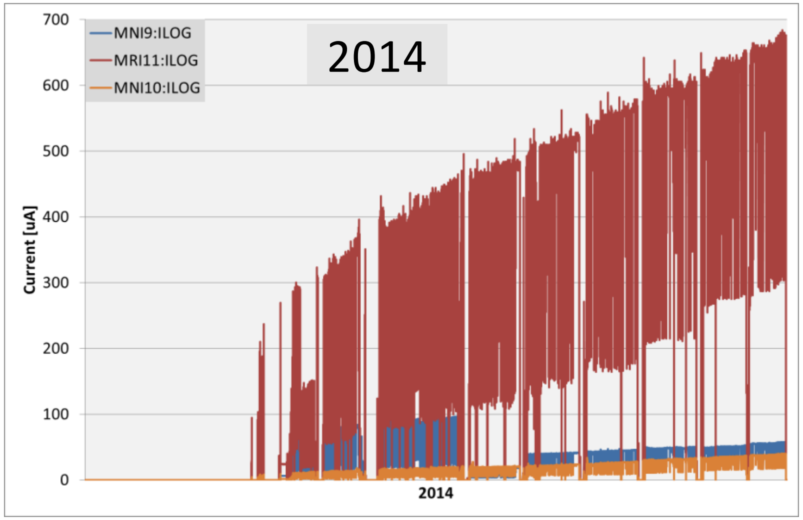
lips

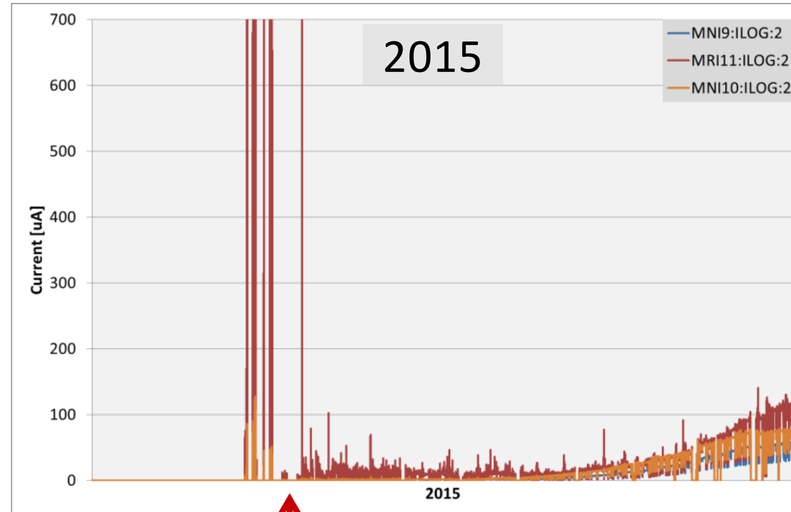
picture take with camera during rf on
view inside cavity towards center

Painting inside flattop cavity and….

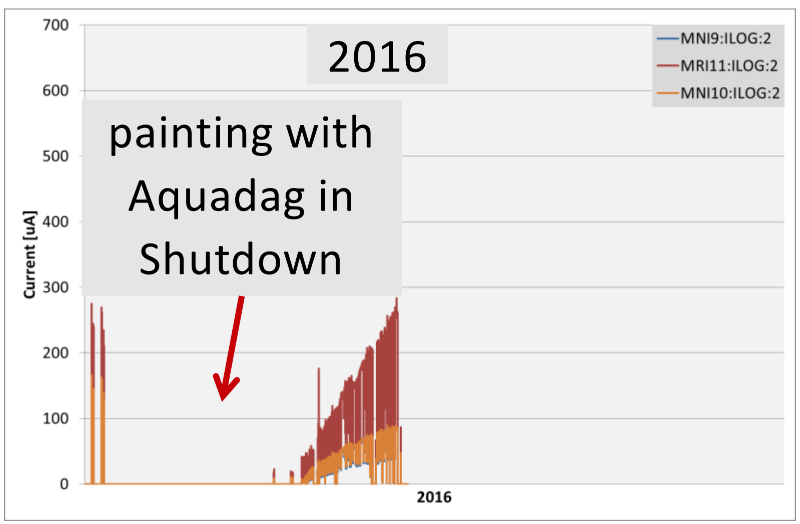
Painting inside vacuum chamber and lips

Ionization chambers around flattop cavity





painting with Aquadag



- Ionization chambers to determine losses of beam.
- Ionization chambers around Flattop are disturbed by X-ray from flattop cavity.

Operation parameters Ring rf without beam

		cavity 1	cavity 2	cavity 3	cavity 4	flattop cavity
gap voltage	kVp	782	844	848	882	454
1MW P forward	kW	225	250	280	265	110
1MW P reflected	kW	17	16	20	17	9.9
VSWR		1.76	1.68	1.73	1.68	1.86
100kW P forward	kW	7	7.5	6	6	6.5
100kW P reflected	kW	0.2	0	0.2	0.1	0.09
1MW P in driver	kW	6.8	7.5	5.8	5.9	6.41
1MW P produced	kW	218	243	274	259	104
1MW U Anode	kV	15.9	15.9	16.5	16	11.5
1MW I Anode	A	23.8	23.3	25.4	25.4	16.6
1MW P Anode DC	kW	378	370	419	406	191
1MW Anode PS 16kV grid power	kW	413	413	456	435	
tetrode cooling water inlet temperature	°C	53.6	53.5	53.7	53.4	54.8
tetrode cooling water outlet temperature	°C	66.6	63.8	65.3	63.9	66.9
tetrode cooling water delta temperature	°C	13.0	10.3	11.6	10.5	12.1
tetrode cooling water flow rate	l/min	213	227	221	231	112
P calorimetric	kW	194	163	179	170	95
efficiency RF/DC		**0.58**	**0.65**	**0.65**	**0.64**	**0.54**
efficiency RF/AC 16kV Mains		**0.53**	**0.59**	**0.60**	**0.60**	

Operation parameters Ring rf with beam 2.4mA

		cavity 1	cavity 2	cavity 3	cavity 4	flattop cavity
gap voltage	kVp	844	842	846	889	553
1MW P forward	kW	649	620	640	625	36
1MW P reflected	kW	22.5	32	21	30	22
VSWR		1.46	1.59	1.44	1.56	8.16
100kW P forward	kW	35	35.5	34	34	0.4
100kW P reflected	kW	1.2	0.05	1.1	1.5	0.4
1MW P in driver	kW	33.8	35.45	32.9	32.5	0
1MW P produced	kW	615	585	607	593	36
1MW U Anode	kV	15.9	15.9	16.5	15.9	11.5
1MW I Anode	A	57.1	55.7	58.3	57.7	4.8
1MW P Anode DC	kW	908	886	962	917	55
1MW Anode PS 16kV grid power	kW	1002	995	1052	1016	
tetrode cooling water inlet temperature	°C	54.2	53.6	54.2	54.1	55.3
tetrode cooling water outlet temperature	°C	79.7	77.4	79.1	76.2	60.4
tetrode cooling water delta temperature	°C	25.5	23.8	24.9	22.1	5.1
tetrode cooling water flow rate	l/min	210	220	219	228	107
P calorimetric	kW	374	367	382	353	38
efficiency RF/DC		**0.68**	**0.66**	**0.63**	**0.65**	**0.65**
efficiency RF/AC 16kV Mains		**0.61**	**0.59**	**0.58**	**0.58**	

Power efficiency rf systems for the Ring cyclotron

	filament on	no Beam	2.4 mA beam current
forward rf power			
cavity 1		225 kW	649 kW
cavity 2		250 kW	620 kW
cavity 3		280 kW	640 kW
cavity 4		265 kW	625 kW
Flattop cavity		110 kW	14 kW
Total rf power	**0 kW**	**1130 kW**	**2548 kW**
grid power			
Anode PS 1		413 kW	1002 kW
Anode PS 2		413 kW	995 kW
Anode PS 3		456 kW	1052 kW
Anode PS 4		435 kW	1016 kW
power distribution WSGA	181 kW	526 kW	533 kW
total grid power	**181 kW**	**2244 kW**	**4599 kW**
efficiency	**0**	**0.50**	**0.55**

Total filament power
~ 100kW

Including all rf systems (llrf, tuning system, control system, forced air cooling, transmission line cooling, load for flattop).

Not included power for water cooling circuits.

Cooling system for tetrodes HF0

Cooling circuit HF0 for tetrode amplifiers for the ring cyclotron

- Demineralized water
- Inlet temperature at tube 55°C
- Outlet temperature up to 80°C
- Heat recovering system

  in 2015 -> 3357 MWh recovered

  Suppling ¼ of heat for PSI buildings

  (Shutdown from Christmas to April)

Tetrodes

RS2022CL

RS2074HF

Overview amplifiers for the Injektor 2 cyclotron

amplifier	tube	Res.1	Res.2	Res.3	Res.4	Spare
1kW / 15kW @ 50MHz Zarat, PSI upgrade	YL1056 RS2026CL	1		1		
300kW / 50 MHz Telefunken, PSI upgrade	RS2074HF	1		1		1
1kW / 10kW @ 150 MHz Zarat, PSI upgrade	RS1054L RS2022CL		2			
0.5 / 5 / 70 kW @ 150MHz Philips, PSI upgrade	YL1056 RS2022CL RS2004J				1	

Overview amplifiers for the Ring cyclotron

amplifier	tube	main cavities	flattop cavity	test	spare
1kW / 15kW @ 50MHz Zarat, PSI upgrade	YL1056 RS2024CL			1	
1kW / 10kW @ 50MHz Telefunken, PSI upgrade	YL1056 RS2022CL	4			1
100kW / 50 MHz Telefunken, PSI upgrade	RS2074HF	4		1	
1MW @ 50 MHz PSI	RS2074HF	4		1	1
1kW / 10kW @ 150 MHz Zarat, PSI upgrade	RS1054L RS2022CL		1		1
150kW @ 150MHz PSI	RS2004J		1		1

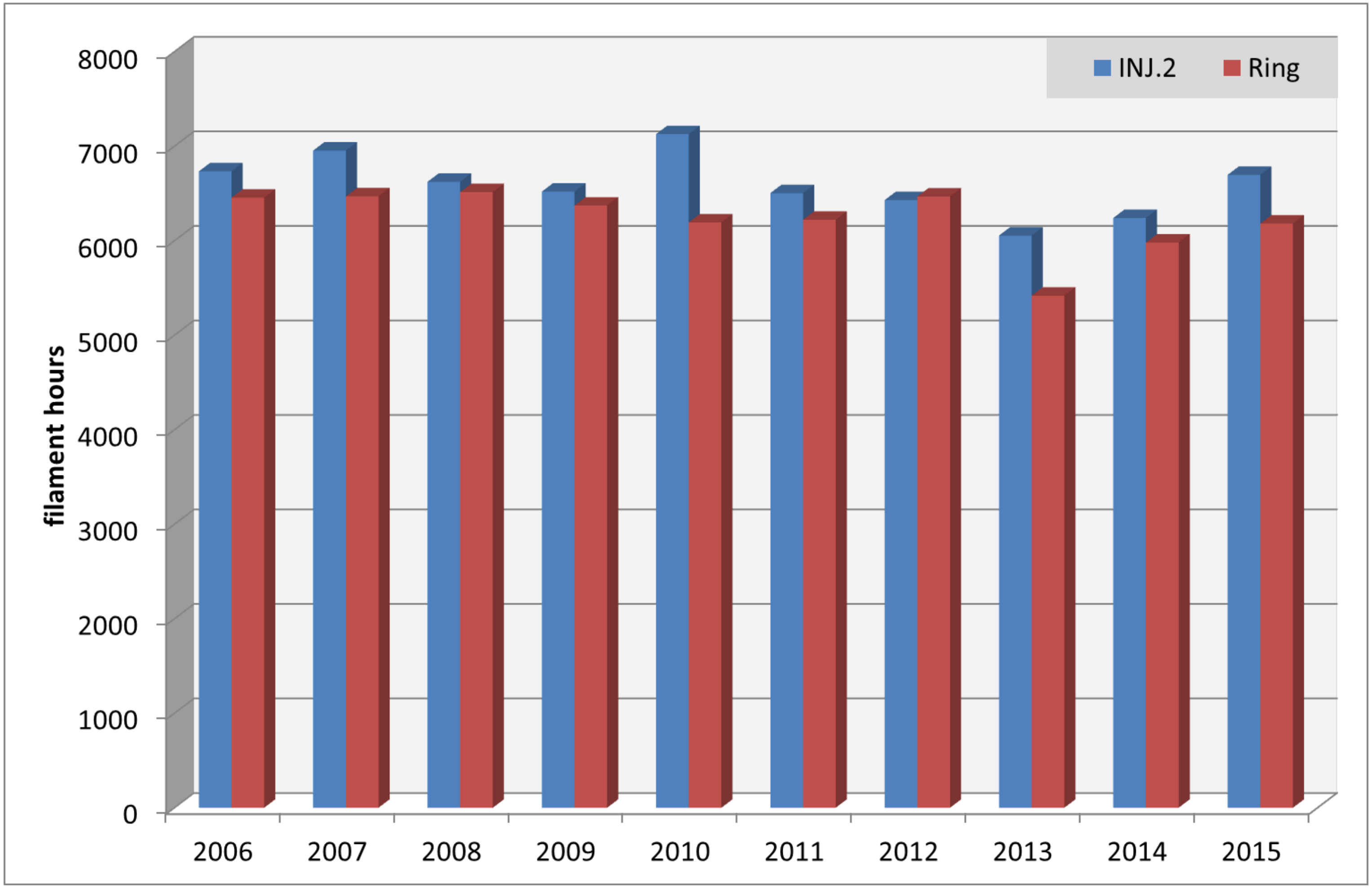
Tetrodes in operation at HIPA

type	cooling	numbers
YL1056	Air	7
RS1054L	Air	3
RS2022CL	Air	8
RS2026CL	Air	2
RS2074HF	water	10
RS2004J	water	2

All tubes are primary design of Siemens,
nowadays produced by Thales Electron Devices.

Amplifiers on test stand not included.

Operating hours per year



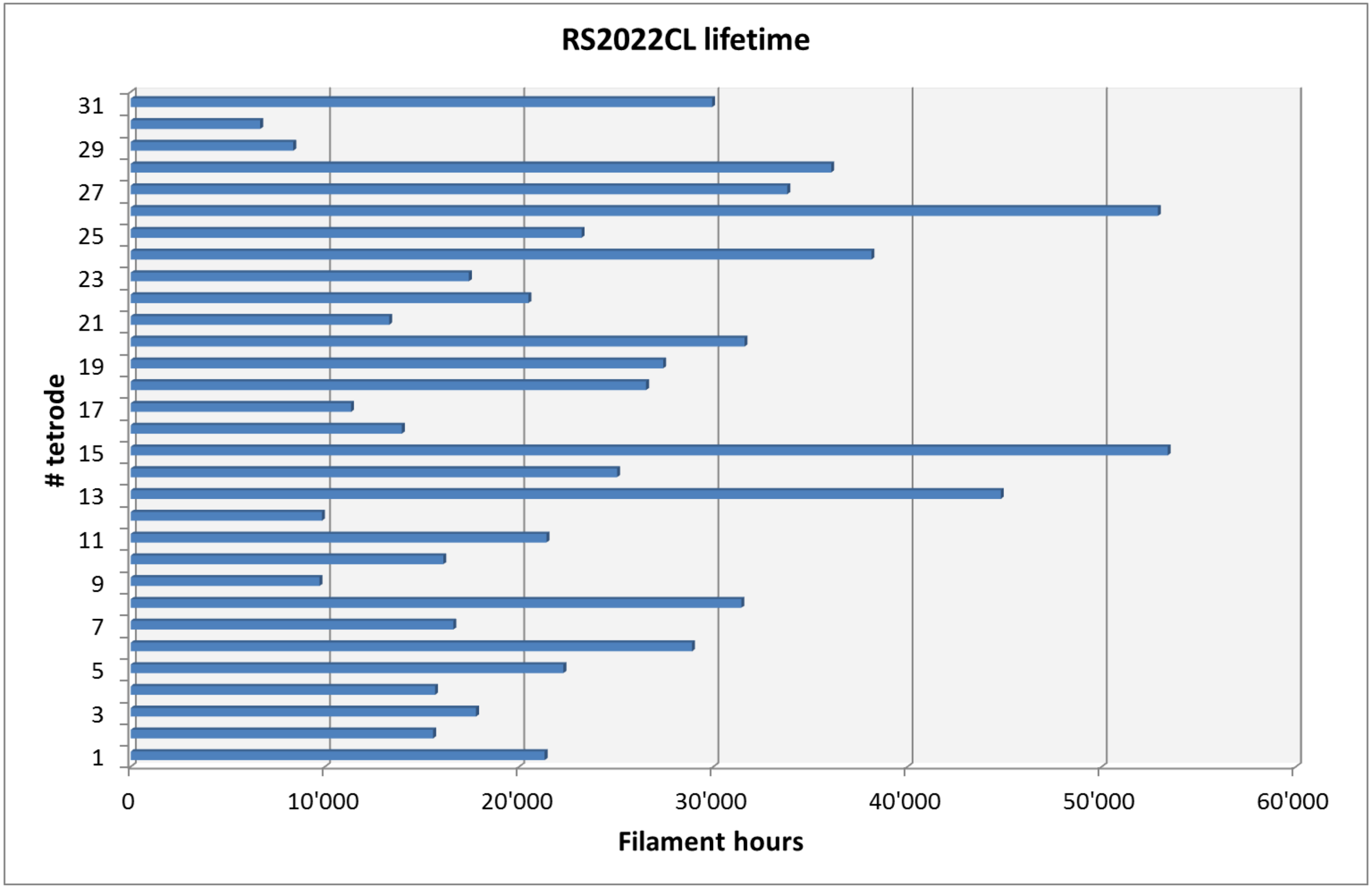
Tetrode lifetime

- Minimize switching of filament on/off
  On maintenance day tetrodes kept on nominal filament power

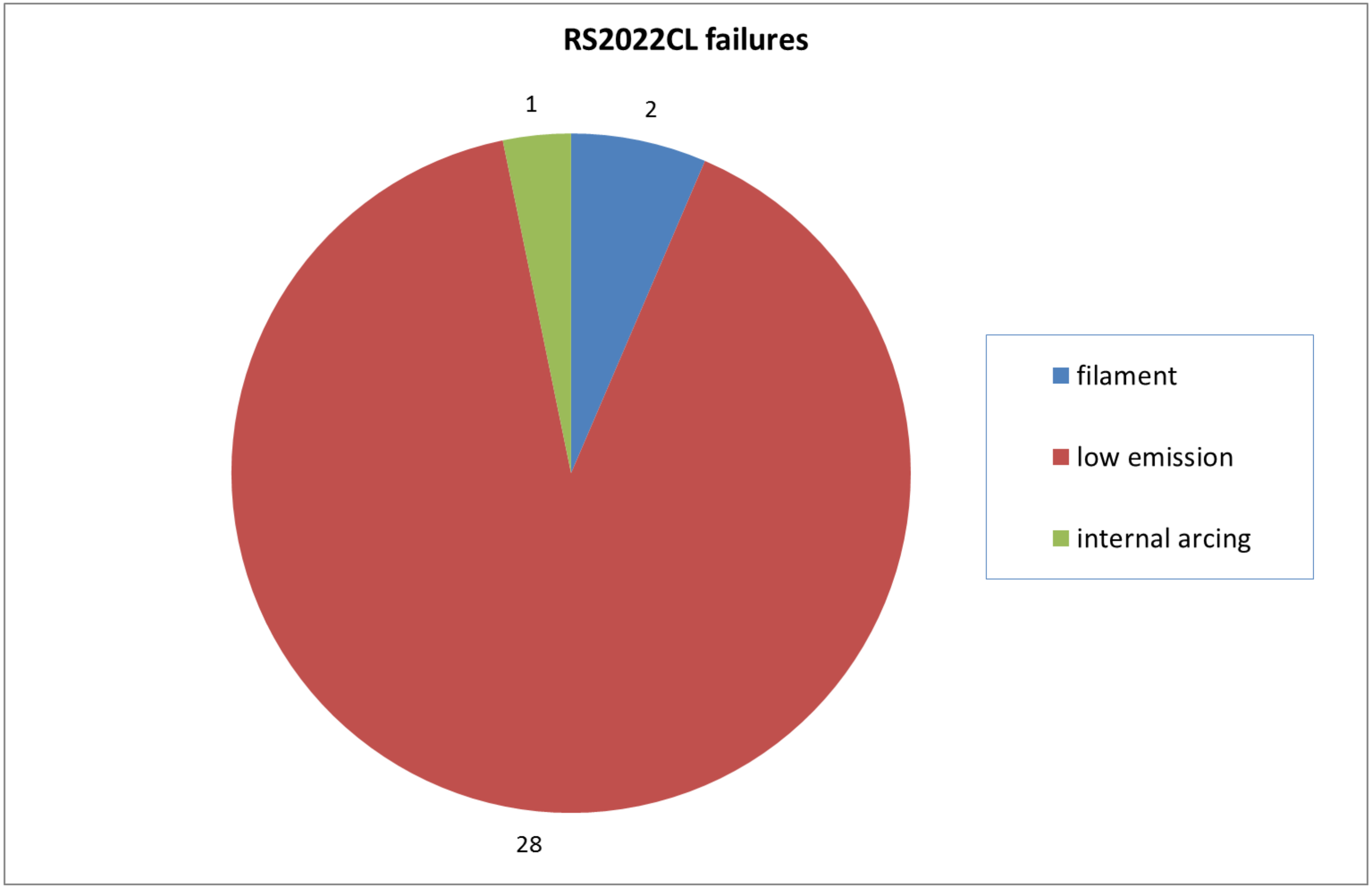
- Under heating of tubes extends lifetime.
  Nominal voltage – 5 to 10%

- For the Ring cyclotron final stage (1MW) and driver (100kW) are using the same tube RS2074HF.
  New tubes are installed in final stage, after 5 to 6 years tubes are replaced. Old tubes run until their end of life in driver.

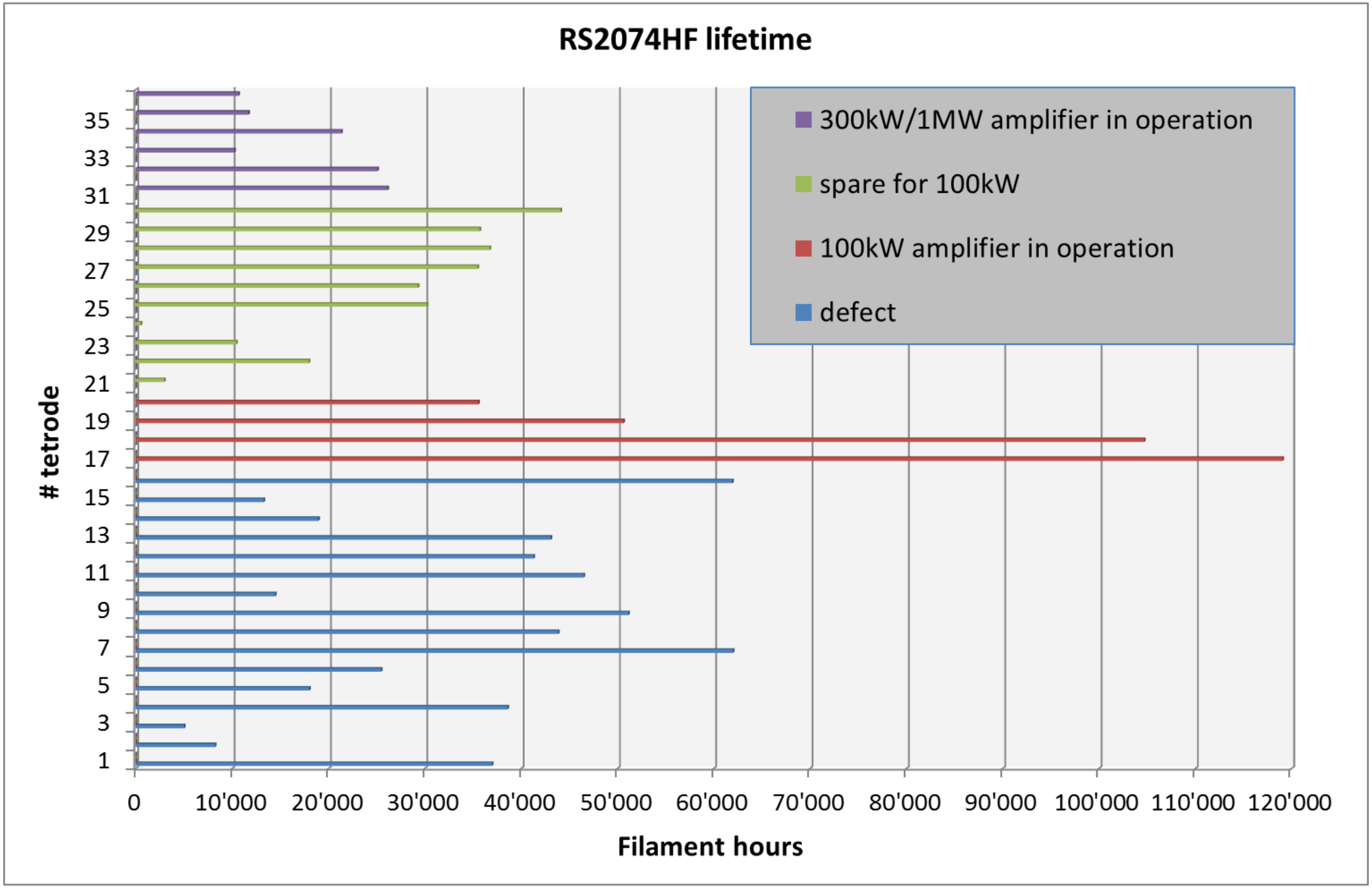
Tetrode lifetime statistic RS2022CL



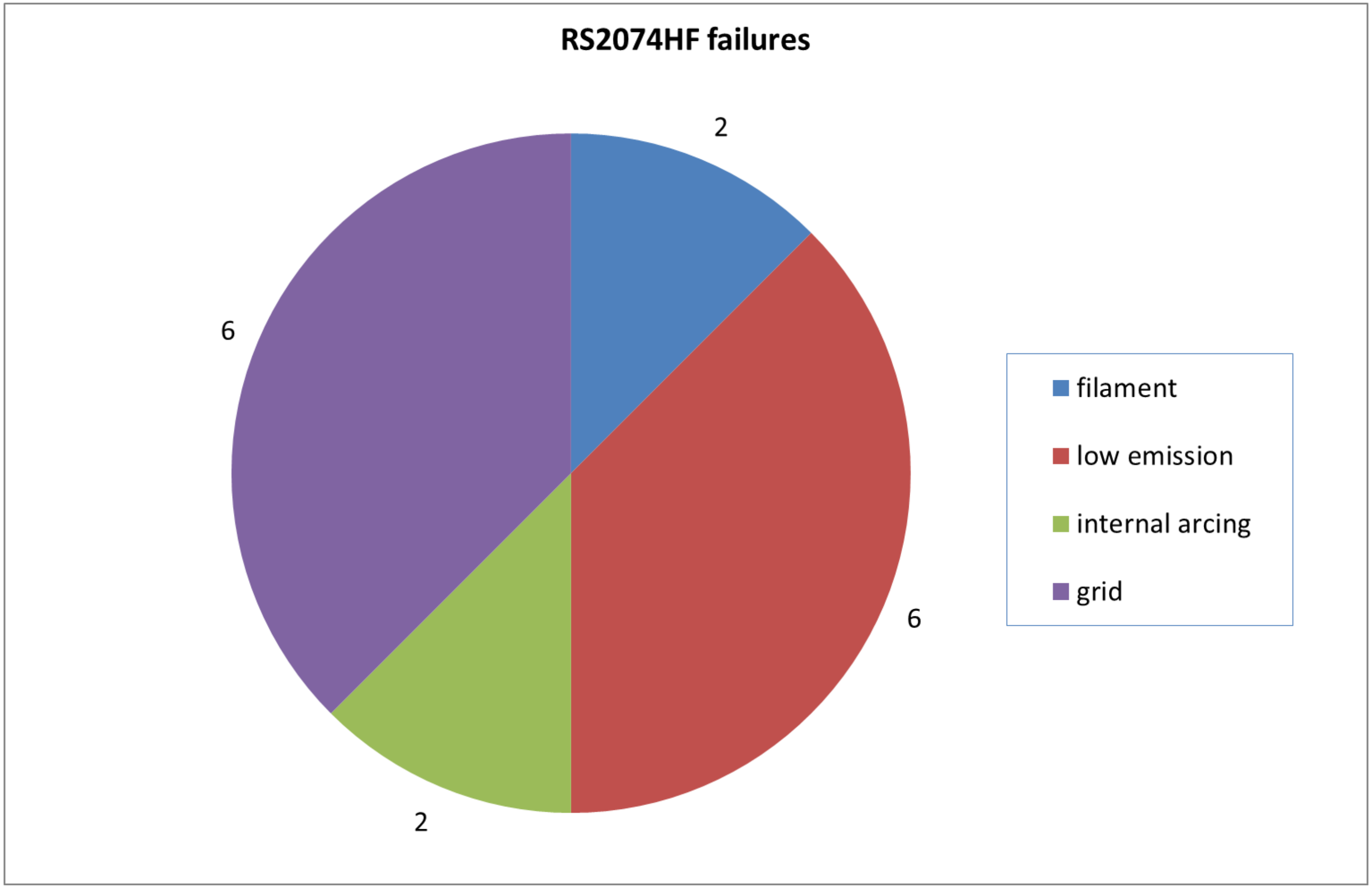
Tetrode cause of failure RS2022CL



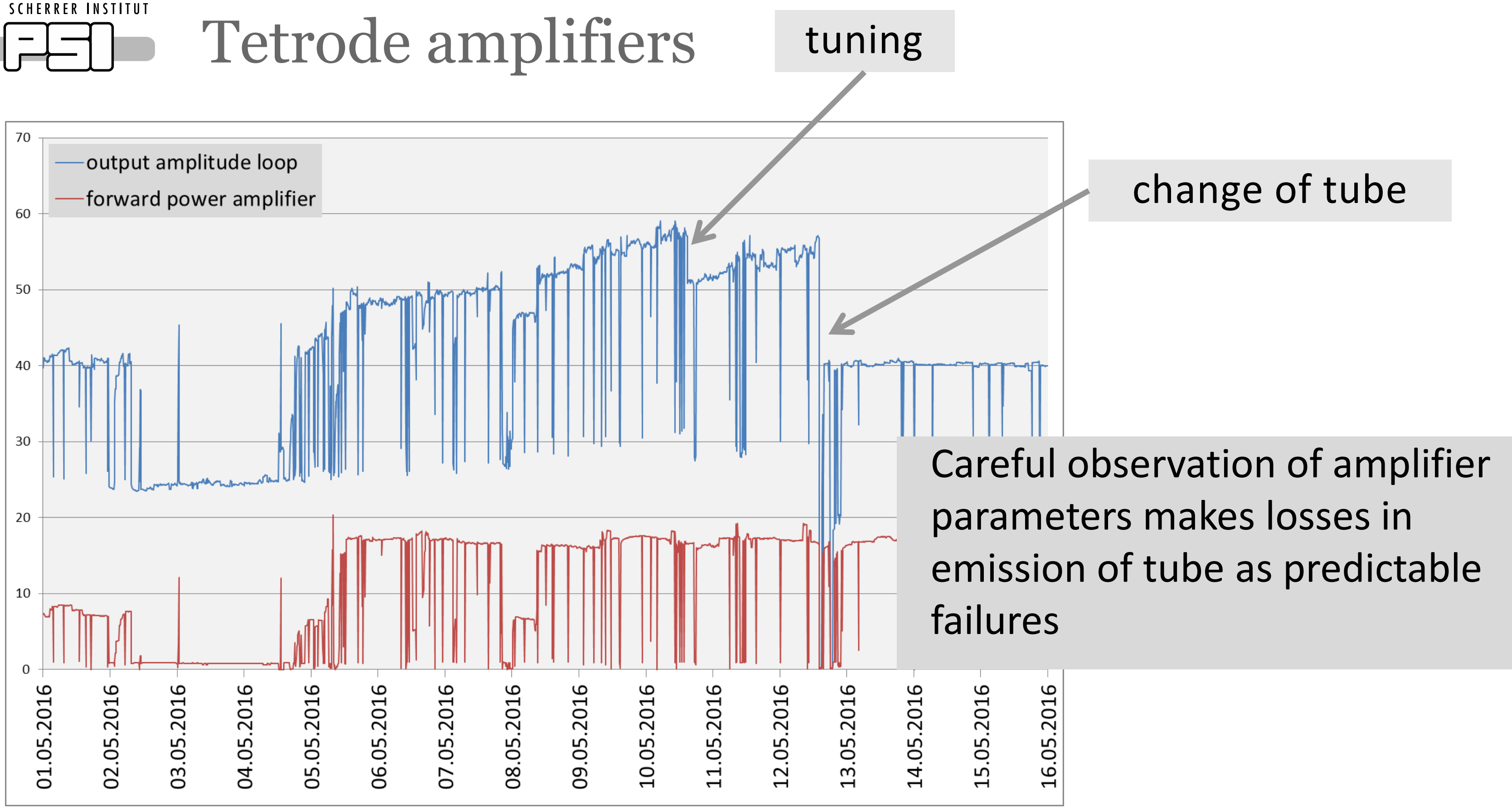
Tetrode lifetime statistic RS2074HF



Tetrode cause of failure RS2022CL



Tetrode amplifiers



- Broken filament, short between grid/screen or grid/cathode are unpredictable failures
- Trained stuff to handle tubes, high voltage and amplifier tuning is needed.

Wir schaffen Wissen – heute für morgen

My thanks go to the HIPA rf support team

- Hansreudi Fitze
- Wolfgang Tron
- Andreas Stadler
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- Oliver Brun
- Sebastian Jetzer
- Arthur Schmidheiny
- Erich Wüthrich
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- Stefan Mair
- Andreas Hauff