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M. Pedrozzi :: In behalf of the PSI RF group :: Paul Scherrer Institute

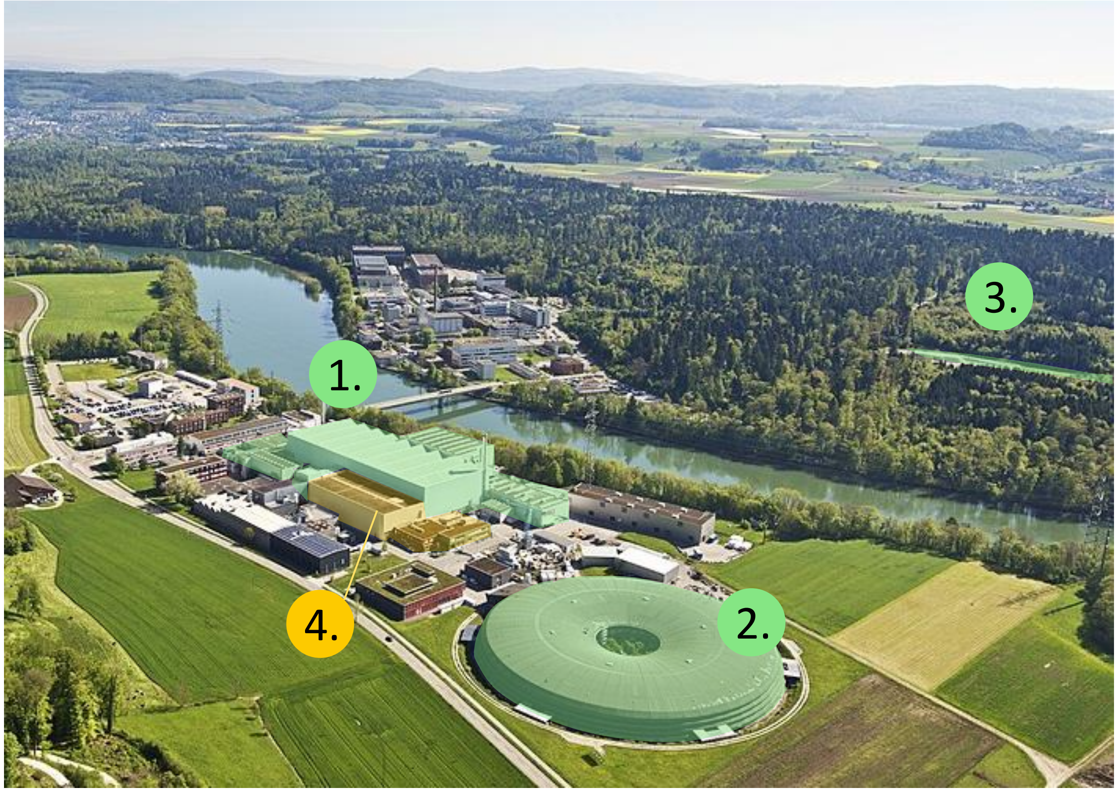
Overview PSI RF Systems power consumption

Workshop on efficient RF sources - July 4-6 2022

PSI's accelerators in the landscape

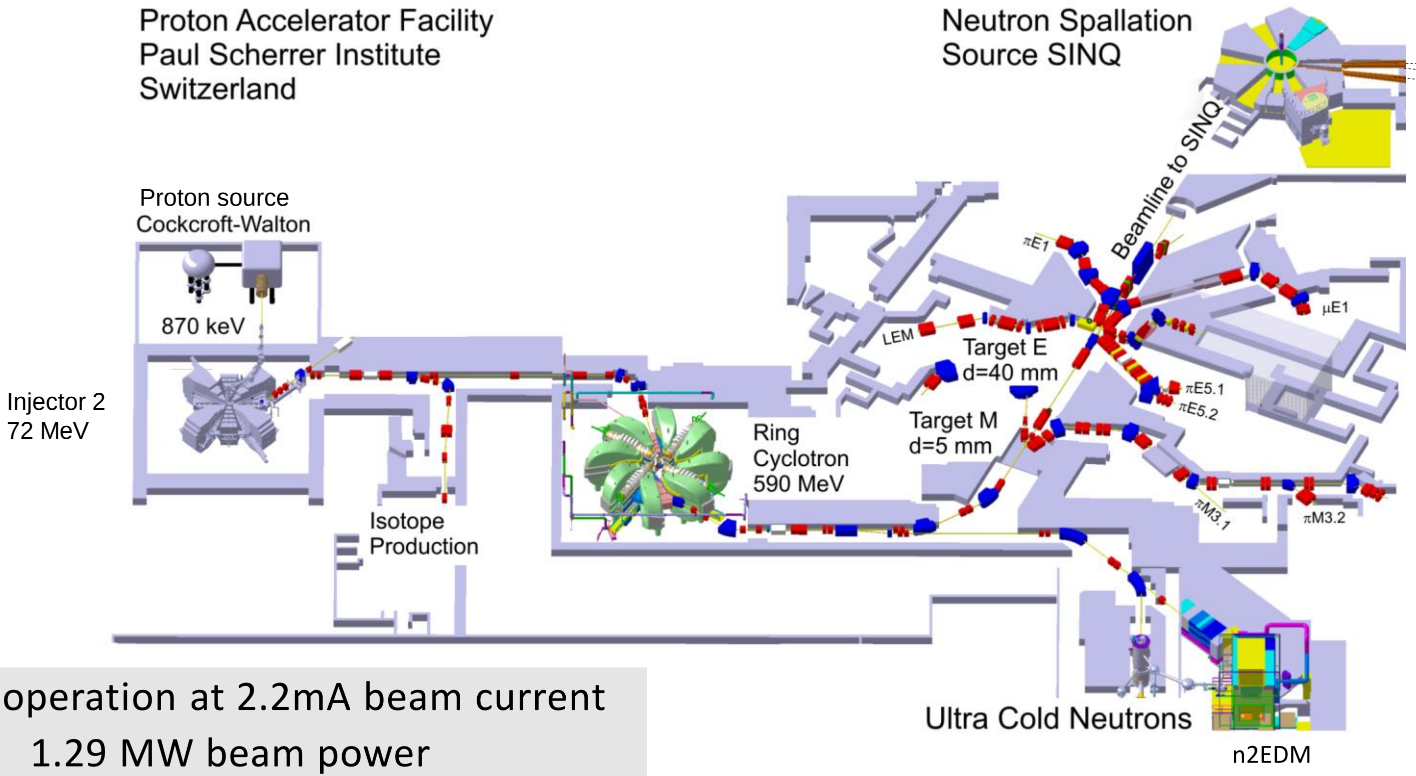
1. HIPA ~52’000 MWh/year
   (High Intensity Proton Accelerator)
2. SLS ~16’000 MWh/year
   (Swiss Synchrotron Light Source)
3. SwissFEL ~22’500 MWh/year
   (Swiss X-Ray Free Electron Laser)

4. PROSCAN ~4’700 MWh/year
   (Proton therapy, not handled here)



Overview High Intensity Proton Accelerator

1.



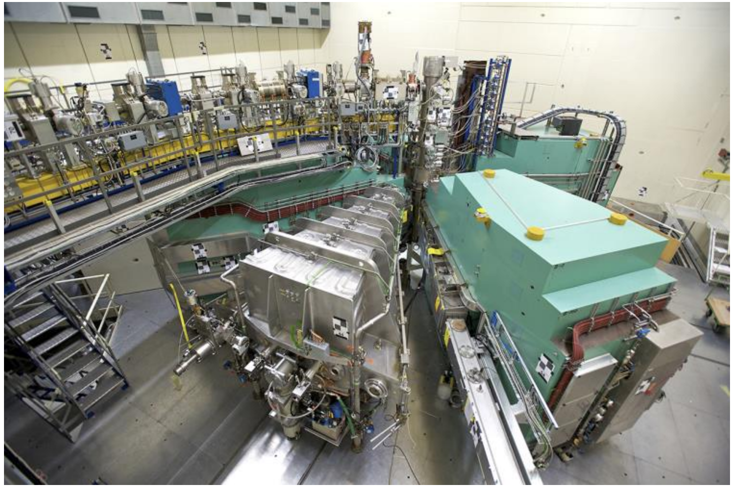
SμS: Swiss Muon Source

Regular operation at 2.2mA beam current
1.29 MW beam power
Tested up to 2.4 mA beam current
1.4 MW beam power

Global Rf power requirement ~6 MW
(50% of overall requirements)

Injector 2 cyclotron

1.



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

Ongoing Upgrade

- Replacement resonator 2&4
- New Tetrode amplifier chain and LLRF all resonators
- Goal: Increase voltage toward 3 mA beam current
- No **efficiency** gain expected

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	~ 100 kW

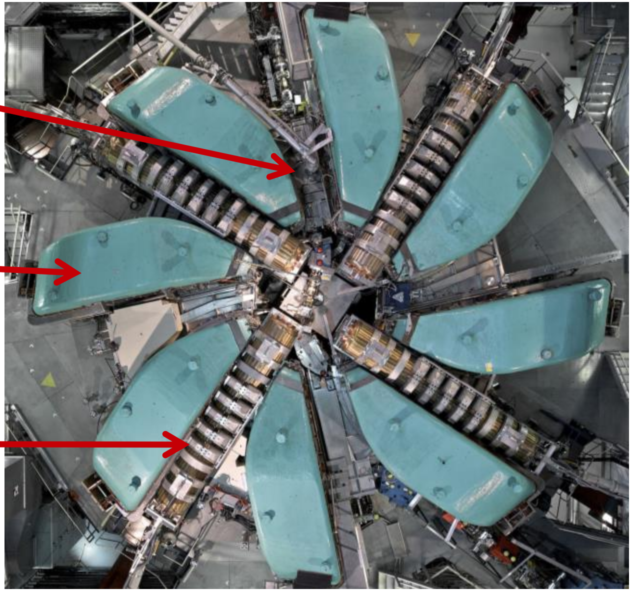
Ring cyclotron

1.

Flattop cavity

Sector magnet

copper cavity

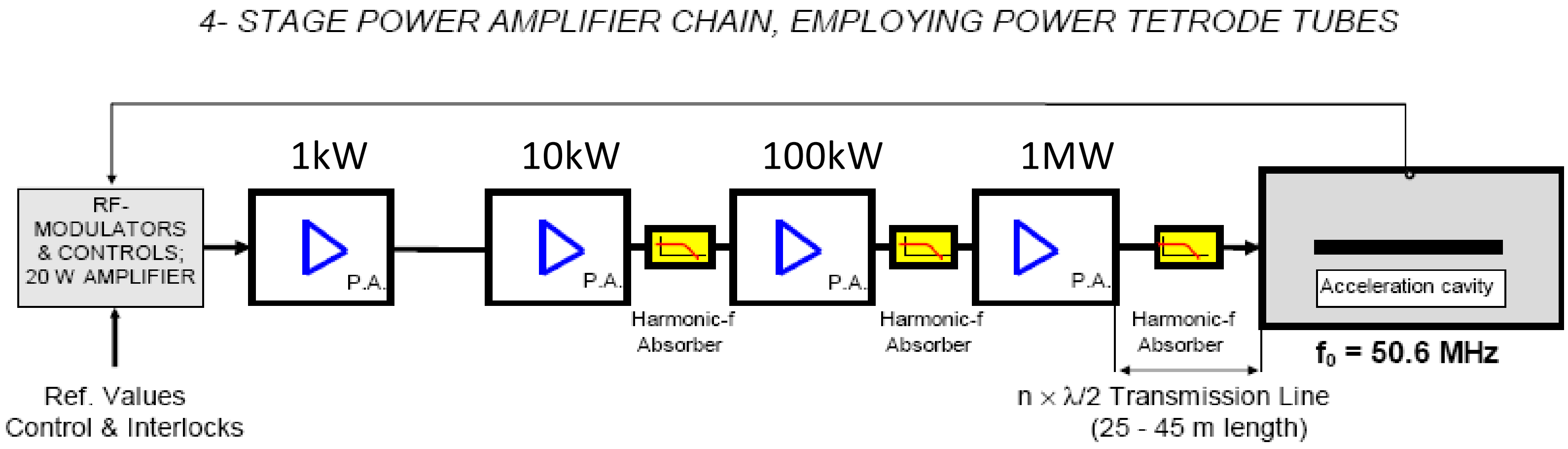


Injection energy: 72 MeV
Extraction energy: 590 MeV
Number of turns: 186

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	~ 110 kW (active)	~ - 36 kW (passive)

Amplifier chain for one copper cavity in ring cyclotron

1.



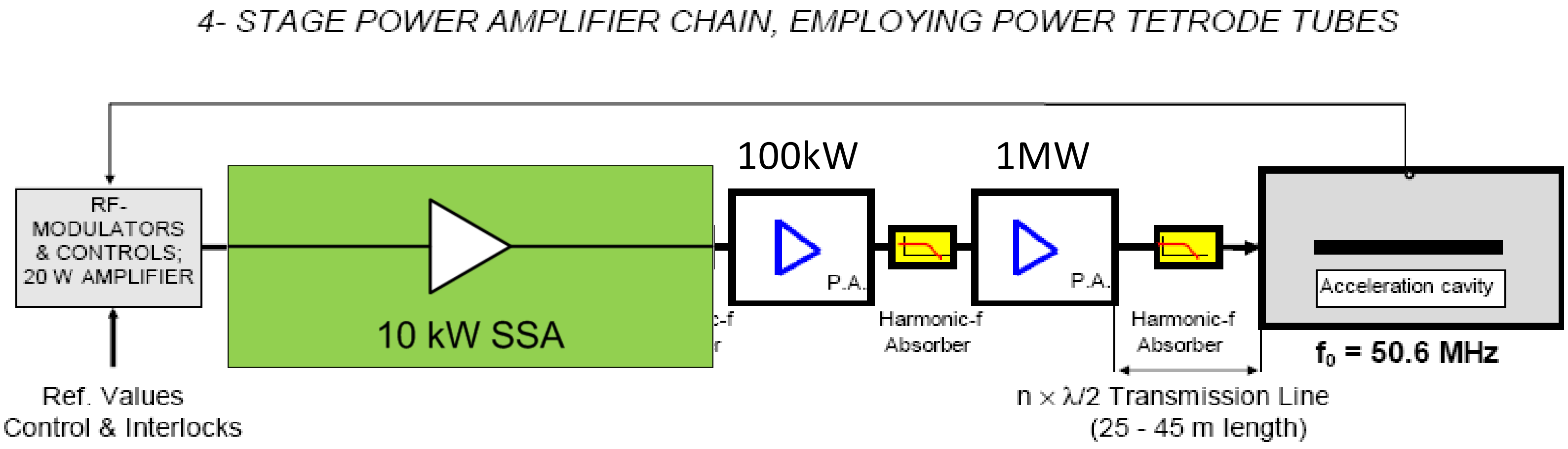
Tube Types:	**YL 1056**	**RS 2022 CL**	**RS 2074 HF**	**RS 2074 HF**
Cooling Method:	forced air	forced air	water	water

Amplifier chains built in early 90s

Some parts were taken over from older rf-system.

Amplifier chain for one copper cavity in ring cyclotron

1.



Tube Types:	**RS 2074 HF**	**RS 2074 HF**
Cooling Method:	water	water

2022: 1/10kW Tetrode Amplifier replaced by 10kW SSA
(BBL200-A10000 from Rohde & Schwarz)
Of the shelf SSA operated in class A -> no **improvement in efficiency**, goal is reliability

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Power efficiency rf systems for the Ring cyclotron

1.

	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 (active)	14 kW (passive)
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).

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Cooling system for Tetrodes

1.

HF0: Cooling circuit for tetrode amplifiers for the ring cyclotron

- Demineralized water
- Inlet temperature at tube 55°C
- Outlet temperature up to 80°C
- **<u>Heat recovery system</u>**
  ~**3’357 MWh/Year**
  (~6.5% of energy consumption)

Suppling ¼ of heat for PSI buildings

(Shutdown from Christmas to April)

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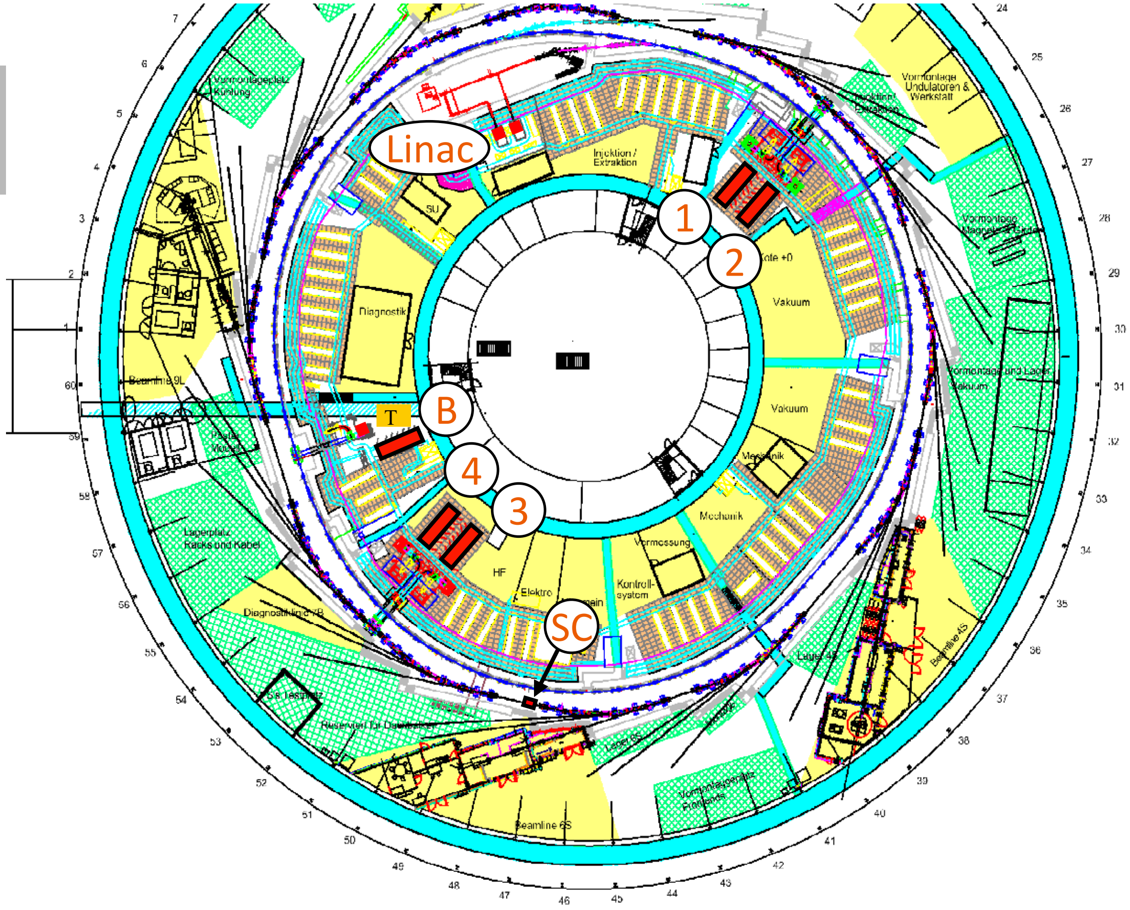
SLS Layout and RF stations

2.



Linac (100MeV):

Two TH2100 (35 MW max) & pfn modulator (3 GHz)

Op. since April 2000

Booster 500 MHz RF

<u>1 Klystron power plant 180 kW (max)</u>

Op. since July 2000

<u>1 in house SSA power plant 65 kW (max)</u>

Op. Since 2016

Both stations can supply the Booster cavity (ramp 2-40 kW) or be used for the RF test facility

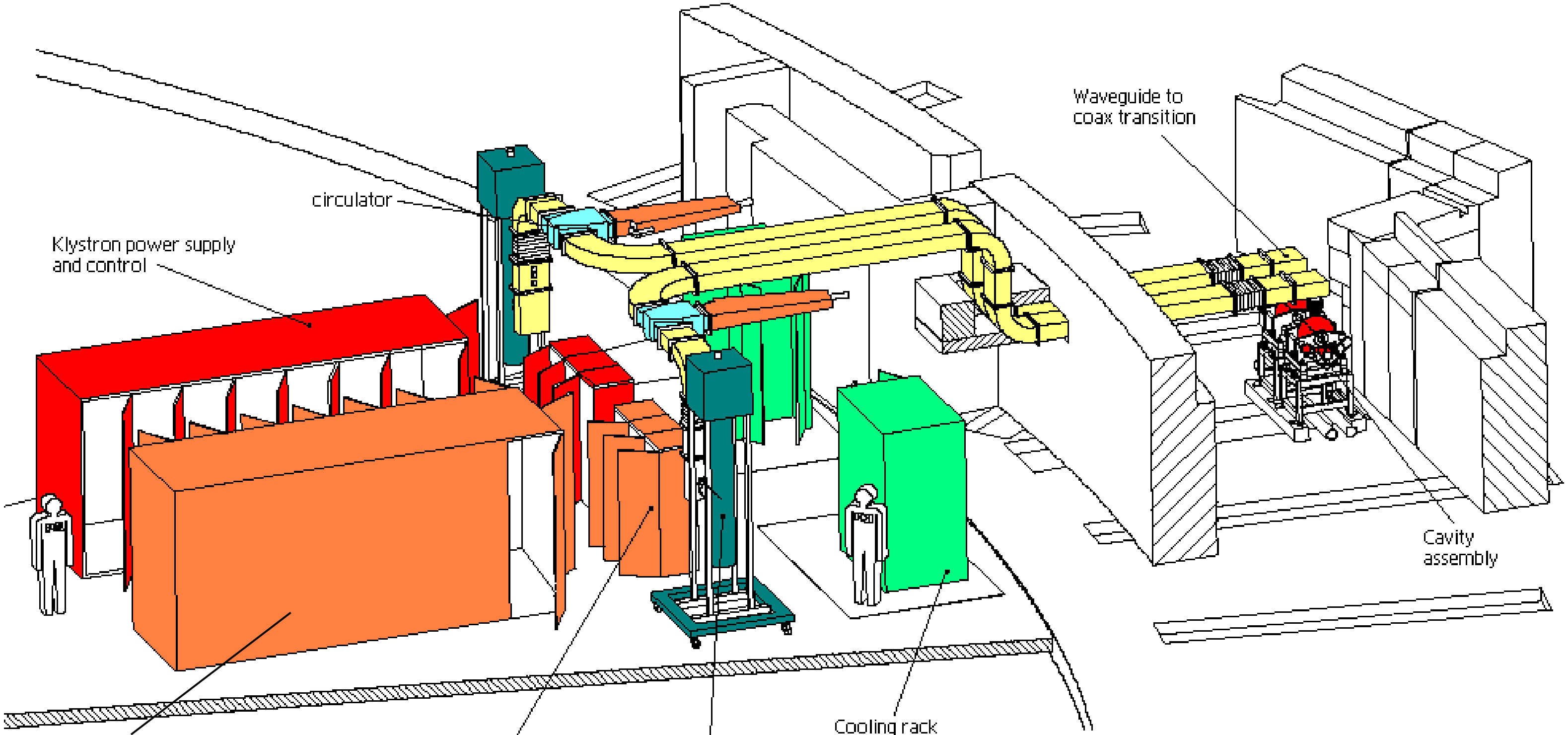
Storage ring 500 MHz RF

<u>4 klystron power plants 180 kW (max)</u>

Op. since December 2000

Layout SR 500 MHz accelerating station
(large contribution to power consumption)

2.

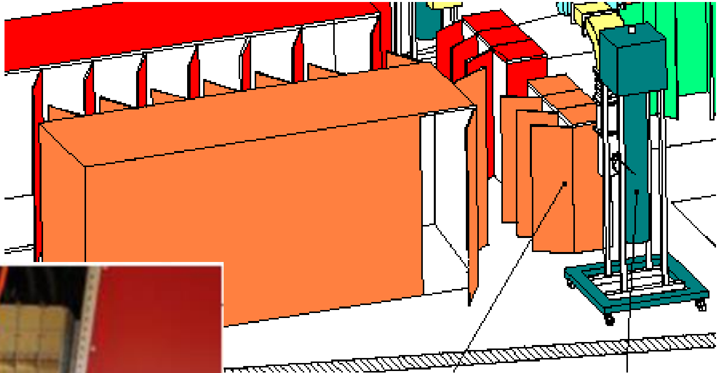


Pulse Step Modulator: 46 kV / 7.5 A
Test 180kW CW at 45.5 kV,/ 6.5 A

η≈60% (supplier) => operational 41-51% (not saturated & matching)

Characterization power consumption SR stations
(measurements on SR2)

2.



Grid Power measurement at PSM input. Includes all energy consumer of the RF plant included klystron auxiliaries

Klystron RF power: **115 kW**

Grid power measurement: **261 kW**

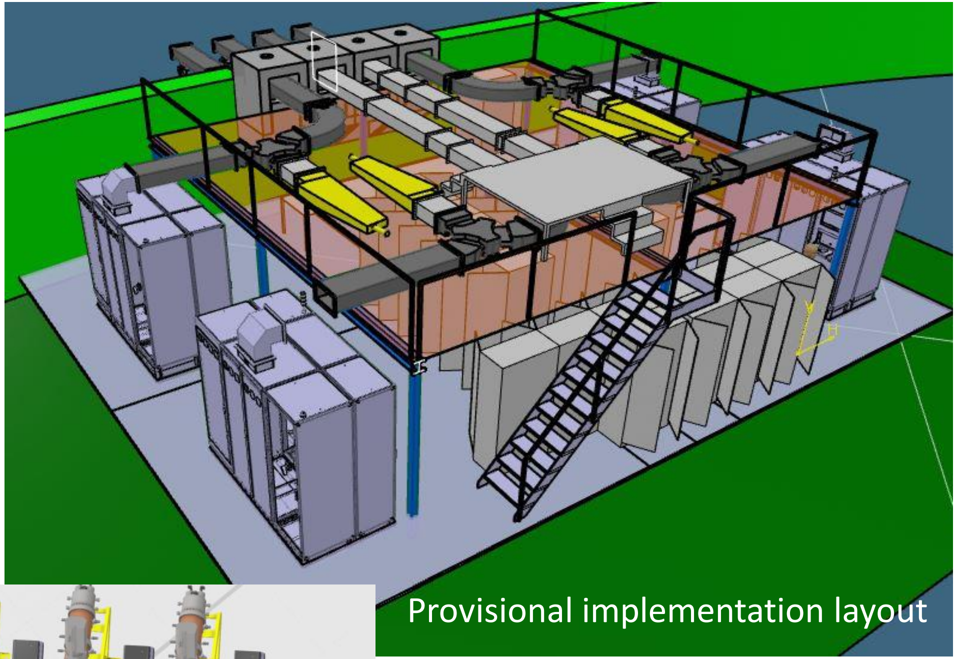
Grid to RF efficiency **44%** (good Klystron)

The electronic efficiency of the klystrons fluctuates from tube to tube, and depends on a non optimal matching of the tube exit to the 50 Ohm line (cirulator) and refurbishinh history.

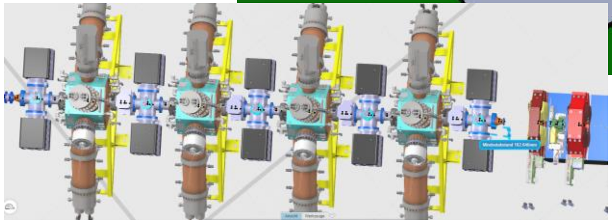
The best case, one klystron reuned for better matching, can reach ~50% efficincy i normal operation

SLS 2 Storage Ring Upgrade & RF

2.



Provisional implementation layout



Storage ring 500 MHz RF

- 4 commercial SSA
  - 150 kW/station maximum
  - 124 kW/station (all ID closed)
  - **Expected global efficiency > 56%**
  - New BLF978P & single ended module
  - Drain voltage can be optimized for max efficiency at each operation point

- 4 HOM damped cavities in same straight section

- Dark-Period 01.10.2023 - 31.12.2024
- Planned commissioning with beam from January 2025

Comparison SLS1 and SLS2

2.

Main RF-System Storage Ring		SLS 1 2.4 GeV – 400 mA	SLS 2.0 2.7 GeV – 400 mA
Total RF voltage	kV	2080	**1780**
Number of cavities		4	4
Voltage per cavity	kV	520	445
Wall loss per cavity	kW	40	30
RF-power/cavity with beam and max. ID Power	kW	102	**124**
Grid to RF efficiency	%	0.44	0.56
Grid Power/RF amplifier max ID Power	kW	227.3 (909.1*)	221.4 (885.7*)
Grid Power /RF amplifier Average ID Power	kW	227.3 (909.1*)	**196.4 (786*)**

Global heat recovery **~200 MWh/year**
RF contribute as all other systems, low temperature => low efficiency (~1.6% of energy consumption)

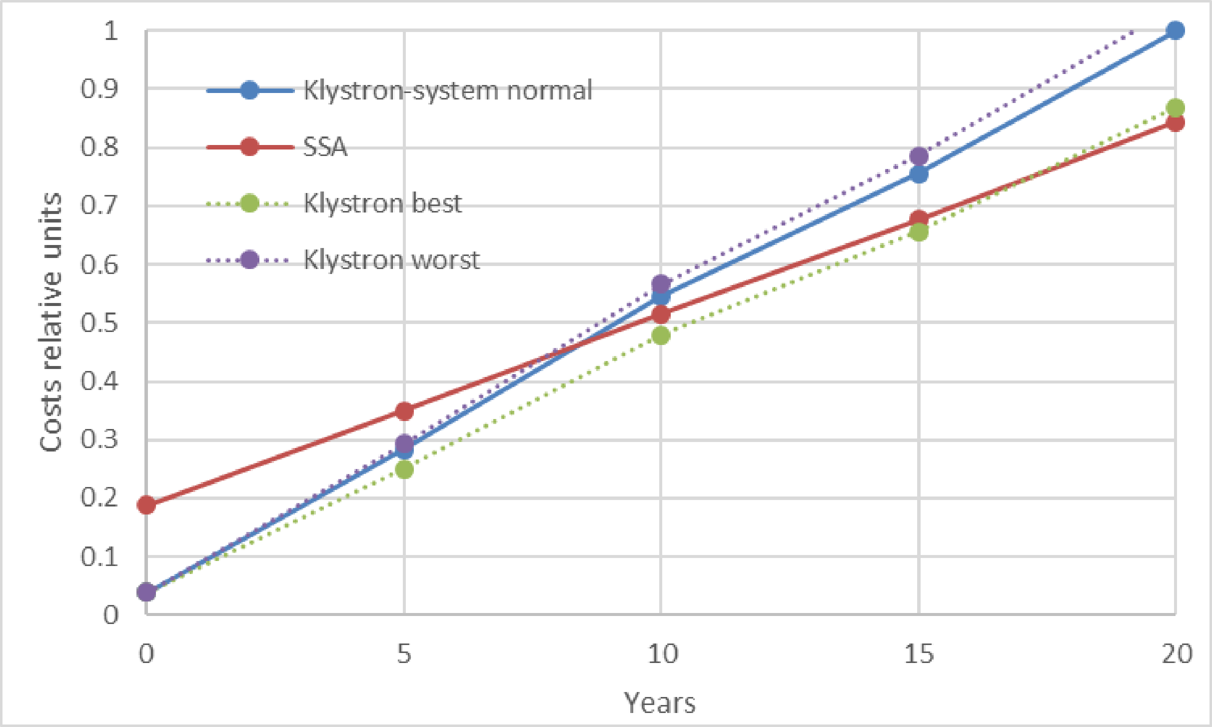
* For 4 RF amplifier stations

Indication operational RF costs for SLS2

2.

Cost delopments assuming:

- 1 Kly. refurbising/20years/station
- 1 Kly. new/20years/station
- 0.1 CHF/kWh



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Rational behind the upgrade to SSA

2.

Motivations	
RELIABILITY	Cope with the risk of aging and discontinued components Built-in redundancy
Phase noise	Old Station not fulfilling the SLS2 requirements (keep energy fluctuations below ID BW)
Maintenance	Modular system allows for fast maintenance / In house expertise on SSA (no HV)
Klystron availability	Only few klystron suppliers and growing costs
Grid to RF efficiency	Wasn’t the driving argument, but an improvement is expected
Operational costs	Beside better efficiency, expected low maintenance costs (klystrons)

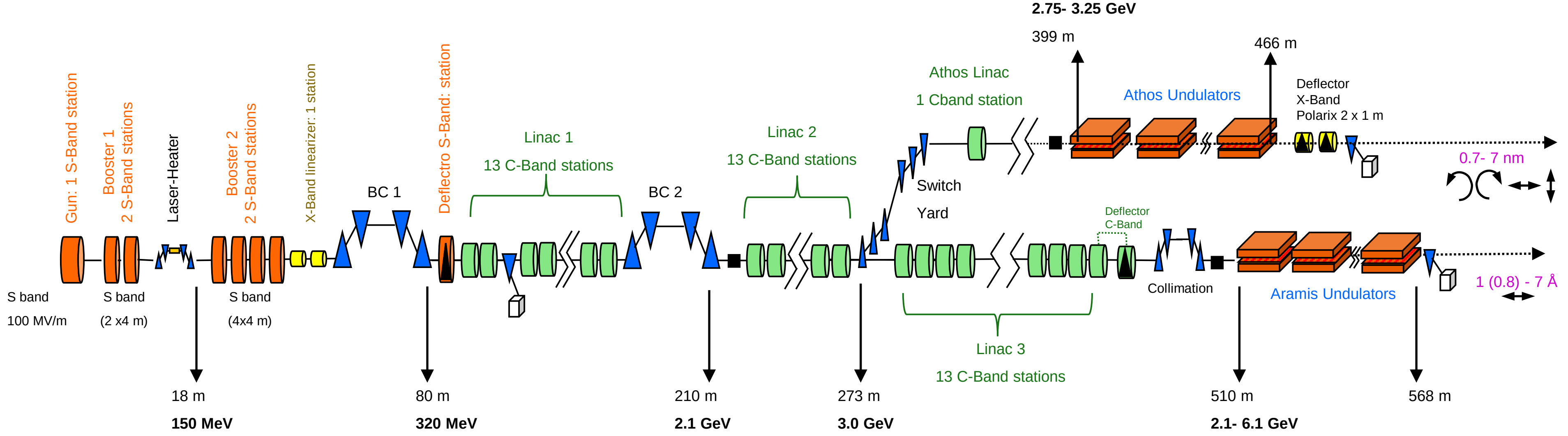
Overview RF stations in SwissFEL

3.

Regular operation

- 100 Hz repetition rate
- 2 Bunches / RF pulse (10 to 200 pC)
- Up to 6 GeV beam energy in Aramis

- S-Band: **7**
- C-Band: **27** => dominate power consumption
- X-Band: **2**
- **Global RF power requirement ~1.9 MW**



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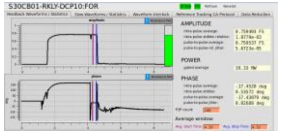
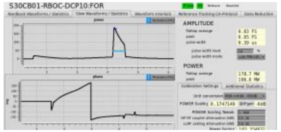
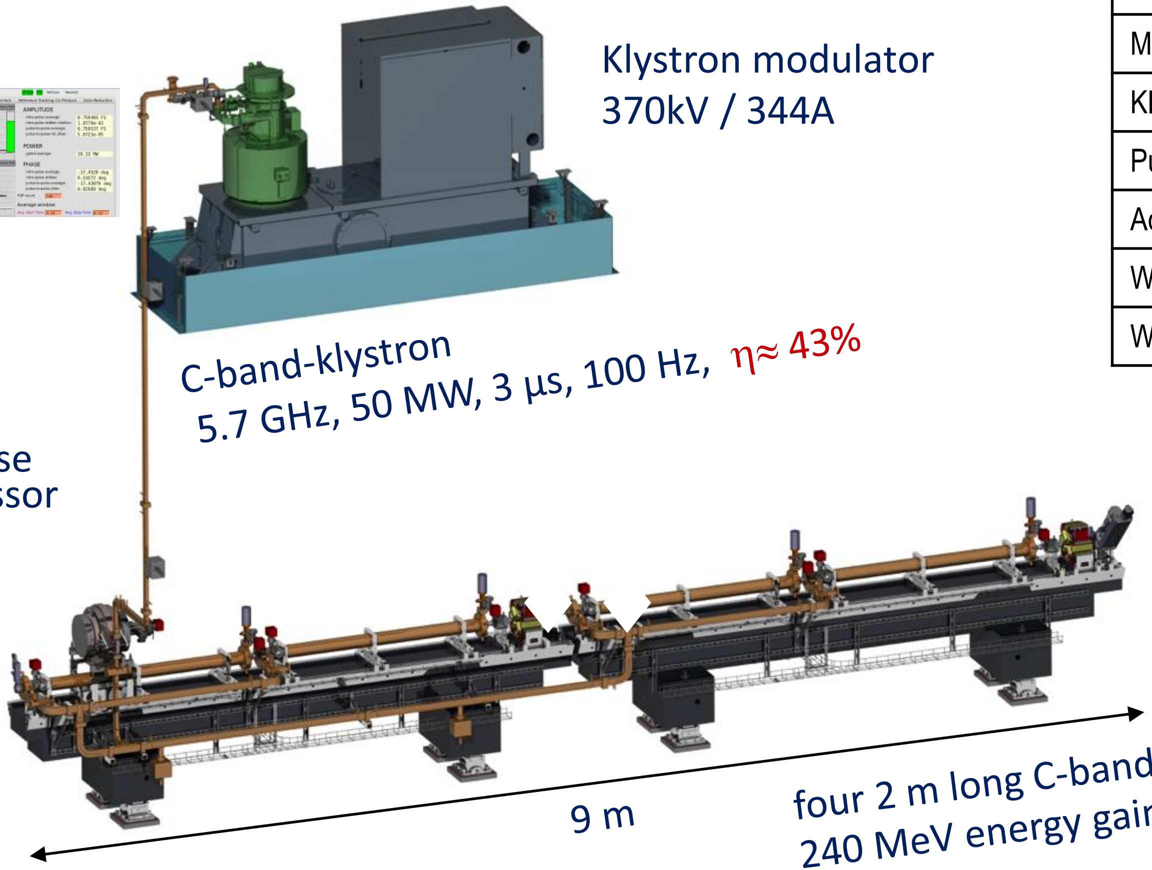
C-band Linac modules

3.

Main LINAC + Athos	#
LINAC module	27
Modulator	27
Klystron	27
Pulse compressor	27
Accelerating structure	108
Waveguide splitter	81
Waveguide load	108







C-Band Linac Klystron modulators

3.

Specified for 50 MW / 3µs RF, 370kV / 344A / < 15 ppm voltage stability pulse to pulse @ 100 Hz

Two technologies (suppliers) were qualified at PSI

AMPEGON

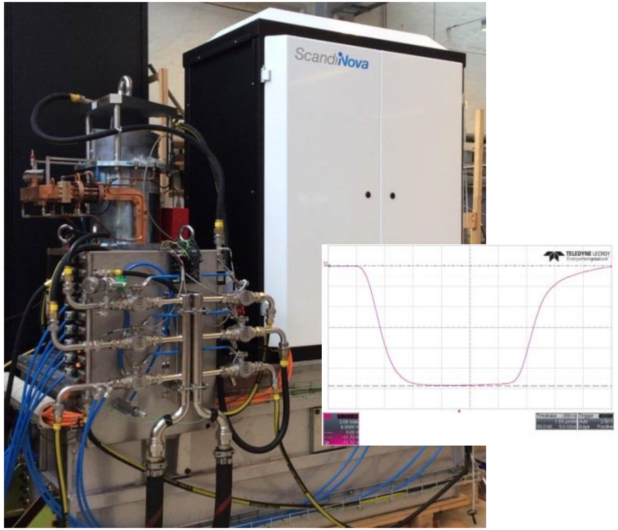
12 IGBT Switches
4.5 kV max
3.0 kA max

13 units for Linac 1 & 2 + 1 unit for the Athos Linac

Since 2019: Ampegon Power Electronics AG, founded by the group group Aretè & Cocchi Technology (OCEM)

ScandiNova

60 IGBT Switches
1.7 kV max
1.6 kA max



13 K2-3 type (Linac 3)

Grid to RF Global Picture S-, C- and X-Band

3.

Efficiency at the nominal operational conditions at 100 Hz

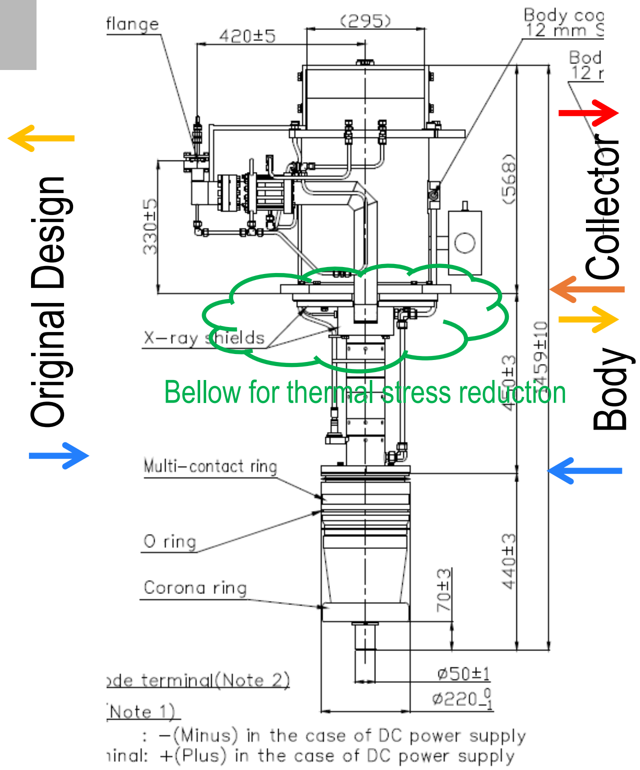
	Ampegon	Scandinova
RF FWHM (µs)	3.0	
Peak RF (MW)	37.65	
average RF (kW)	11.3	
Power station av. Power (kW) Measured, includes auxiliaries (solenoid ~6 kW)	57.2	
Grid to RF efficiency (%) Klystron efficiency 43%	~ 20	
Voltage rise time 10-90% (us)	0.77	1.1
Voltage fall time 90-10% (us)	1.23	1.8

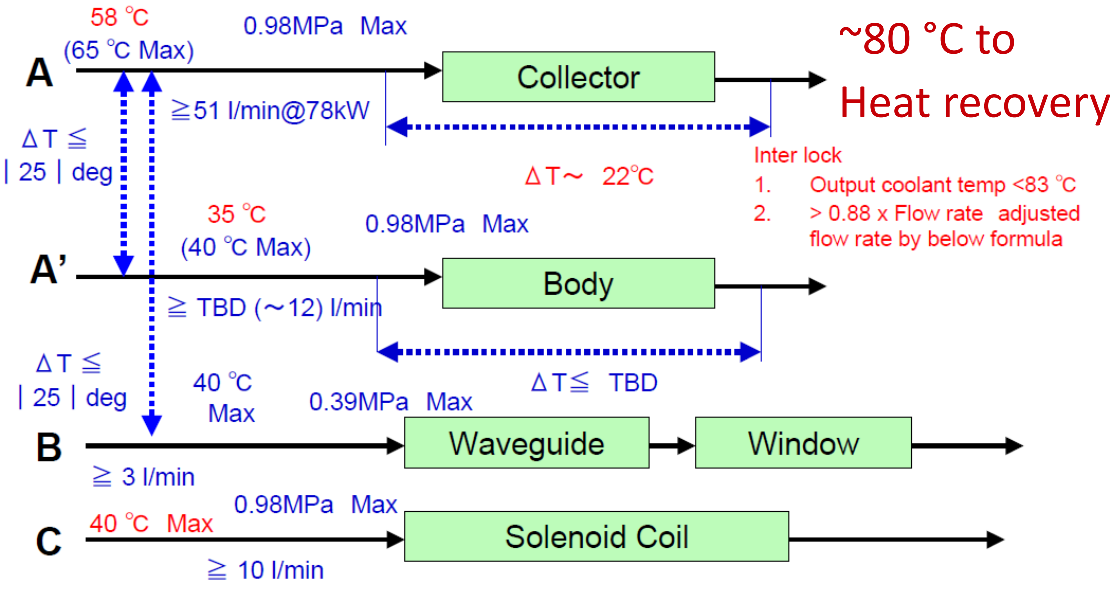
Nominal for 240 MeV energy gain

Heat recovery

3.

Modification of klystron agreed with Supplier





Global heat recovery ~2'600 MWh/year

(~11% of energy consumption)

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Rational/priorities behind power source design

3.

Priorities	
RELIABILITY	Keep the components between safety margin => large number of sources increases probabilities of failures and shot to shot deviations
Pulse to pulse stability	Essential for pulse to pulse FEL stability (1e-4 energy, fs arrival time, peak current, …) => reached < 10 ppm
Maintenance	Modular system and reasonable HV
Klystron	Allow for hot collector operation (90 °C) & energy recovery
Grid to RF efficiency	Wasn't a driving argument

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Wir schaffen Wissen – heute für morgen

Many thanks to:

M. Schneider (HIPA),
L. Stingelin (SLS)
J. Alex (SwissFEL)
D. Reinhard (Building services)
M. Jörg (Infra. & el. inst.)

For providing material for this presentation

Resereve Material

PSI

Zurich
30 km
bird's-eye view

Basel
49 km
bird's-eye view

CERN
220 km bird's-eye view

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Operation parameters Ring rf without beam

1.

		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**	

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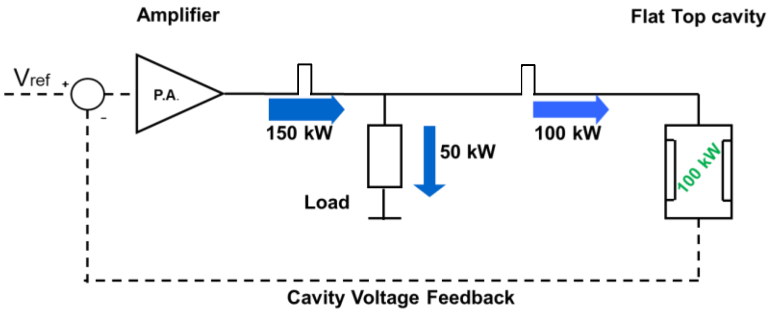
Operation parameters Ring rf with beam 2.4mA

1.

		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**	

RingCyclotron: Operation Flattop

@ 0 mA (active cavity operation)



@ 2.4 mA (~passive cavity operation)