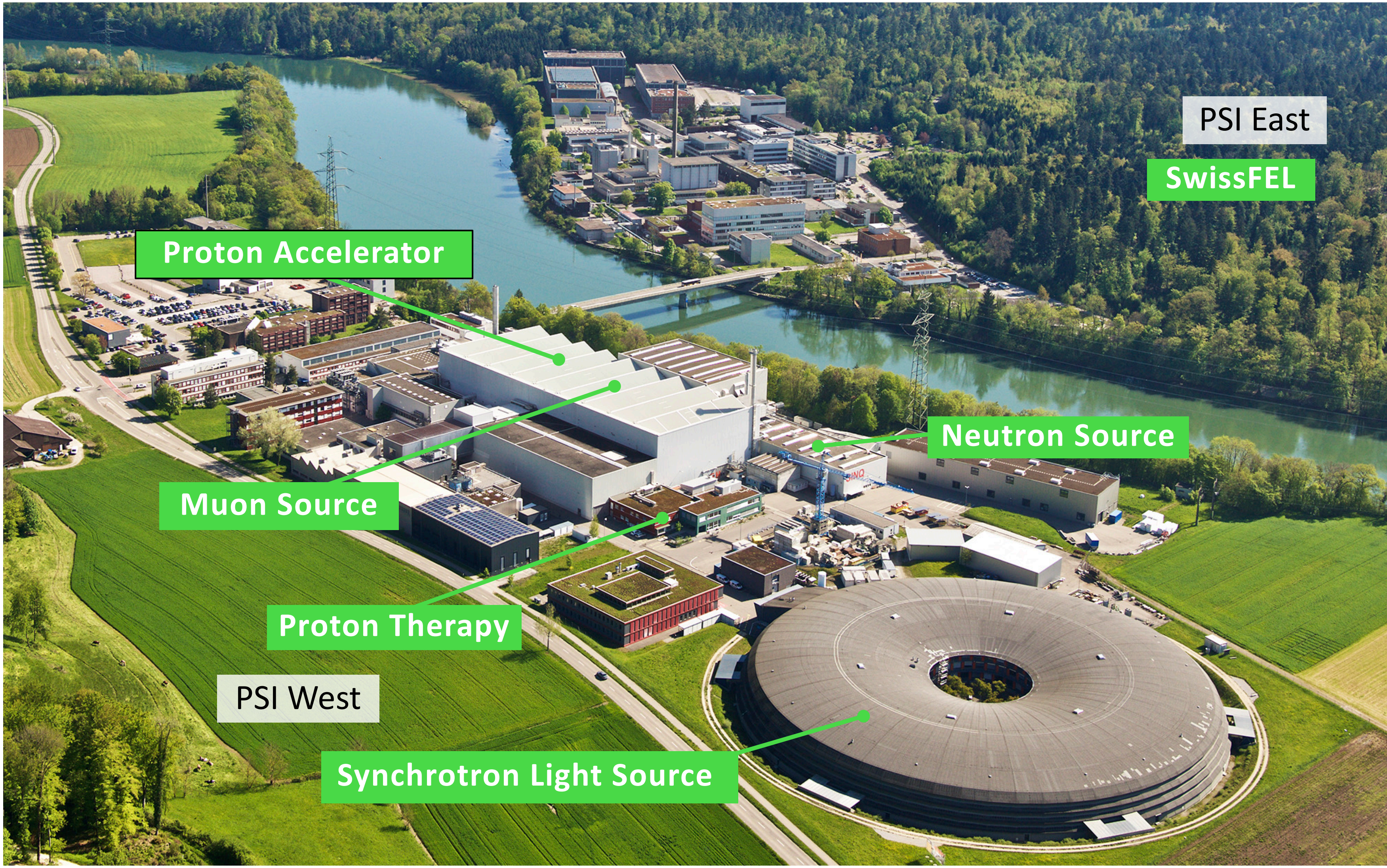
Joachim Grillenberger :: Paul Scherrer Institut :: Head of Proton Facilities

Is a Megawatt Accelerator Sustainable?

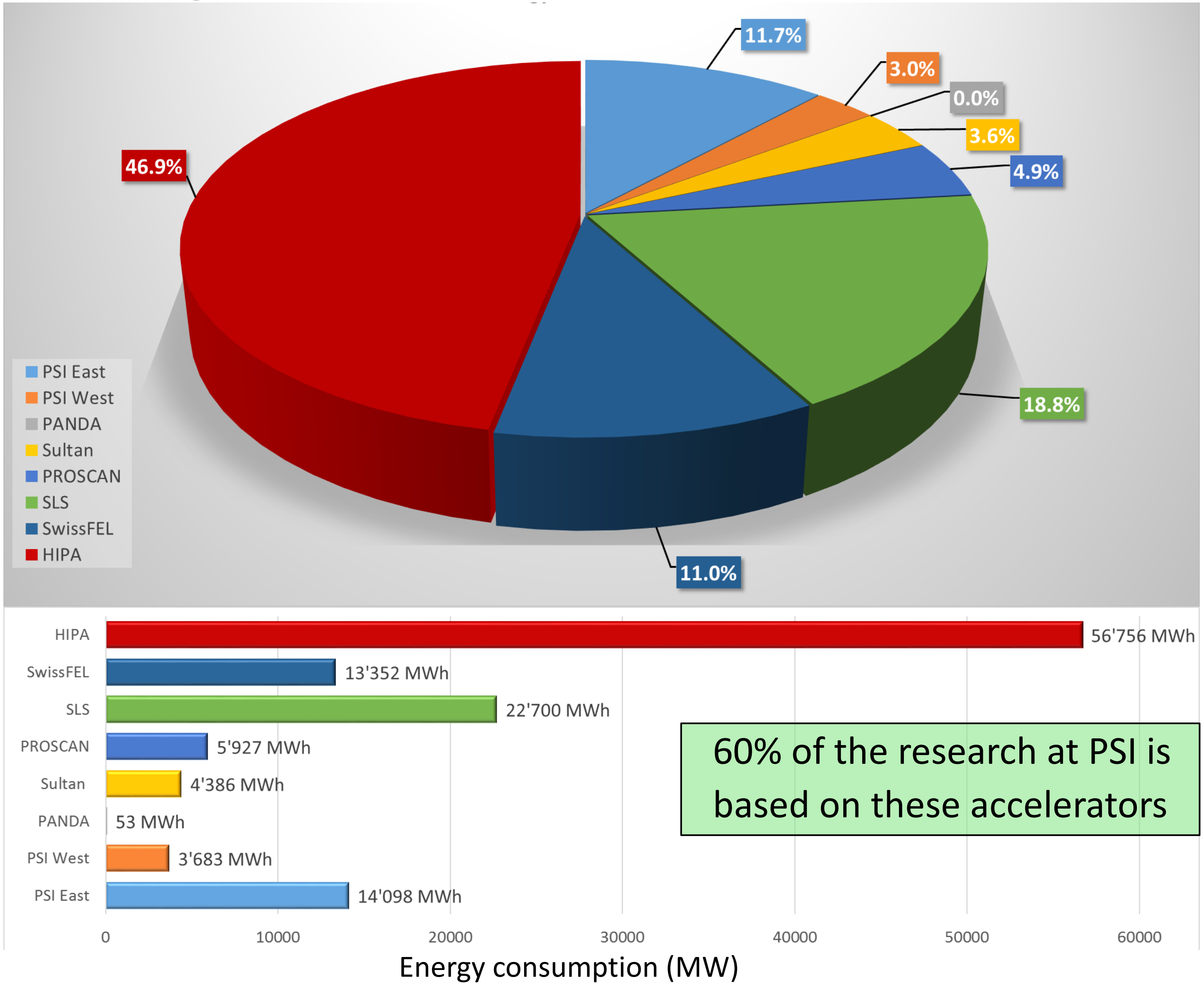
Sustainable Accelerators Workshop 2022
Daresbury Laboratory

PSI Overview

← Basel　　Germany ↑　　Aarau/Bern ↓　　Zurich →

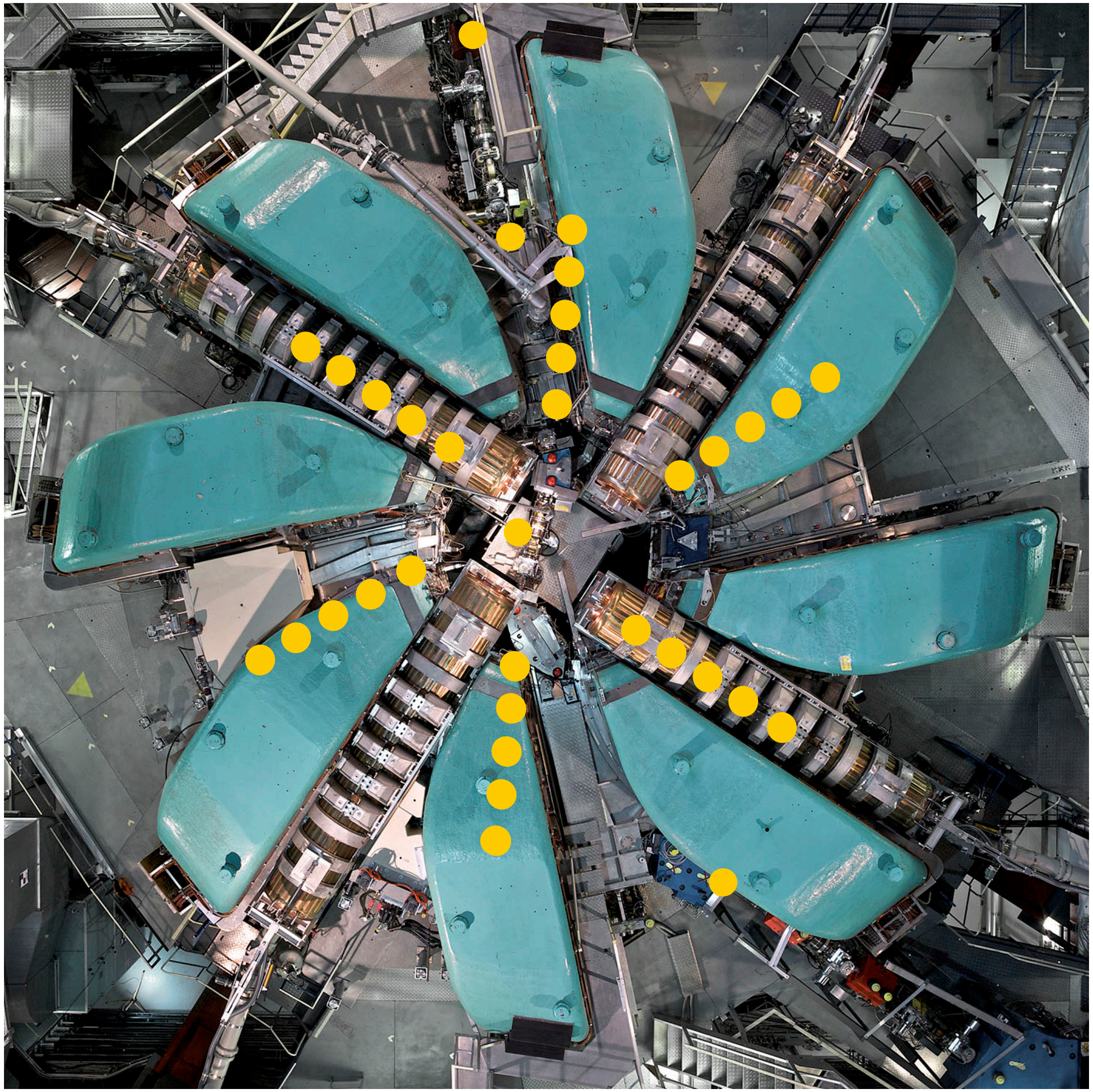


PSI Energy Distribution
P_{grid} = 24 MW, E_{tot} = 130 GWh/a



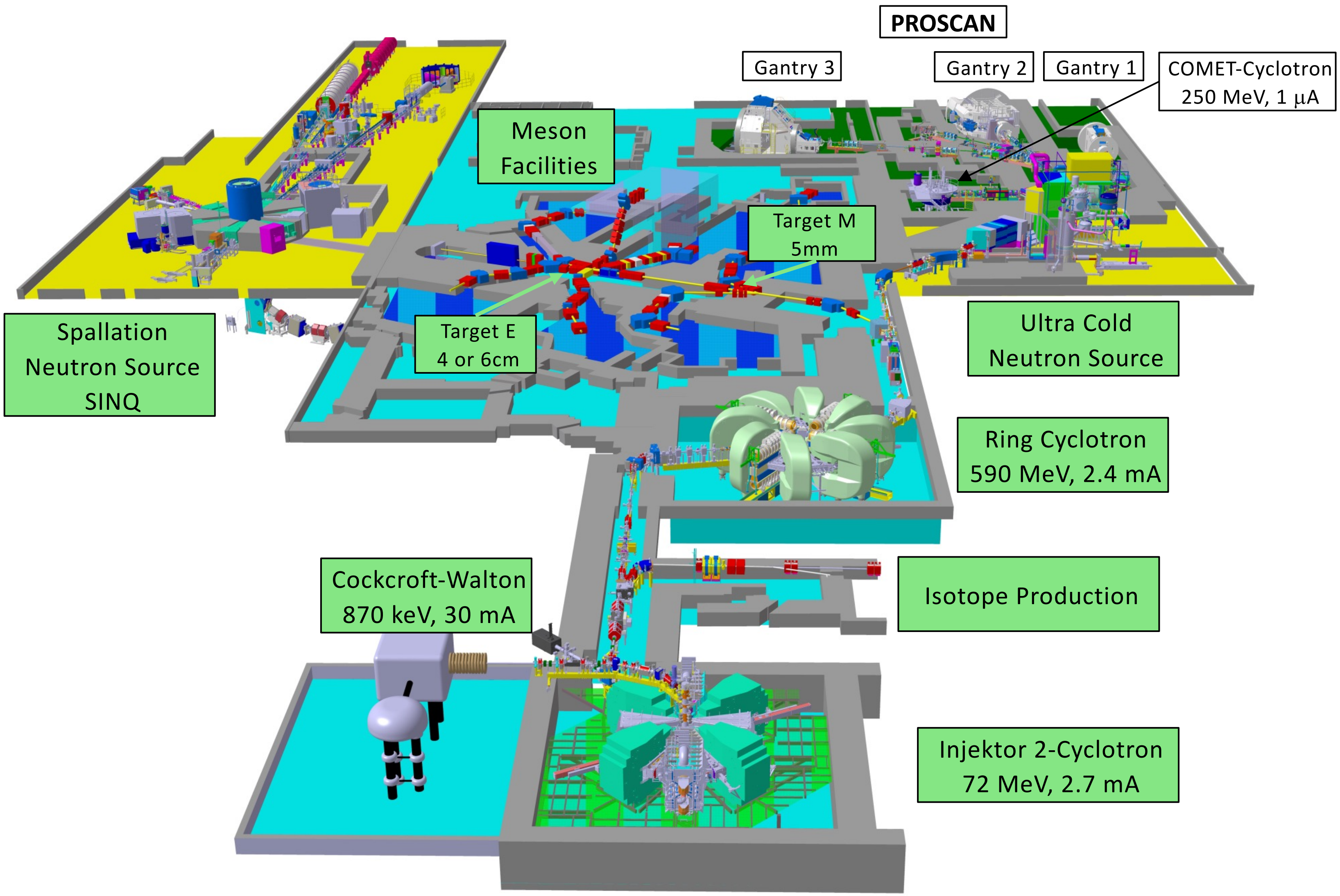
590 MeV Ring Cyclotron at PSI

1.4 MW beam power (2.4 mA)



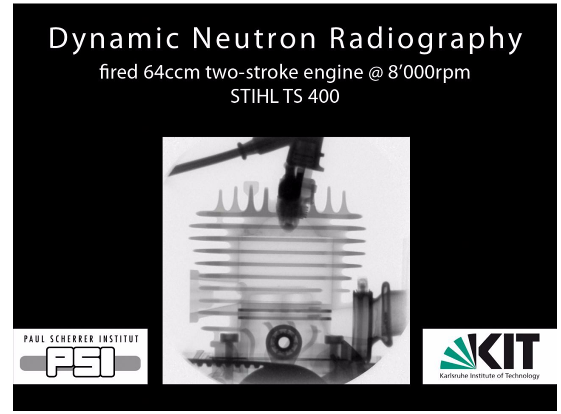
Beam energy:	590 MeV
Beam current:	2.4 mA
Beam power:	1.4 MW
U_{cav}:	850 kVp
Number of turns:	186
8 sector magnets:	0.6 – 0.9 T
R_{in}:	2.1 m
R_{out}:	4.5 m

High Intensity Proton Accelerator Facility
a Megawatt Accelerator



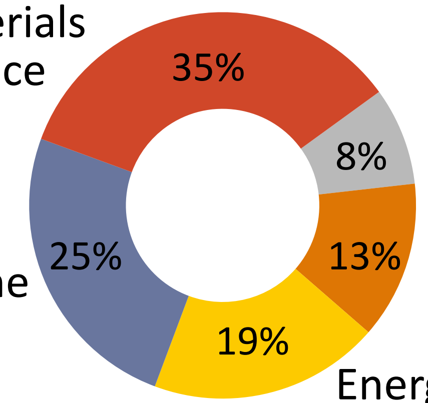
Is a Megawatt Accelerator Sustainable?

Muon spectrometry at PSI



Neutron imaging at PSI

60% of the research at PSI is based on these accelerators



Yes, if the scientific output leads to sustainability

Yes, if the most efficient (accelerator) technology is being used

Cyclotron Efficiency at PSI

$$\eta_{acc} = \frac{P_{beam}}{P_{Grid}}$$

COMET 250 MeV
Medical Cyclotron

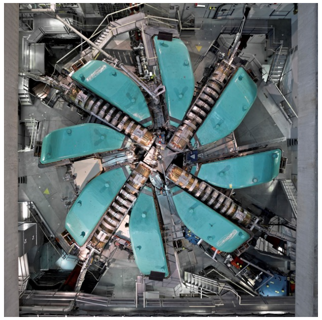
0.5 MW from public grid

< 1 μA for patient treatment

efficiency 0.05%

Running costs for electricity: 400 000 sFr/year

PSI 590 MeV cyclotron



12 MW from public grid

1.4 MW beam power (2.4 mA)

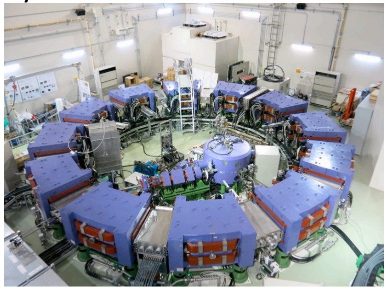
efficiency 12%

Running costs for electricity: 5 MsFr/year

Is a Cyclotron efficient?

$$\eta_{acc} = \frac{P_{beam}}{P_{Grid}}$$

Kyushu FFA

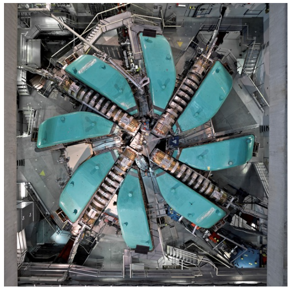


Energy up to 10 GeV
P_{beam}= to be demonstrated
η_{acc} = ?%
Footprint 30’000 sqm

Spallation Neutron Source

1 GeV protons, 60 Hz
P_{beam}=1.4 MW, P_{grid}=26 MW
η_{acc} = 5%
Footprint 100’000 sqm

PSI Proton Facility

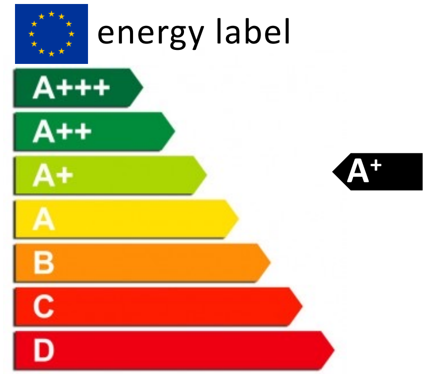


590 MeV, 50 MHz
P_{beam} = 1.4 MW, P_{grid}=8 MW
η_{acc} = 18%
Footprint 20’000 sqm

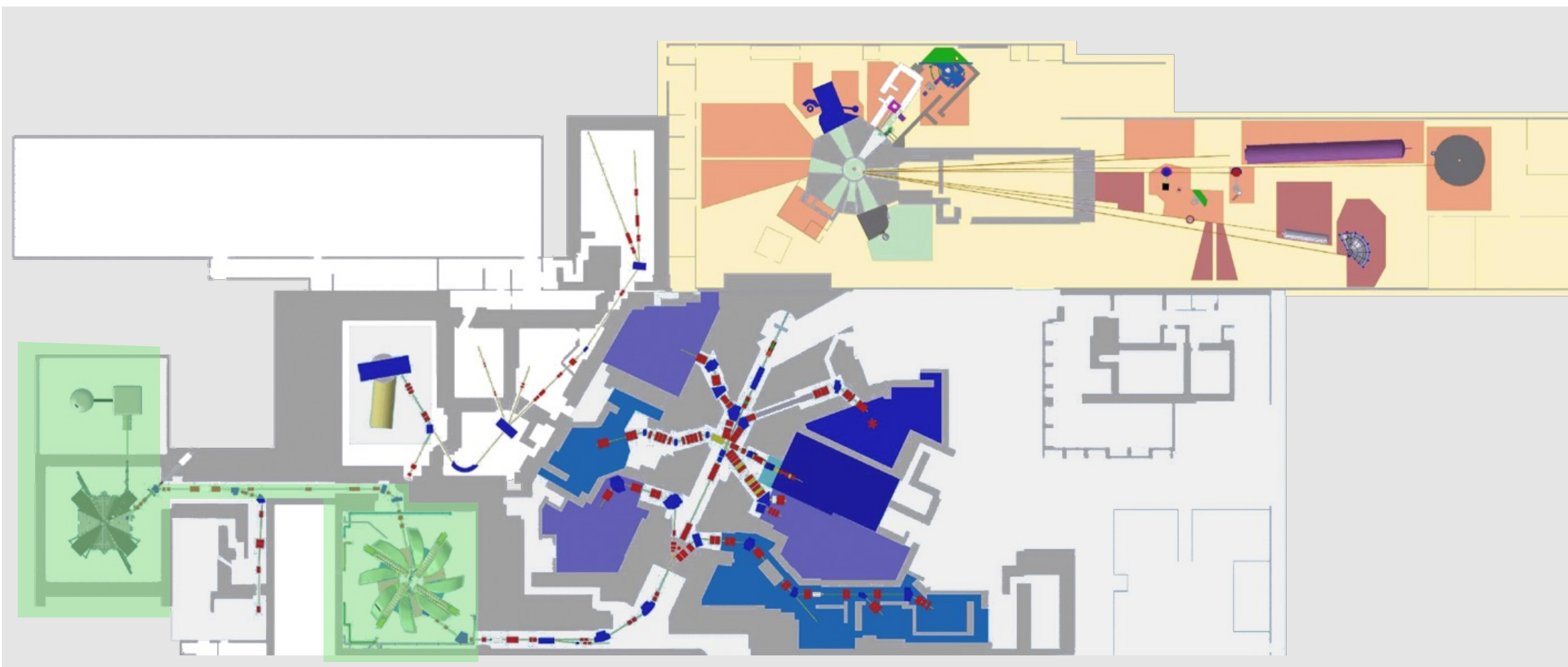
High power machines that are used to generate (secondary) particles at high intensities (neutrons, muons or neutrinos).

- They cover a broad spectrum of particle physics and material science
- Consume large amounts of electrical energy
- Scientists want better flux, rate, brightness, luminosity...
- Even more power is needed

Overall Efficiency



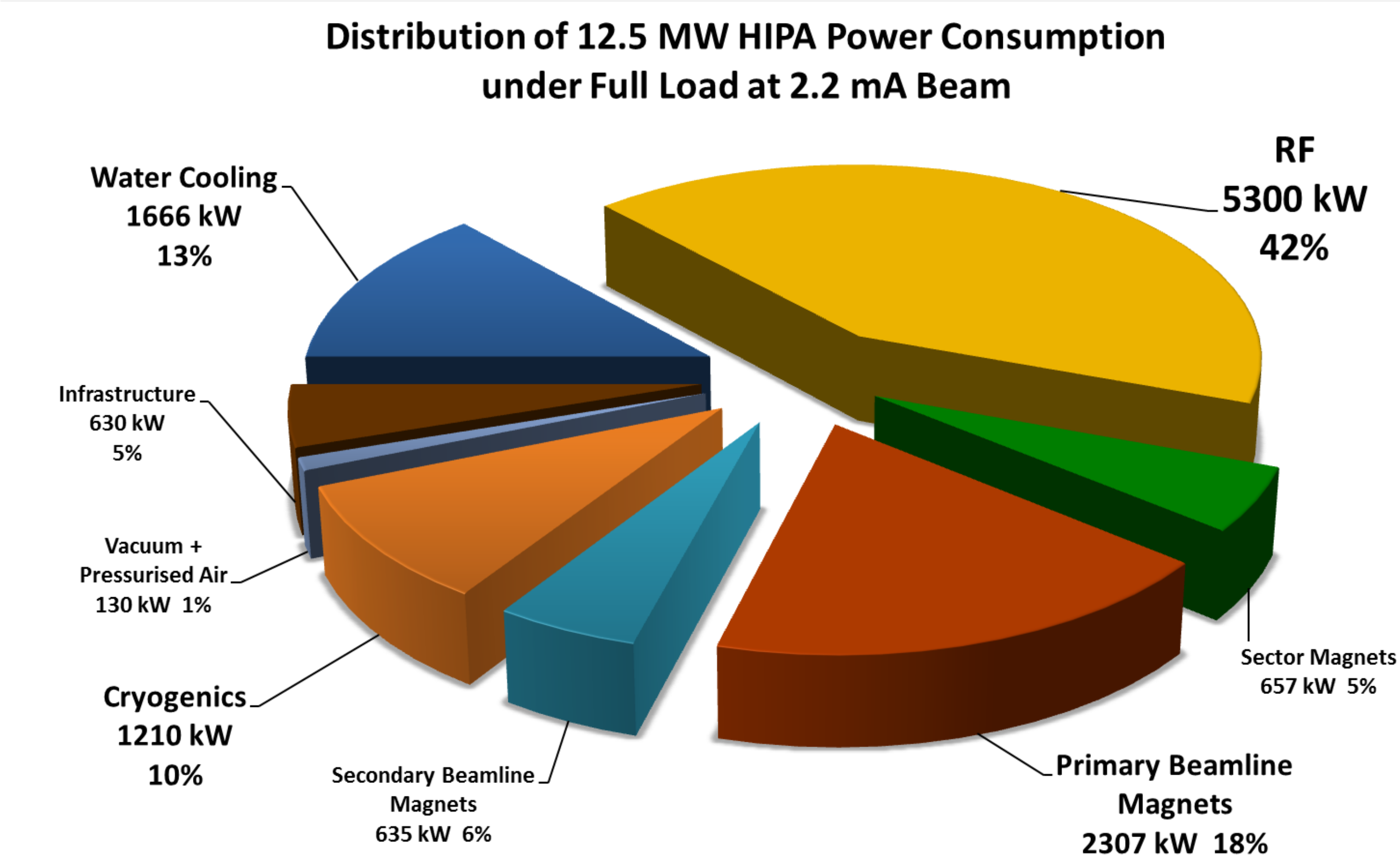
Total power consumption:	12 MW
Beam Power:	1.4 MW
Efficiency:	12%
Just the accelerator:	**18%**



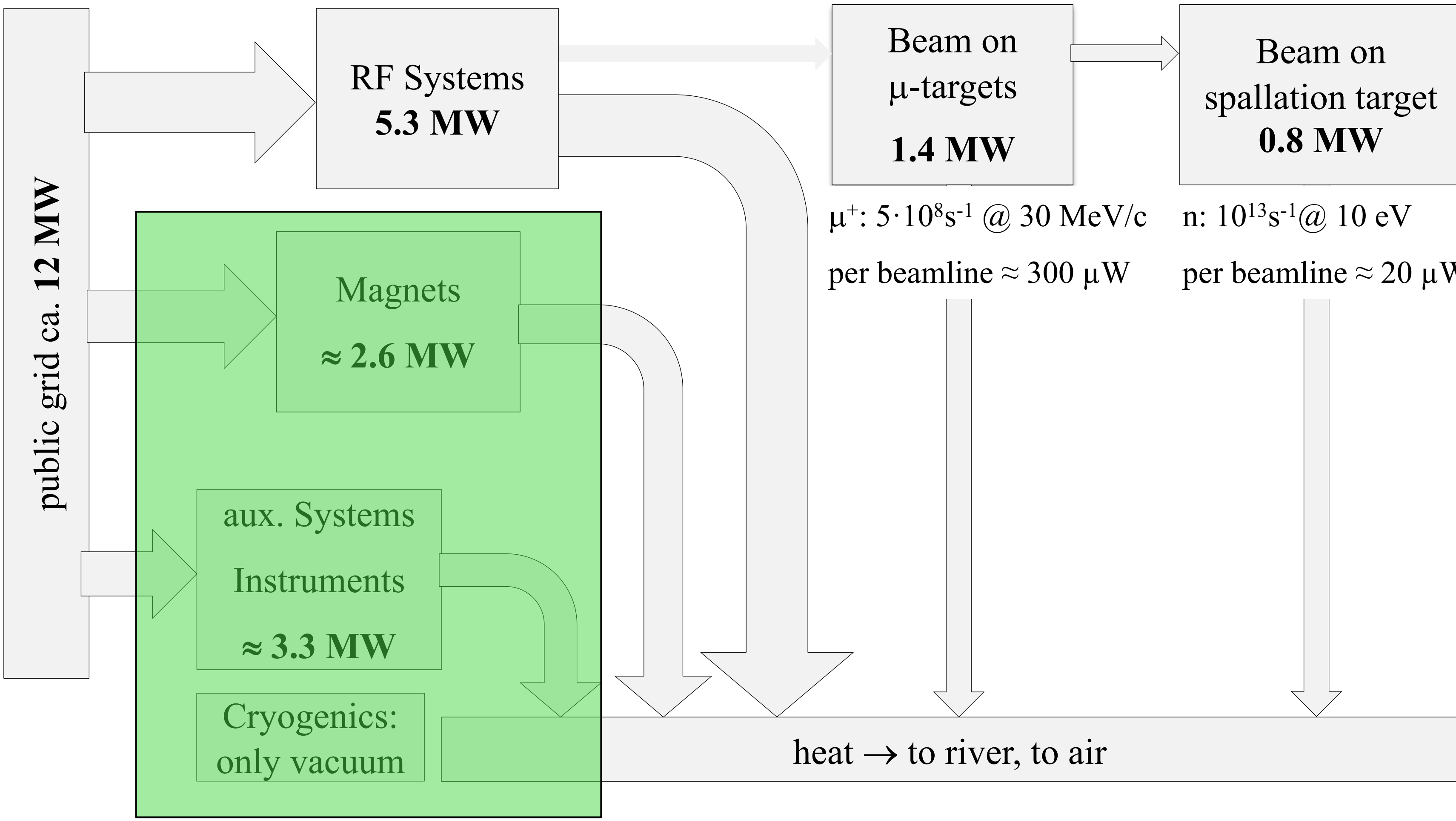
Most efficient accelerator

50% of PSI's total energy consumption

Power Distribution Proton Facility

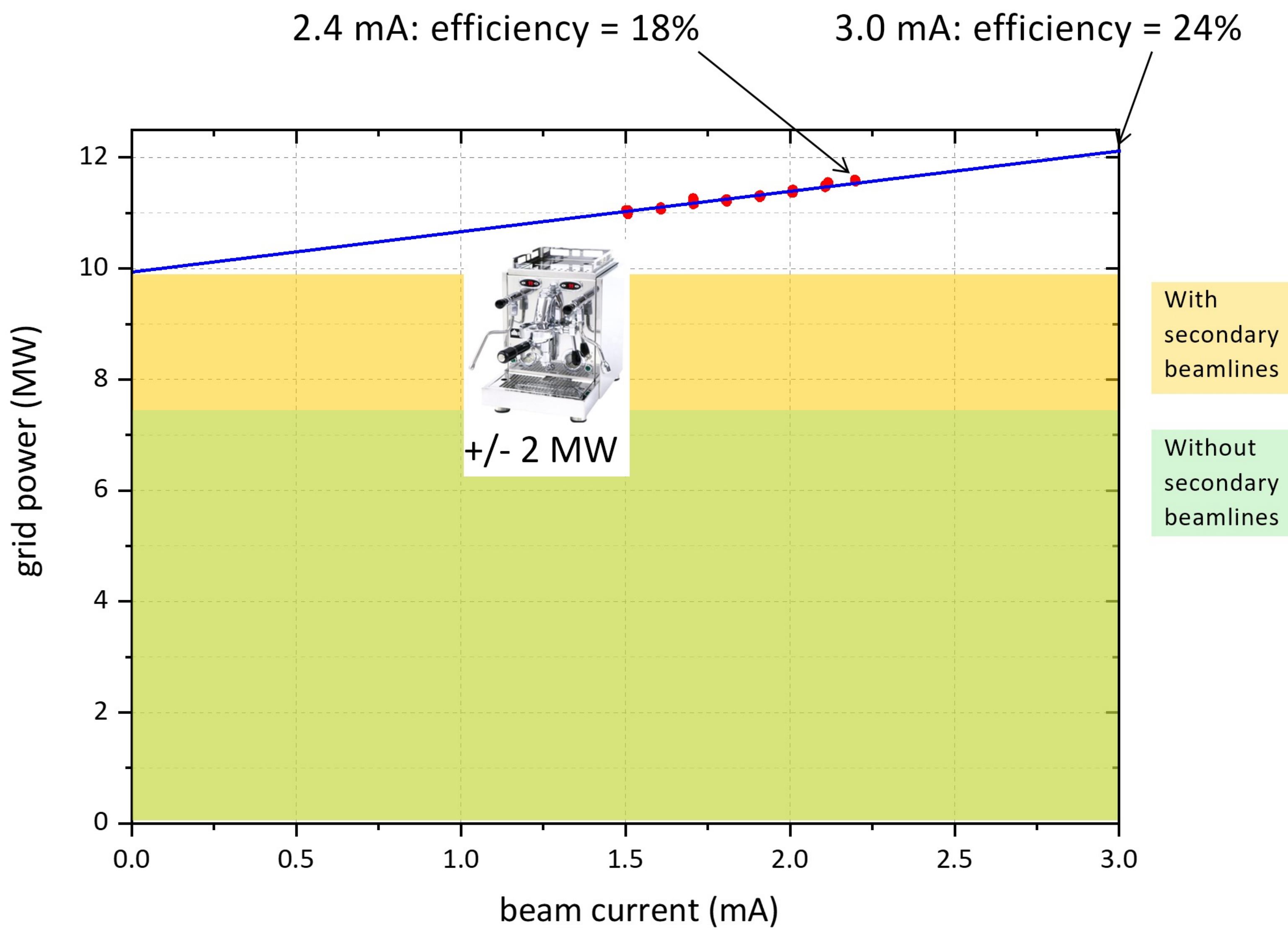


Grid to Beam Power Conversion



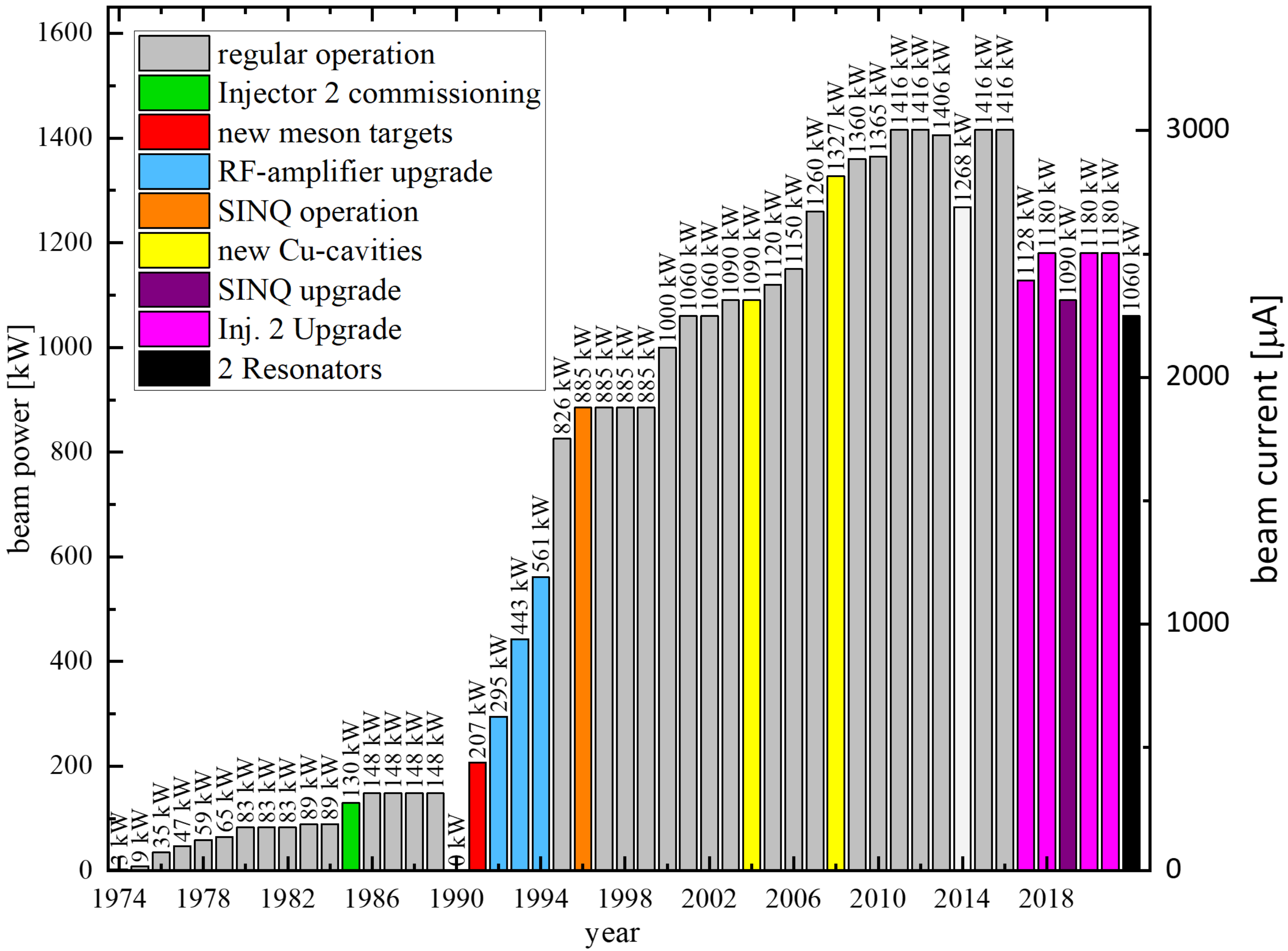
Almost independent from the beam power

Grid to Beam Power Conversion

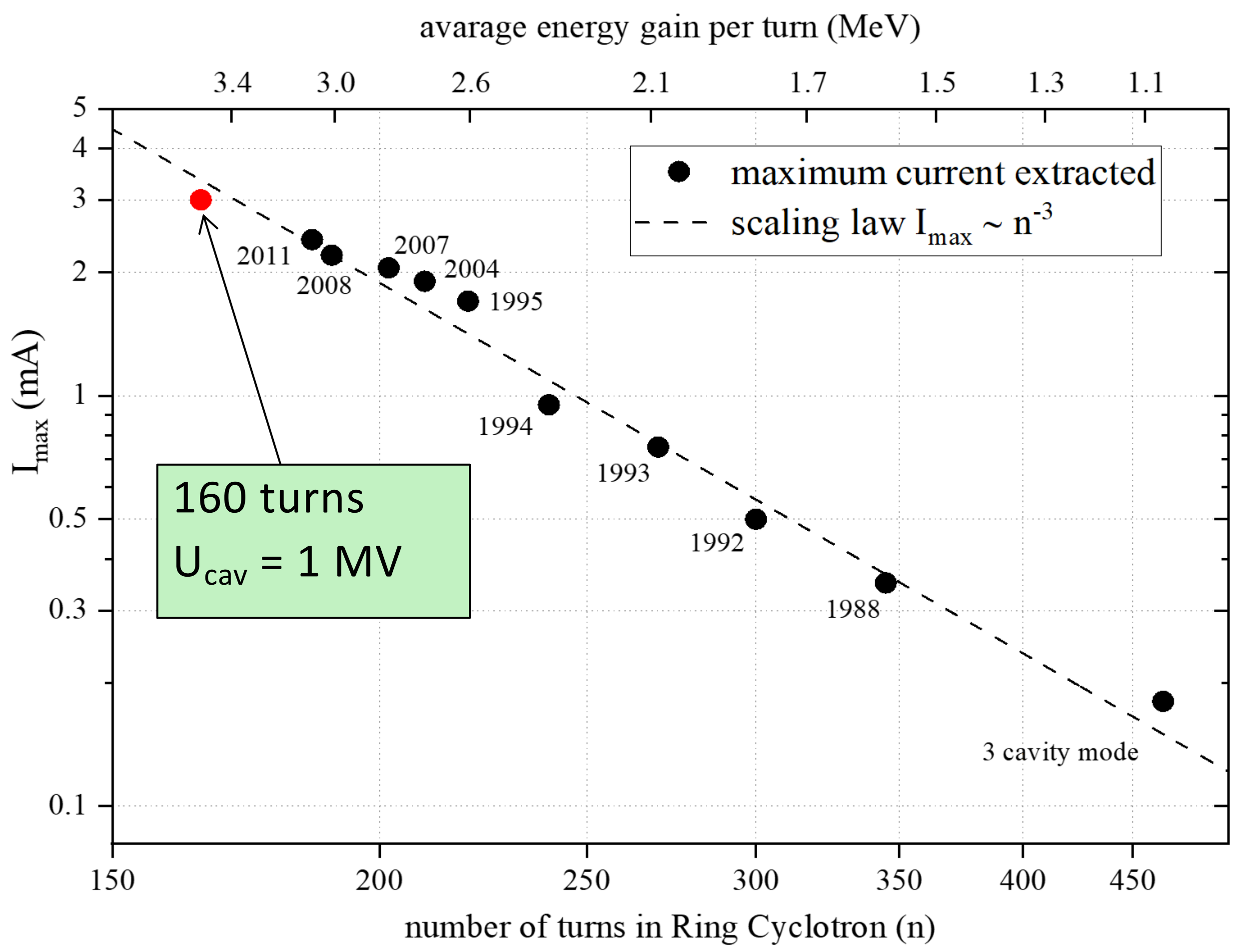


History of the Beam Power

Designed for 60 kW



Scaling Law by W. Joho[1]



Losses scale with

- (turn separation at the extraction)$^{-1}$ $\propto$ **N**
- Charge density in the cyclotron $\propto$ **N**
- Acceleration time $\propto$ **N**

[1] W. Joho, High intensity problems in cyclotrons, Proceedings of the 9th International Conference on Cyclotron and their Applications, pp. 337–47. Les Editions de Physique, BP 112, 91402 Orsay (France), ISBN 978-3-95450-160-1 (1981).

Efficiency and Beam Power

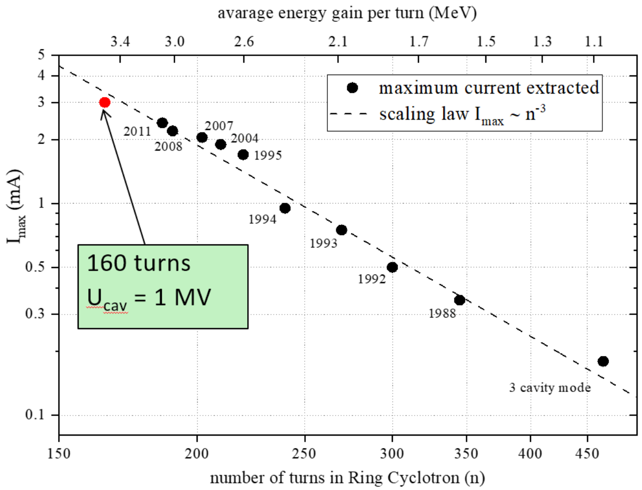


Fig.: number of turns vs beam current

Beam power increases with gap voltage

$I_{max} \sim V^3$ (Joho)

Cavity wall losses increase with gap voltage

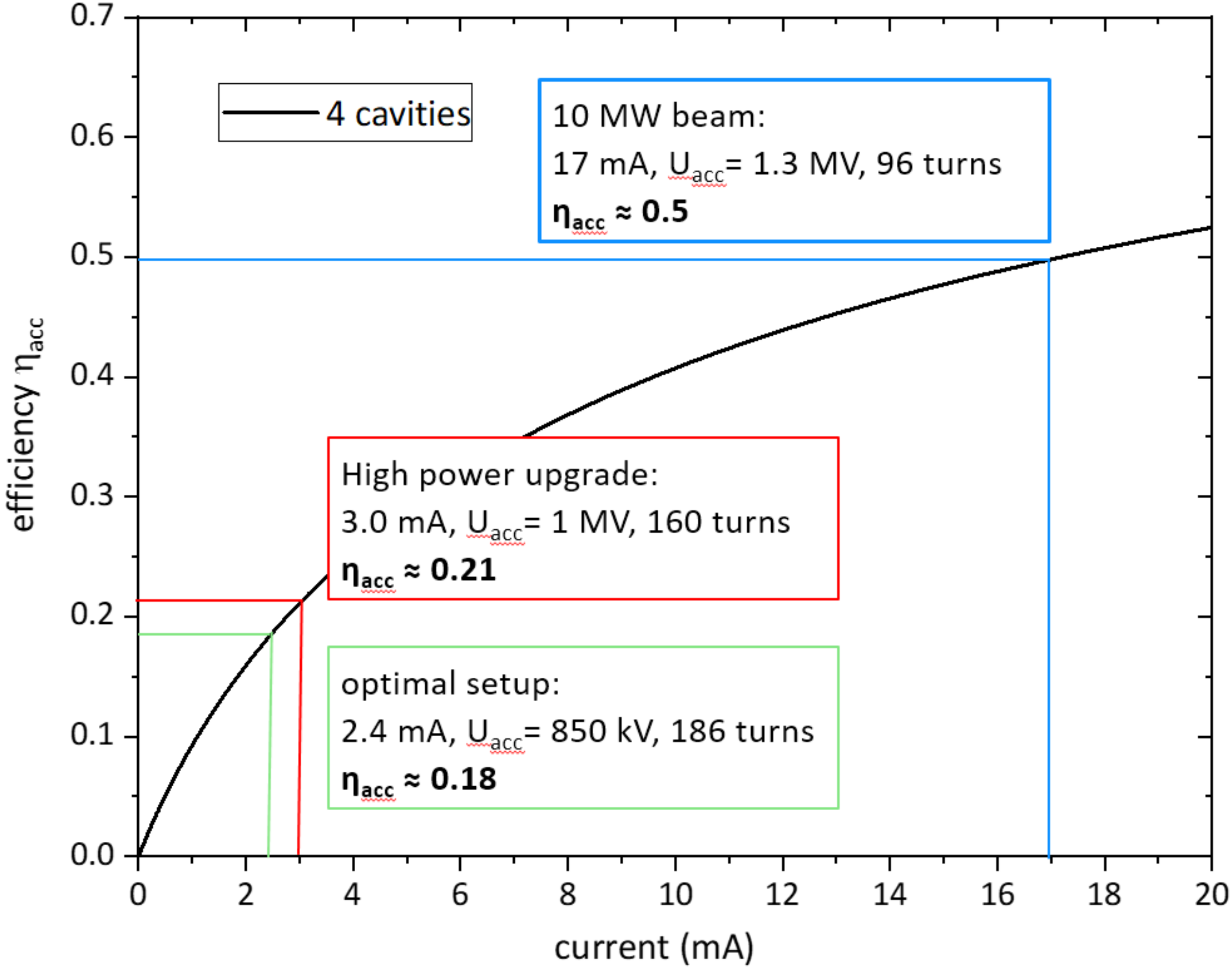
$$P_{loss} = \frac{|V_{acc}|^2}{2 \cdot R}$$

Base load (magnets, infrastructure, instruments, …) stays the same

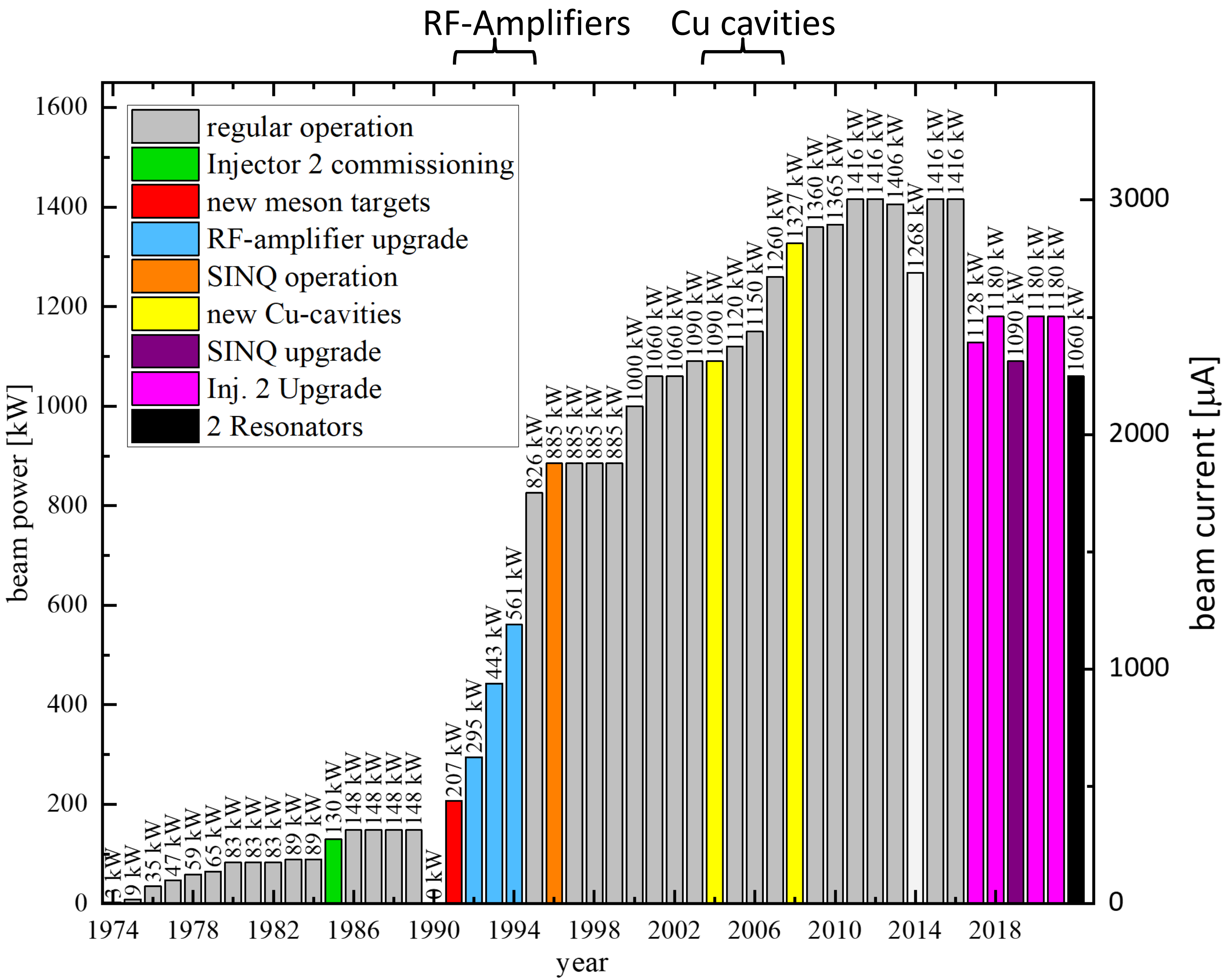
$$\Rightarrow \quad \eta_{acc} = \frac{I \cdot E_{kin} / q}{\frac{(I/c)^{\frac{2}{3}} \cdot E_{kin}^2}{2 \cdot R \cdot q^2} + k \cdot I \cdot E_{kin} / q + P_{aux}}$$

(Grillenberger)

Efficiency vs Beam current

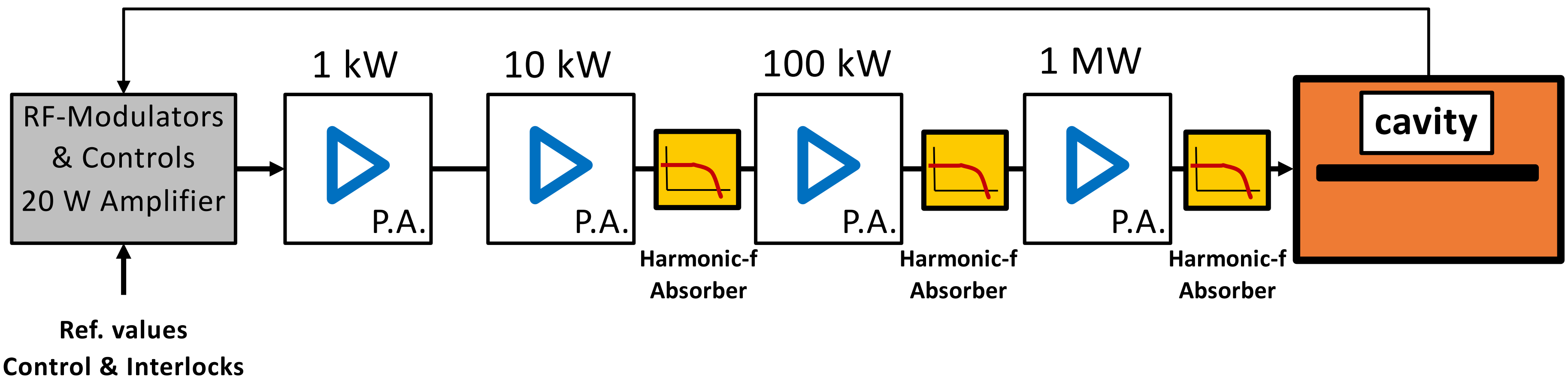


History of the Beam Power



Amplifier Efficiency

4-stage power amplifier chain with power Tetrode Tubes

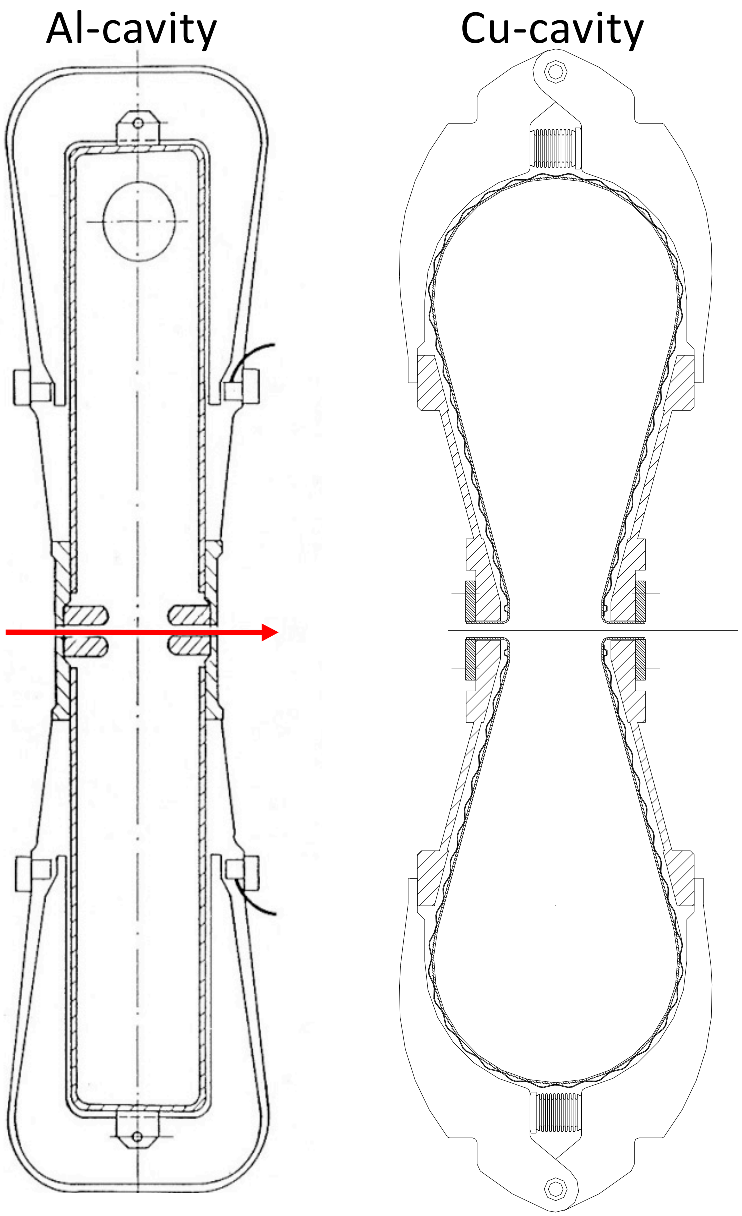


Wall plug to beam efficiency:
- AC to DC: 90%
- DC to RF: 64%
- RF to beam: 55%
- **All over: 32%**

Solid State Amplifiers:
- AC to DC: 90%
- DC to RF: 90%
- RF to beam: 55%
- **All over: 45%**

Huge and expensive (5-10€/Watt)

Cyclotron Cavities



	Al-Cavity	Cu-Cavity
Frequency	50.6 MHz	50.6 MHz
Voltage	750 kV_p	1.2 MV_p
Dissipated Power	300 kW	500 kW
Q-value	28‘000	48‘000
Bandwidth	1.8 kHz	1 kHz
Tuning Range	240 kHz	560 kHz

Efficiency was not really the reason for replacing the cavities

Copper Cavities at PSI

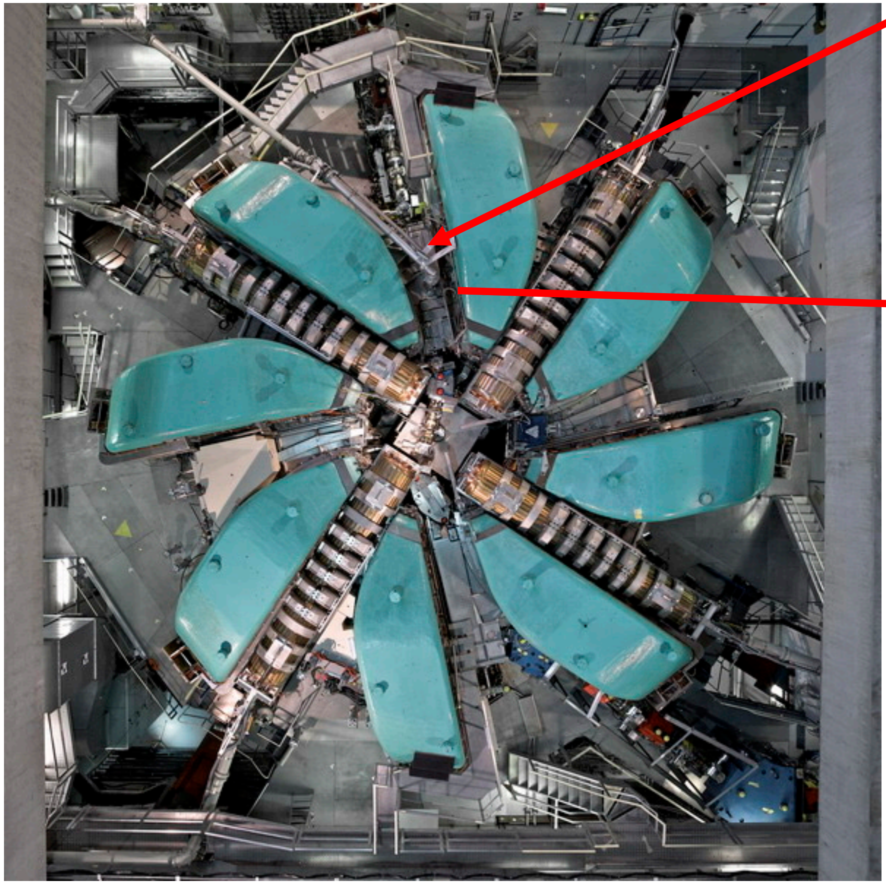
- f = 50.6 MHz
- U_{max} = 1.2 MV (presently 850 kVp)
- Q = $4.8 \cdot 10^4$
- Transfer of up to 400 kW power to the beam per cavity

Inside the resonator

hydraulic tuning devices (5x)

150 MHz Flattop Cavity (1979)

Increase efficiency by decreasing particle losses



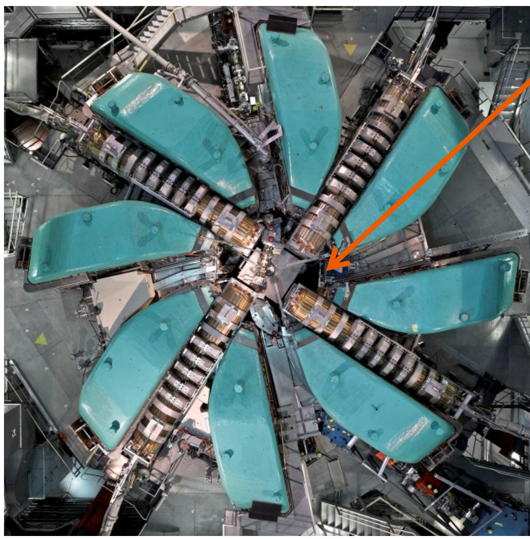
3rd harmonic «flattop» cavity

- 150 MHz
- **550 kVp maximum**
- Q = 28000
- Gap g = 0.4 m

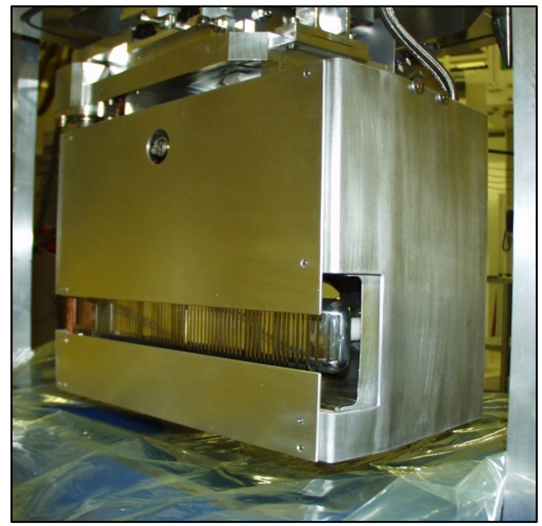
- Larger phase acceptance (40° instead of 9°)
- **Factor of 10 less losses at extraction @ 1mA**
- **Factor of 2 higher beam current**
- **Factor of 1.8 higher effciency**

Extraction with off-center orbits

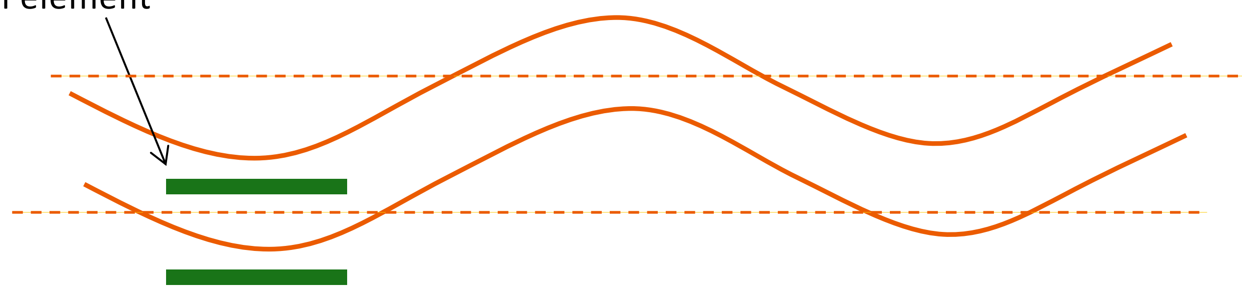
Induce betatron oscillations around the «closed orbit» to increase the radial separation between the last two turns



Electrostatic Injection Channel



Extraction element



Equilibrium orbit

Equilibrium orbit

Extraction with off-center orbits

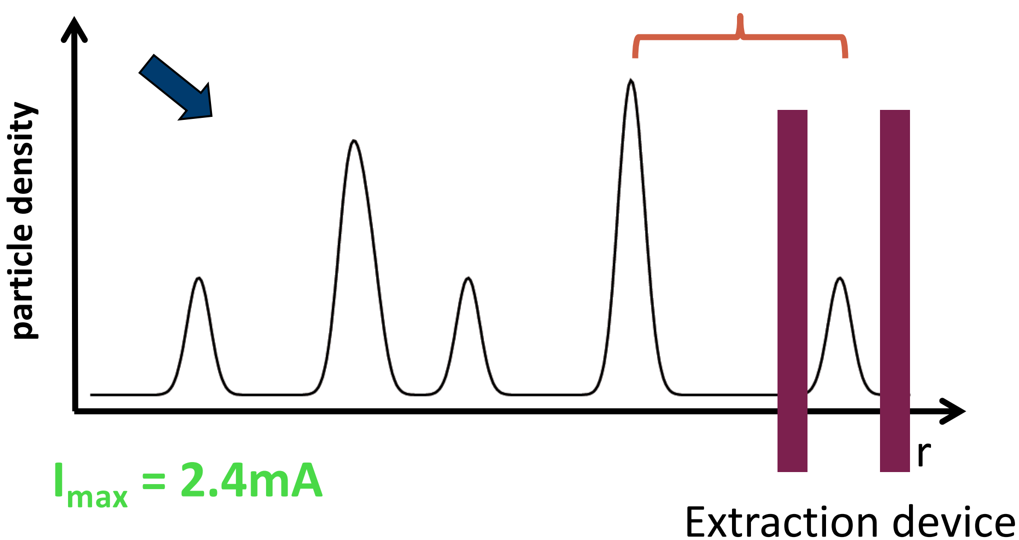
Induce betatron oscillations around the «closed orbit» to increase the radial separation between the last two turns

without orbit oscillations: stepwidth from E_k-gain (PSI: 6mm)

$$\eta_{acc} \approx \frac{1\ MW}{9.5\ MW} \approx 0.11$$

I_{max} = 1.7mA

with orbit oscillations: extraction gap; up to 3 x stepwidth possible (PSI: 18mm)

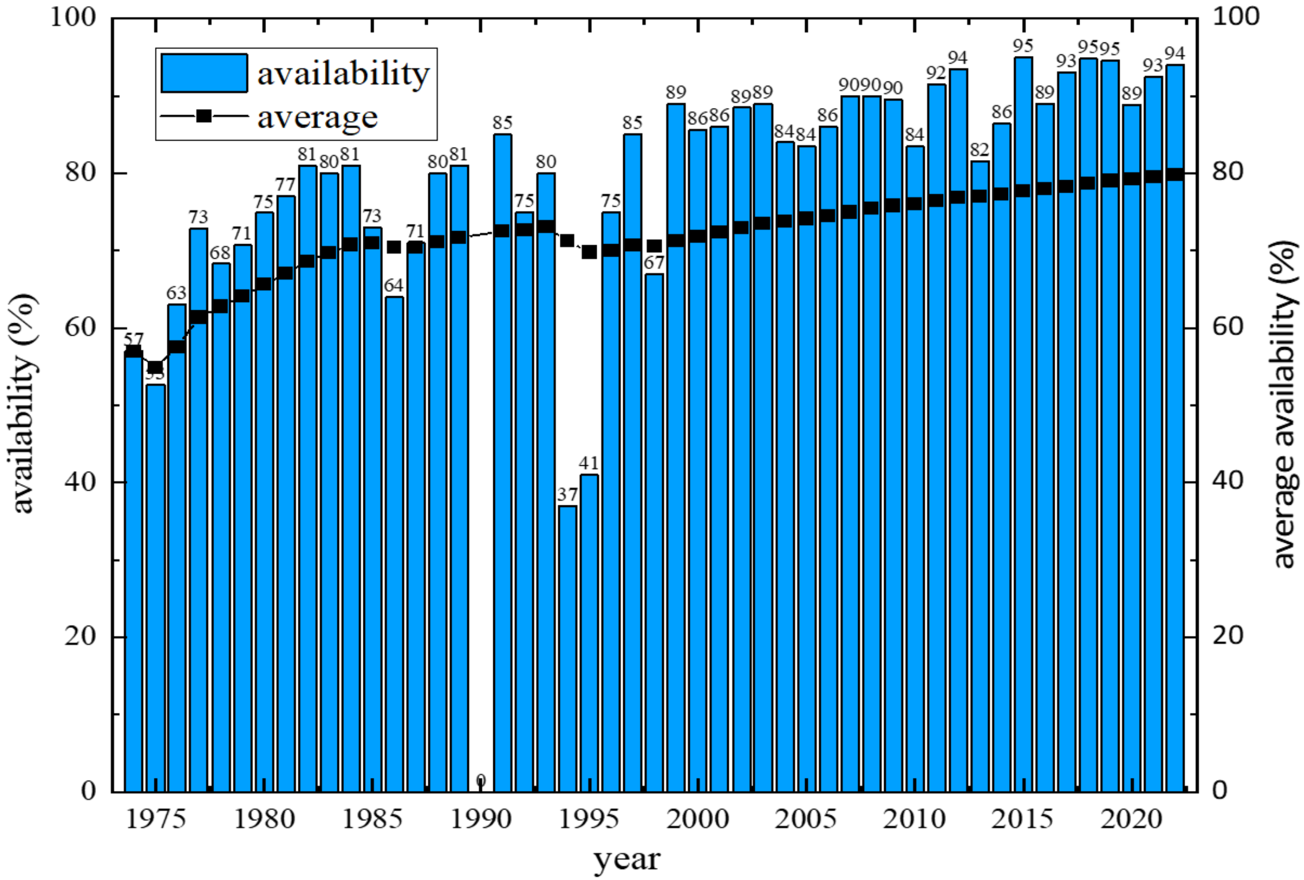


$$\eta_{acc} \approx \frac{1.4\ MW}{10\ MW} \approx 0.14$$

I_{max} = 2.4mA

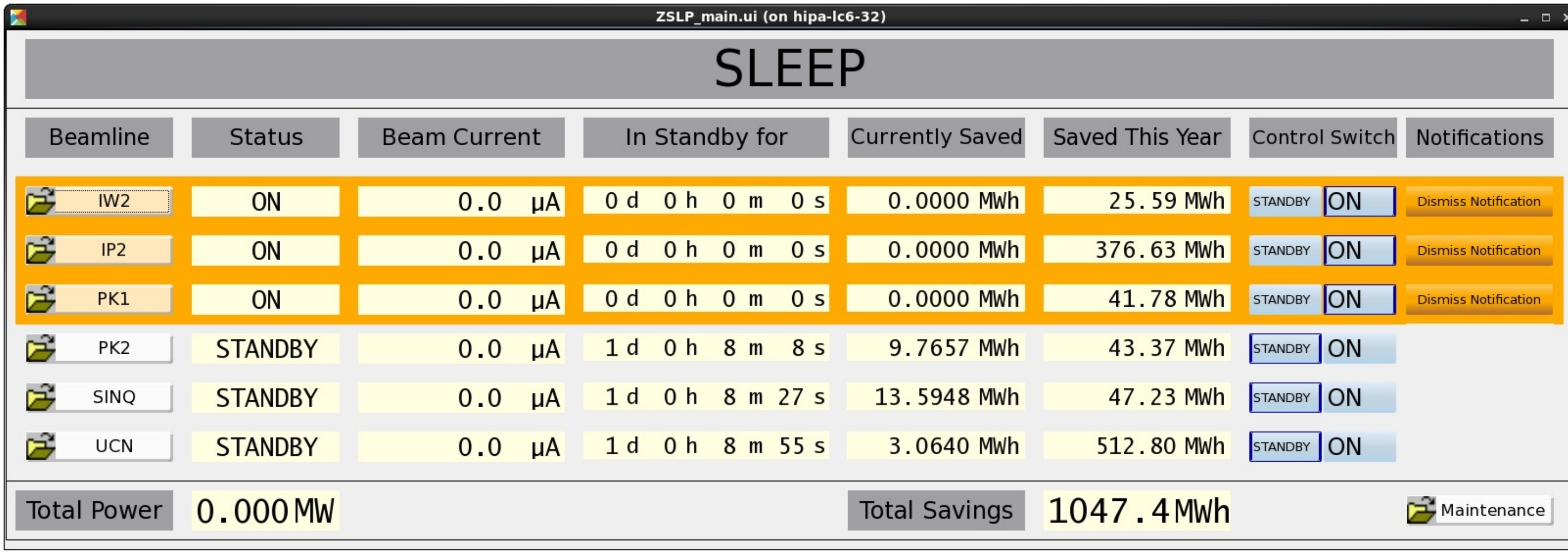
Availability and Efficiency

- **High availability is of uttermost importance for the users (repeat experiments, travel)**
- **Availability has an impact on the energy efficiency especially if systems are running without beam!**



SLEEP at PSI

System for Lucrative Energy Economization in Proton accelerators



Similar to a Start-Stop system in cars

A. Kovach, PSI

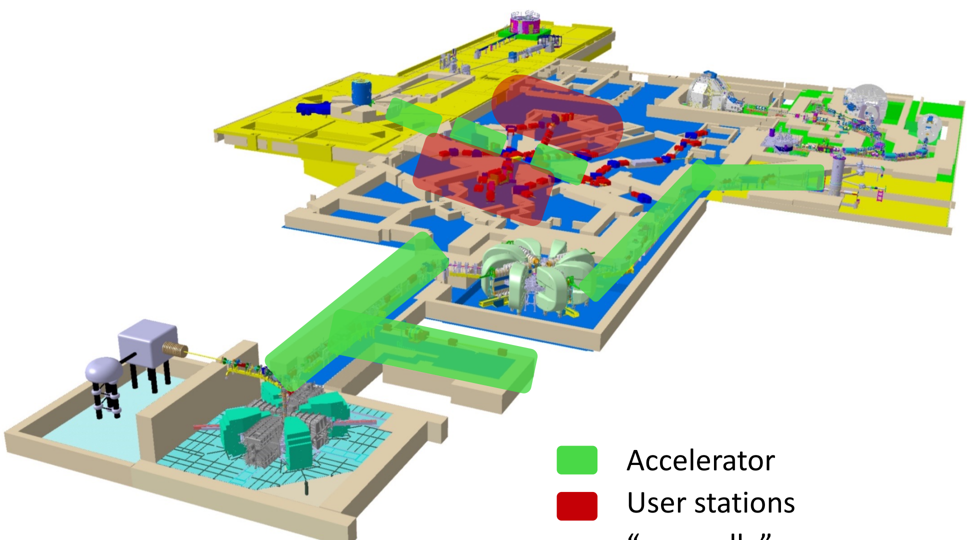
- Runs in parallel with control software EPICS
- Used to switch off beamline magnets during outages
- Intuitive: Switching a set of magnets On/Standby by only one click
- “No-Beam” notification every 30 minutes (orange) for operators
- **Displays and logs the amount of energy saved (refunds!)**

SLEEP Savings

Average power of all beamline magnets (300): ~1.8 MW

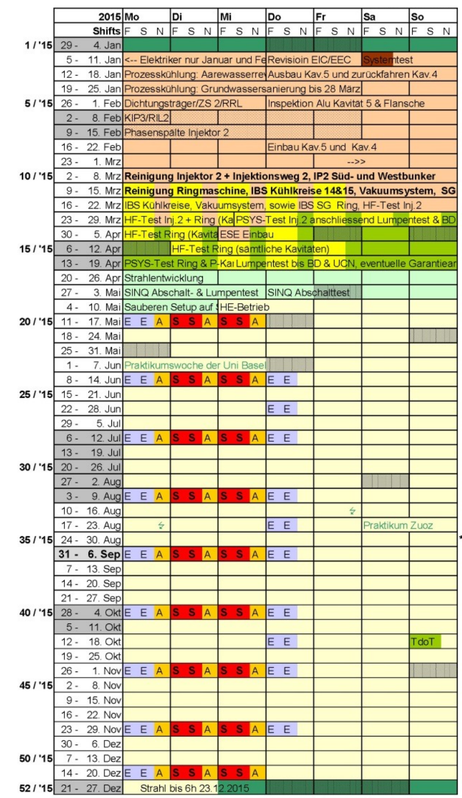
Potential energy savings with 220d of operation*:

- for outages >30min: 570 MWh/a
- Beam development / setup / training: 409 MWh/a



Accelerator

User stations "manually"



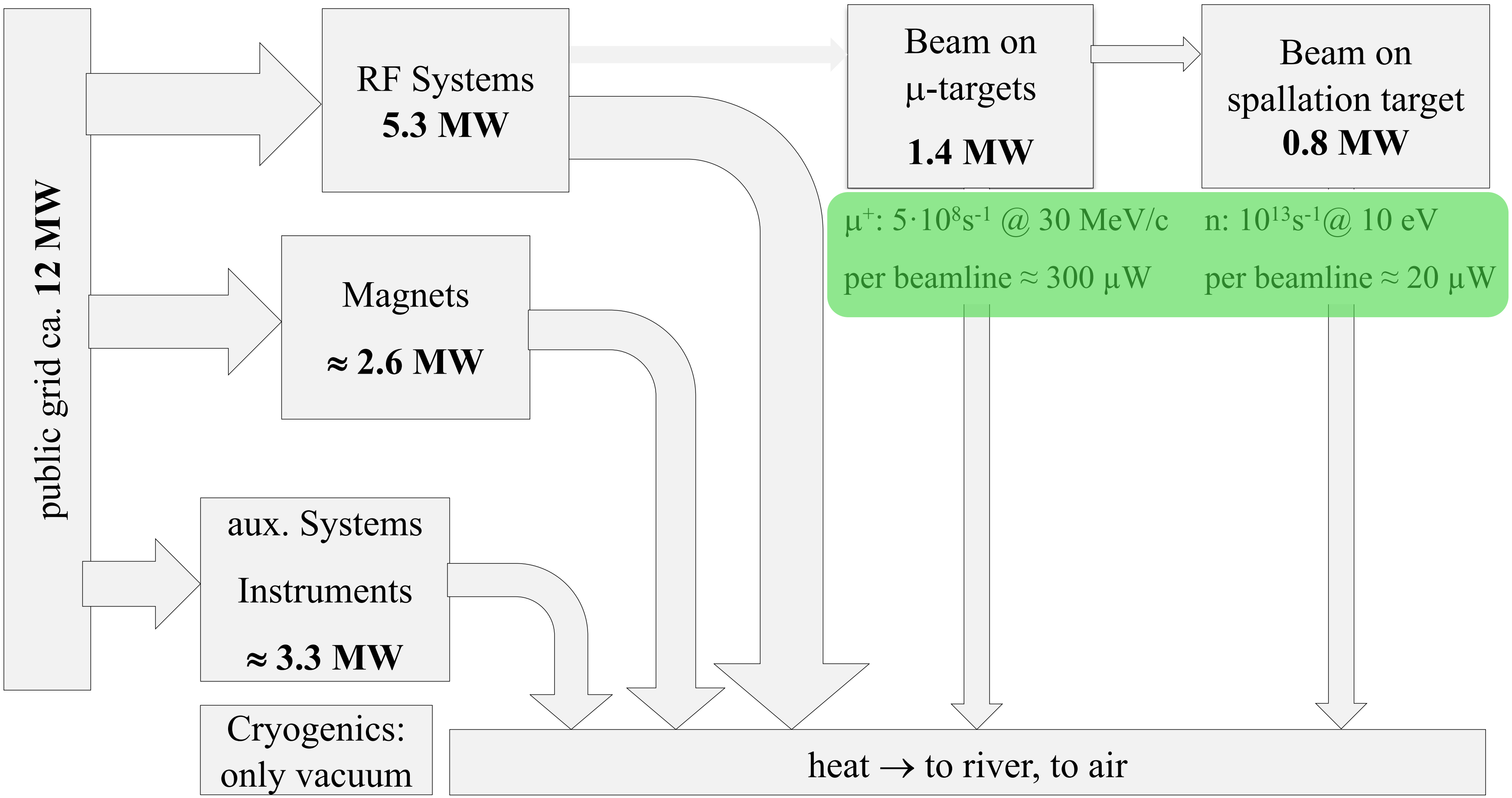
	2015	Mo	Di	Mi	Do	Fr	Sa	So
	Shifts	F S N	F S N	F S N	F S N	F S N	F S N	F S N
1 / '15	29 - 4. Jan							
	5 - 11. Jan	<-- Elektriker nur Januar und Fe			Revisioin EIC/EEC		Systemtest	
	12 - 18. Jan	Prozesskühlung: Aarewasserrev			Ausbau Kav.5 und zurückfahren Kav.4			
	19 - 25. Jan	Prozesskühlung: Grundwassersanierung bis 28 März						
5 / '15	26 - 1. Feb	Dichtungsträger/ZS 2/RRL			Inspektion Alu Kavität 5 & Flansche			
	2 - 8. Feb	KIP3/RIL2						
	9 - 15. Feb	Phasenspälte Injektor 2						
	16 - 22. Feb				Einbau Kav.5 und Kav.4			
	23 - 1. Mrz					-->>		
10 / '15	2 - 8. Mrz	**Reinigung Injektor 2 + Injektionsweg 2, IP2 Süd- und Westbunker**						
	9 - 15. Mrz	**Reinigung Ringmaschine, IBS Kühlkreise 14&15, Vakuumsystem, SG**						
	16 - 22. Mrz	IBS Kühlkreise, Vakuumsystem, sowie IBS SG Ring, HF-Test Inj.2						
	23 - 29. Mrz	HF-Test Inj.2 + Ring (Ka		PSYS-Test Inj.2 anschliessend Lumpentest & BD				
	30 - 5. Apr	HF-Test Ring (Kavitä		ESE Einbau				
15 / '15	6 - 12. Apr		HF-Test Ring (sämtliche Kavitäten)					
	13 - 19. Apr	PSYS-Test Ring & P-Ka		Lumpentest bis BD & UCN, eventuelle Garantiear				
	20 - 26. Apr	Strahlentwicklung						
	27 - 3. Mai	SINQ Abschalt- & Lumpentest			SINQ Abschalttest			
	4 - 10. Mai	Sauberen Setup auf S		HE-Betrieb				
20 / '15	11 - 17. Mai	E E A	S S A	S S A				
	18 - 24. Mai							
	25 - 31. Mai							
	1 - 7. Jun	Praktikumswoche der Uni Basel						
	8 - 14. Jun	E E A	S S A	S S A	E E			
25 / '15	15 - 21. Jun							
	22 - 28. Jun				E E			
	29 - 5. Jul							
	6 - 12. Jul	E E A	S S A	S S A	E E			
	13 - 19. Jul							
30 / '15	20 - 26. Jul							
	27 - 2. Aug							
	3 - 9. Aug	E E A	S S A	S S A	E E			
	10 - 16. Aug					ϟ		
	17 - 23. Aug	ϟ			E E		Praktikum Zuoz	
35 / '15	24 - 30. Aug							*
	31 - 6. Sep	E E A	S S A	S S A	E E			
	7 - 13. Sep							
	14 - 20. Sep							
	21 - 27. Sep							
40 / '15	28 - 4. Okt	E E A	S S A	S S A	E E			
	5 - 11. Okt							
	12 - 18. Okt				E E			TdoT
	19 - 25. Okt							
	26 - 1. Nov	E E A	S S A	S S A	E E			
45 / '15	2 - 8. Nov							
	9 - 15. Nov							
	16 - 22. Nov							
	23 - 29. Nov	E E A	S S A	S S A	E E			
	30 - 6. Dez							
50 / '15	7 - 13. Dez							
	14 - 20. Dez	E E A	S S A	S S A				
52 / '15	21 - 27. Dez	Strahl bis 6h 23.12.2015						

*average downtime 170h/a

average outage time: 120 min (average over past 10 years)

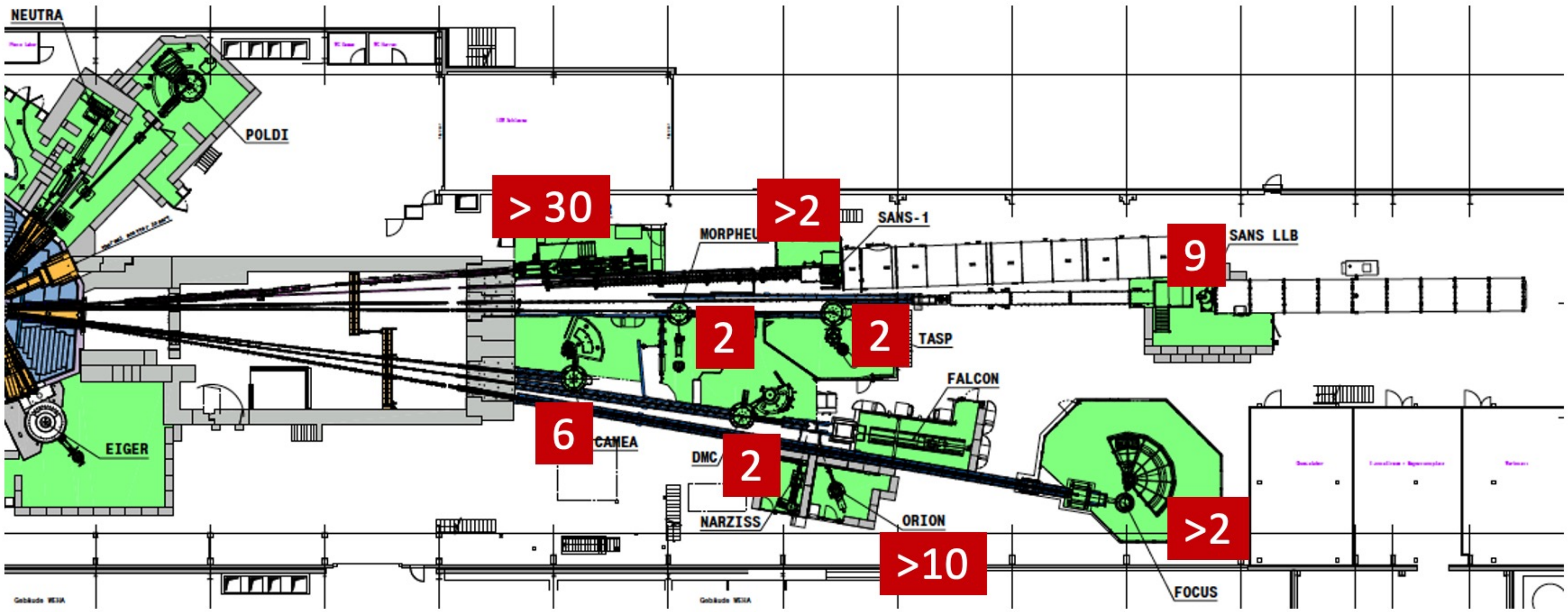
Grid to Beam Power Conversion

Secondary particle flux is the key figure for users



Steps Towards a Higher Efficiency SINQ – Upgrade 2019

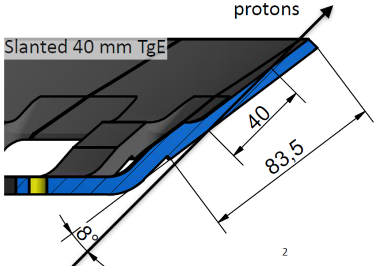
- Replacement of neutron guides
- optimization of instruments
- Optimization of D_2O moderator geometry

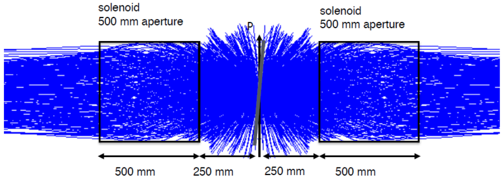


- measured flux gains ranging from 2–30 depending on the instrument
- signal to noise ratio increased by a factor of 6
- Accelerator can't compete ☹

The High Intensity Muon Beam Project
Financial period: 2025 – 2028

- New target design (slanted)
- New beamline setup (solenoids)
- Factor of 100 higher muon rate (10^{10} muons/s)





Heat Recovery

Office heating

Connected wattage 2 MW

- Cooling power primary circuit 7 MW
- Cooling power secondary circuit 3 MW

Operating load:

- Primary circuit 0.3 MW
- Secondary circuit 0.25 MW

Overall efficiency: 94%

9 GWh / year

Improvements:

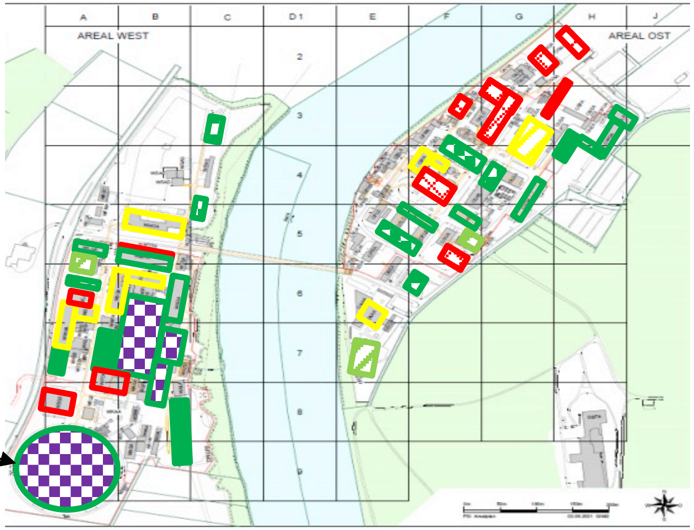
- Energy recovery
- Piping design (higher cross section)
- Office and district heating
- Heat pumps

Photovoltaics at PSI

Nr. of PV modules (340 W):	936
Total surface:	5’500 m^2
Peak power:	600 kW
Energy yield 2021:	600 MWh (0.4% PSI)
Costs:	1’425’000.- CHF
Write-off:	25 years with ∅ 6,5 ct/kWh
Commissioning:	October 2020

Feasability study:

Total surface:	40’000 m^2
Peak power:	5-7 MW (5% PSI)
Total cost (including restoration)	11 Mio CHF



Cryogenics
He-Compressors

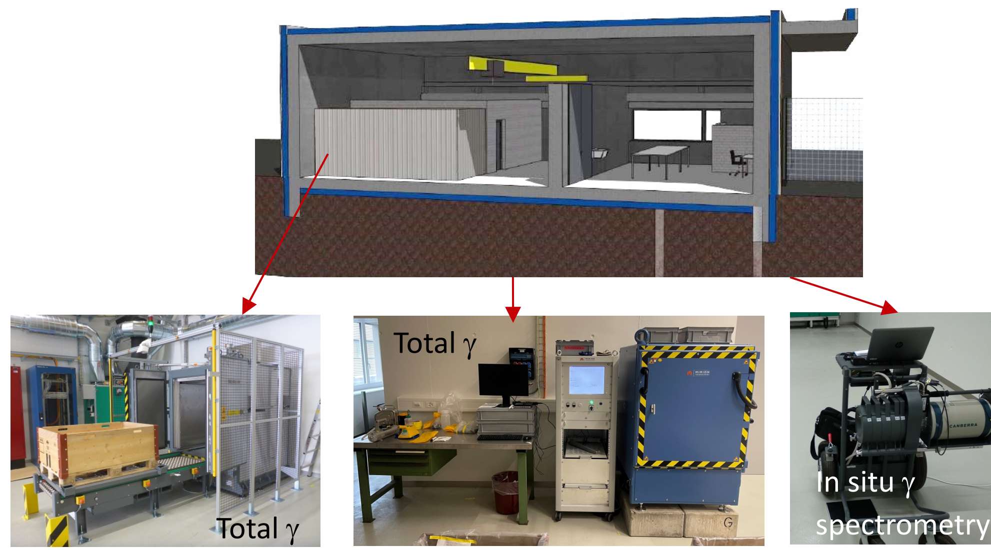
Replacement of piston compressors with screw compressors

- 180 kW lower power consumption
- 1.3 GWh yearly savings

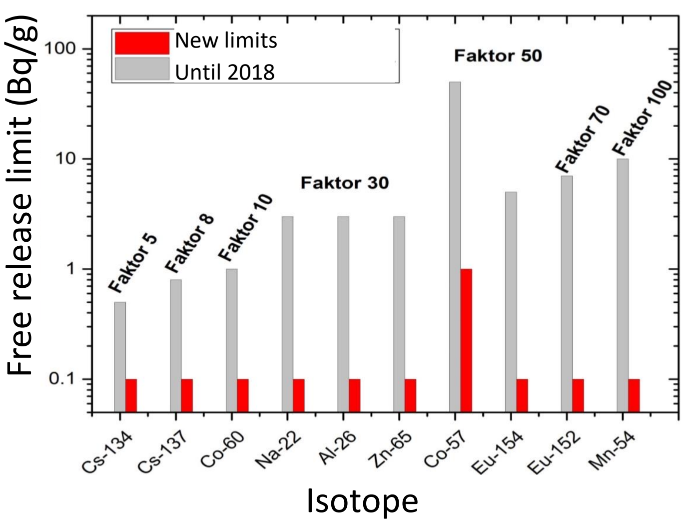
PAUL SCHERRER INSTITUT PSI

Characterization of activated material

- Building with necessary infrastructure available (total γ, in-situ γ spectrometry)
- Experience from former and ongoing dismantling projects (e.g. injector 1)
- Waste sorting
- Re-use of activated material



New Radiological Protection Ordinance 2018



Energy Issues at PSI in 2022

- 133.5 GWh of electric energy were purchased for 2022
- Fixed price is 60.71 CHF/MWh
- The fixed prices is valid within +/- 5%

PSI electric power consumption 2022

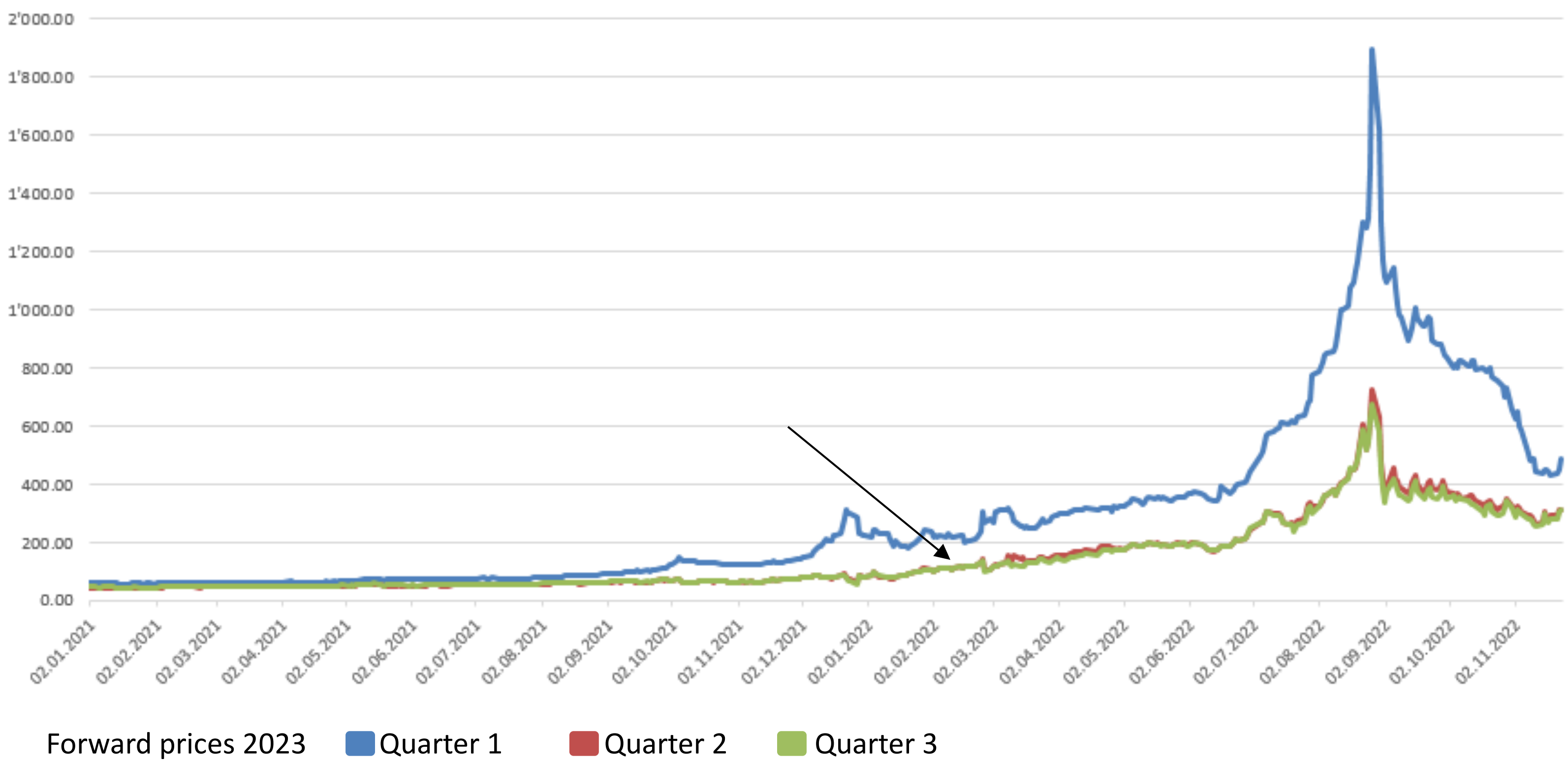
PSI total actual (MWh)
PSI total forecast (MWh)

- above 5%, a penalty + spot market price applies
- currently PSI is 6% above forecast

Electricity Price

Development 2022

Forward prices of quarterly products (Status 23.11.2022)



- Spot price 23.11.2021: ca. 43 EUR/MWh
- Spot price maximum 30.08.2022: ca. 720 EUR/MWh
- Spot price 25.11.2022: ca. **280 EUR/MWh**

With 1% above the forecast, ca. 700 000 EUR could incur for PSI

Measures to save Energy

SwissFEL

- Shutdown 11 days earlier: 450 MWh
- 50 Hz instead of 100 Hz operation: 325 MWh

SLS

- 2 days of additional Shutdown: 100 MWh

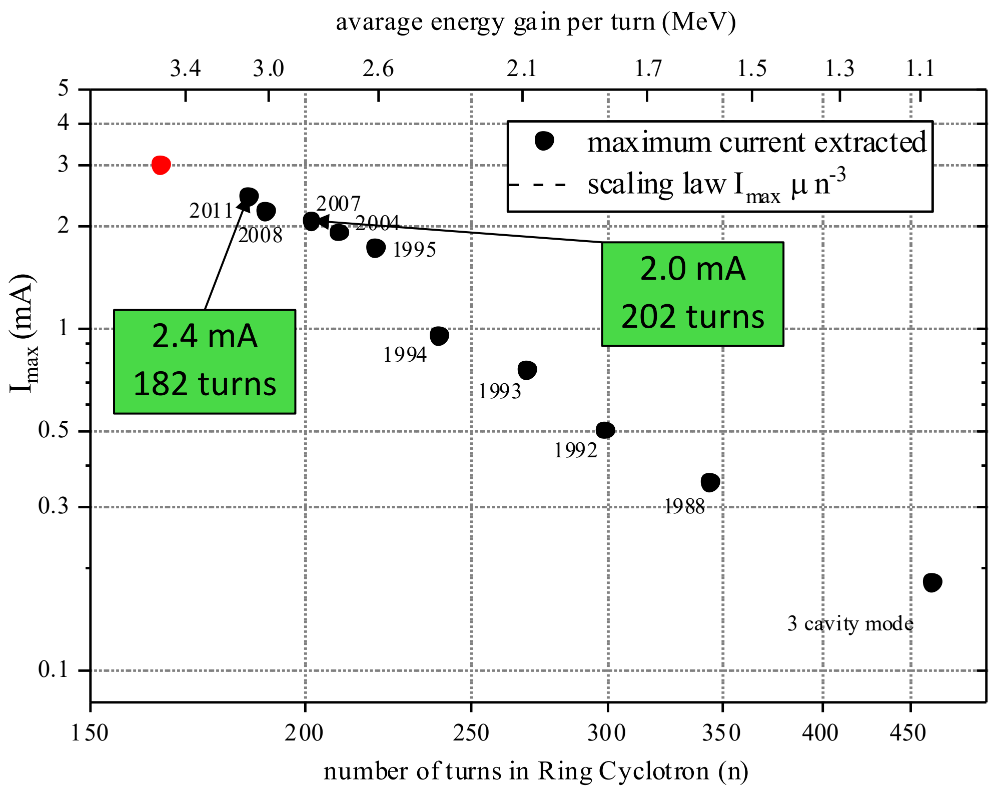
Proton Facility

- Shutdown 5 days earlier: 1150 MWh
- No beam development: 280 MWh
- Unexpected conditioning flattop: -100 MWh

2205 MWh

To save ca. 14 GWh in 2032, measures also taken in 2023
definite SLS darktime in October 23 (4500 MWh) -> SLS 2.0 Upgrade

Efficiency and beam current



$182\ turns$: $|U_{cav}| \approx 850\ kVp$
RF losses: ≈ 900 kW

$202\ turns$: $|U_{cav}| \approx 760\ kVp$
RF losses: ≈ 720 kW
savings ca. 180 kW

$flattop$: $|U_{cav}| \approx 470\ kVp$
savings ≈ 20 kW

Current reduction 2.0 to 1.8 mA
$590\ MV \cdot 0.2\ mA = 120\ kW$

RF-Amplifier efficiency (0.6)

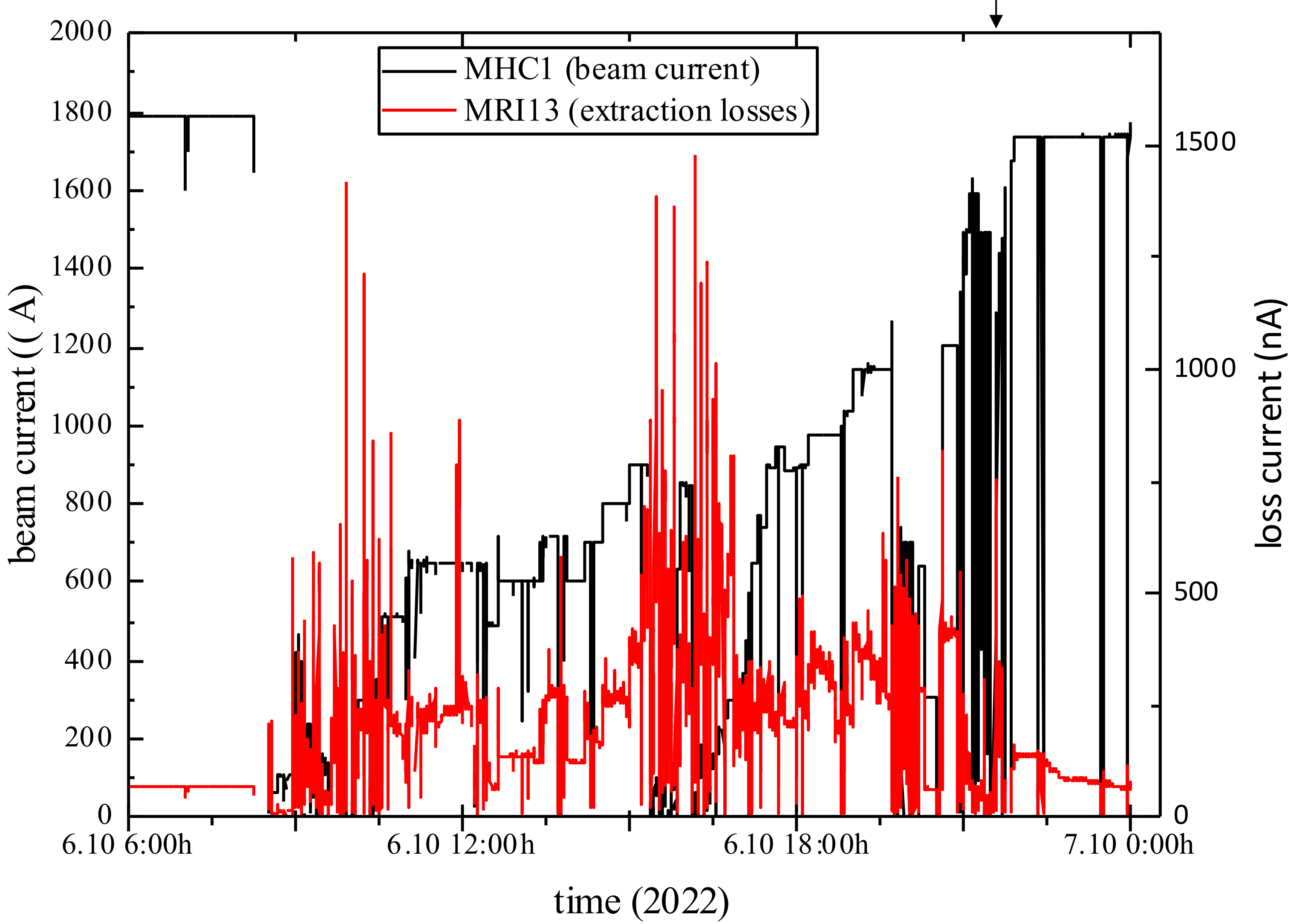
$$\frac{900 - 720 + 20 + 120}{0.6} = 500$$

Total savings at 1.8 mA: **0.5 MW**
During 70 d of operation: **840 MWh**
Corresponds to 3 days of user operation

Increase of Number of Turns

Gap voltage 760 kVp (202 turns)

Back to normal (850 kVp, 182 turns)

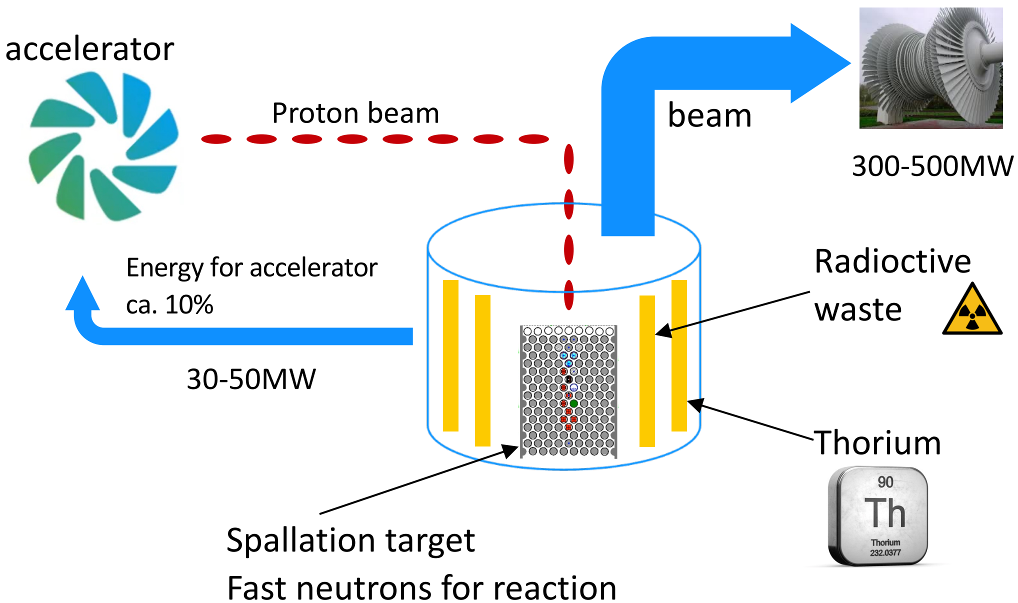


Cyclotrons for Accelerator Driven Systems

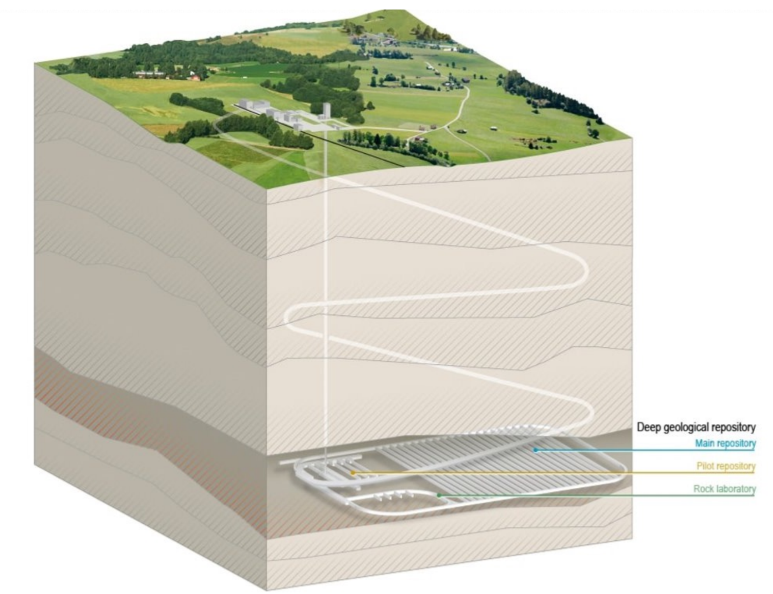
The energy efficiency is specifically important within the context of
Accelerator Driven Systems
E.g.: power generation with a Thorium subcritical device

Transmutation of Radioactive Waste

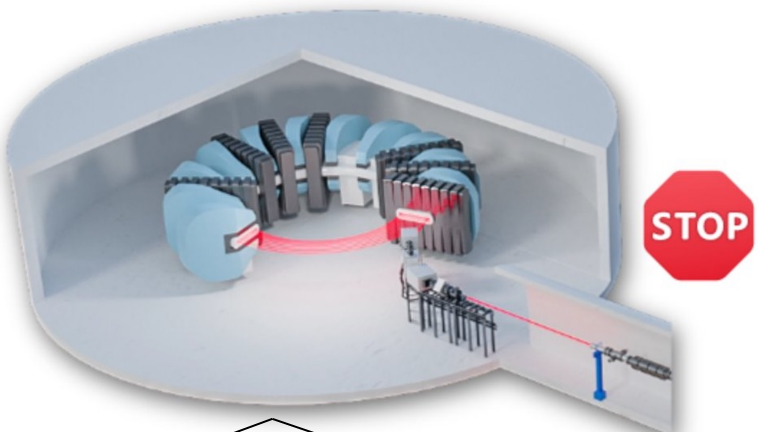
Accelerator Driven System



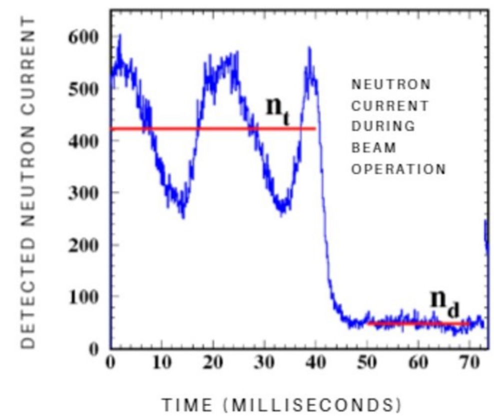
Finite space of deep geological storage

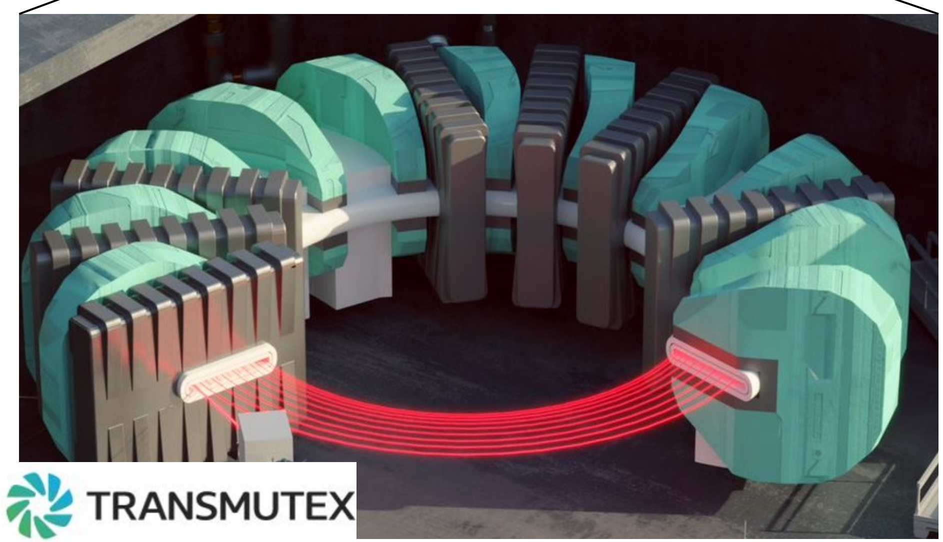


Intrinsic Safety from Subcriticality

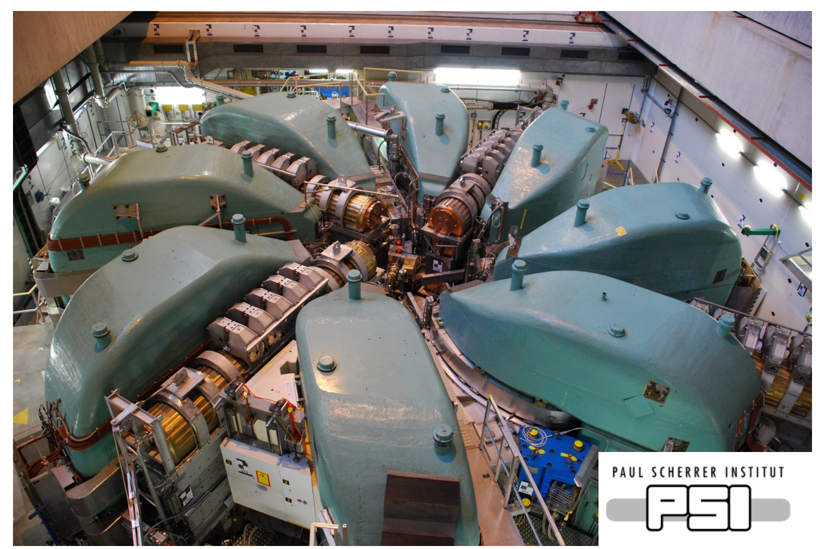


2 ms

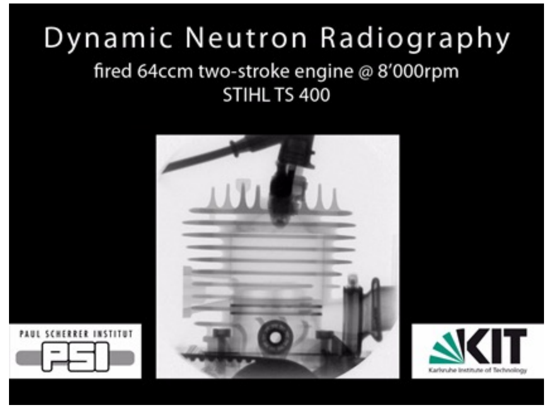


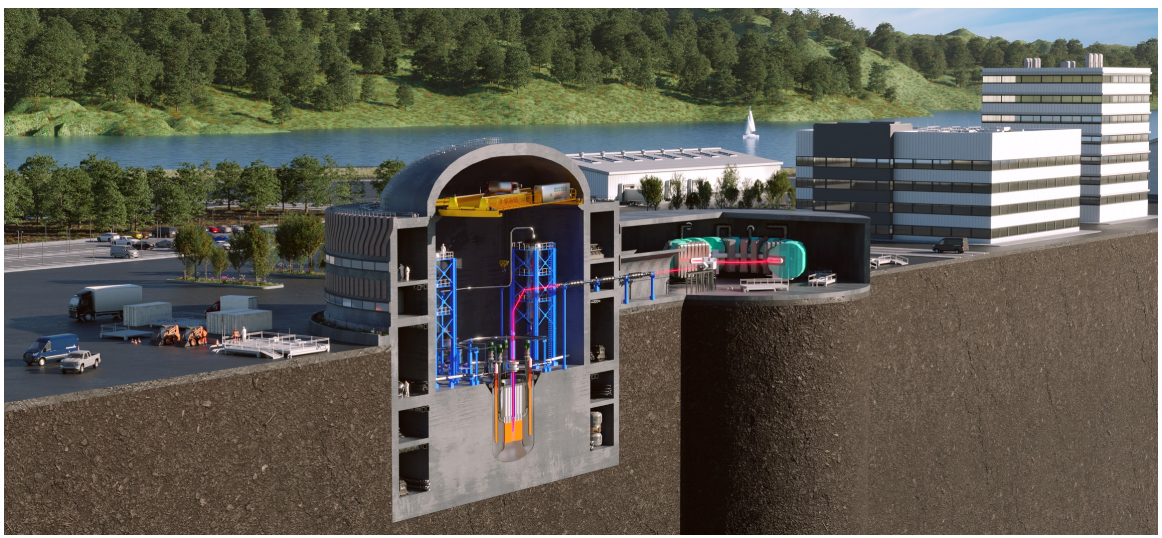


Framework agreement of accelerator



Is a Megawatt Accelerator Sustainable?





Yes, especially if the most efficient system is being used. A Cyclotron.

PSI is a Nature Sanctuary

My thanks go to

- My Colleagues

- Your attention!

Some Sustainability Attempts at PSI

Mobility

- „free" use of eBikes
- Half-fare tickets
- Free charging eCars
- CO_2 compensation travelling
- Remote work

Environment

- Afforestation
- Food waste

  Less meat
- Green Team
- Nature Sanctuary