PAUL SCHERRER INSTITUT

PSI

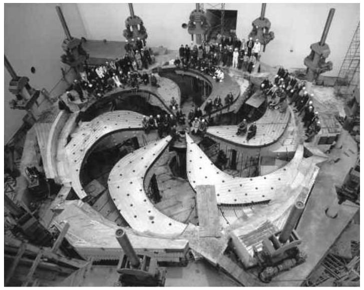
Joachim Grillenberger :: High Intensity Proton Accelerator :: Paul Scherrer Institute

The Energy Efficiency of Cyclotrons

21st International Conference on Cyclotrons and their Applications

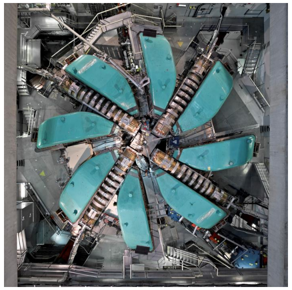
Cyclotron Efficiency - Motivation

TRIUMF 520 MeV protons

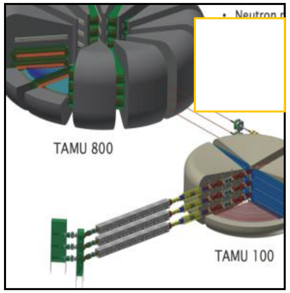


RIKEN K2600 cyclotron

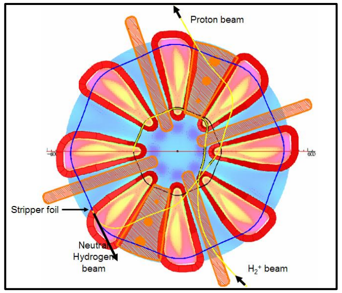
PSI 590 MeV Ring



Texas A&M TAMU



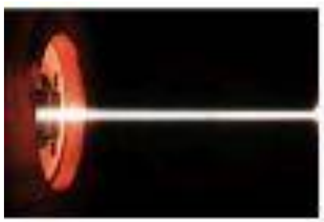
H_2^+ DAEδALUS



- **Cyclotrons cover a broad spectrum of applications**
  - 1200 cyclotrons for nuclear medicine and isotope production
  - 150 commercial cyclotrons
  - 80 cyclotrons for individual applications mostly to generate secondary particles at high intensities (neutrons, muons, neutrinos...)

- **High power machines consume large amounts of electrical energy**
- **Scientists want even better flux, rate, brightness, luminosity...**
- **Even more power is needed**
- ➢ **Energy efficiency becomes a critical aspect**

"This aspect is seen more and more critical in the public society and in funding agencies. New projects and operating facilities must focus on improving the energy efficiency with a higher priority."



EuCARD²

Provides networking

Proton Driver Efficiency Workshop at PSI

- Physics demands
- Efficiency of different acc. concepts
- Targets, RF, ...
- Conventional Systems

http://indico.psi.ch/event/Proton.Driver.Efficiency.Workshop

http://www.psi.ch/enefficient

Idea:	comprehensive approach that covers the entire power chain from grid to user
Goal:	Assess the state of the art and development for each stage. Determine R&D recommendations in each field.

M. Seidel, Pdriver'16

Efficiency of Cyclotrons

COMET 250 MeV
Medical Cyclotron

direct beam application

200 kW from public grid

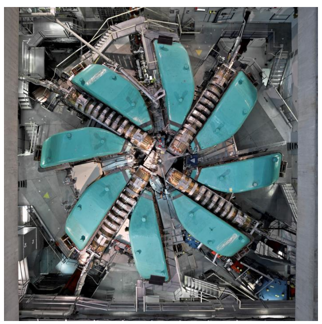
1 μA for patient treatment (250 W beam power)

efficiency ≈ 0.13% (P_{beam}/P_{grid})

running costs for electricity: ≈ 100 ksFr/year

(cost efficient... I think...)

PSI 590 MeV cyclotron



secondary radiation

10 MW from public grid

1.4 MW beam power (2.4 mA)

efficiency 14%

running costs for electricity: 5 MsFr/year

(cost efficiency hard to determine... for me)

μ^+: $5\cdot10^8 s^{-1}$ @ 30 MeV/c
per beamline ≈ 300 μW

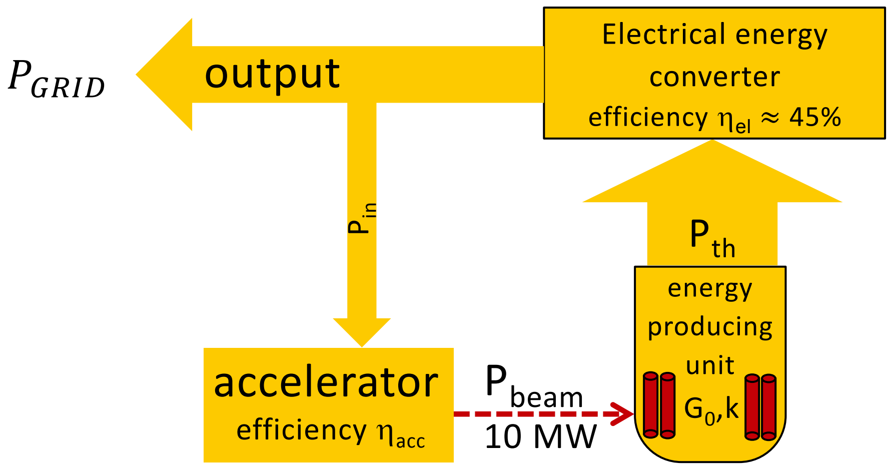
The energy efficiency is not a primary parameter, it is determined and limited by

- The applications of the accelerator
- The accelerator parameter range

⇒ The efficiency of accelerators can only be compared for the same application and for the same basic parameters

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 reactor)



Electric conversion efficiency

$$P_{el} = \eta_{el} \times P_{th}$$

Energy gain in core

$$P_{th} = P_{beam} \times \frac{G_0 k}{1-k}$$

G_0: gain proportionality factor ≈ 2.4

k: fission driven coefficient ≈ 0.98

Running the accelerator

$$P_{beam} = \eta_{acc} \times P_{in}$$

$$P_{GRID} = P_{el} - P_{in} = P_{beam}\left[\frac{\eta_{el} G_0 k}{1-k} - \frac{1}{\eta_{acc}}\right]$$

Power produced by the reactor

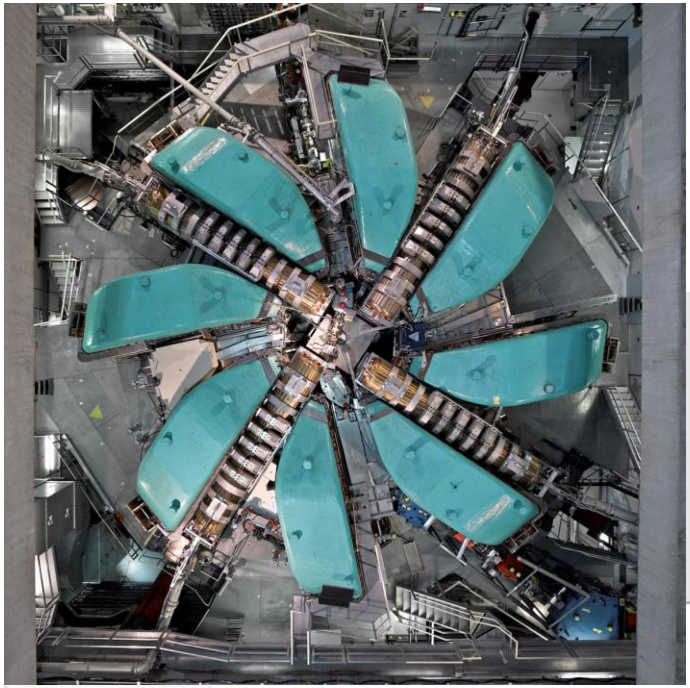
Electric power to run the accelerator

For a typical "Rubbia ADS*" $\approx 50 \Rightarrow \eta_{acc} \gg 0.02$ (breakeven, 0.2 desired)

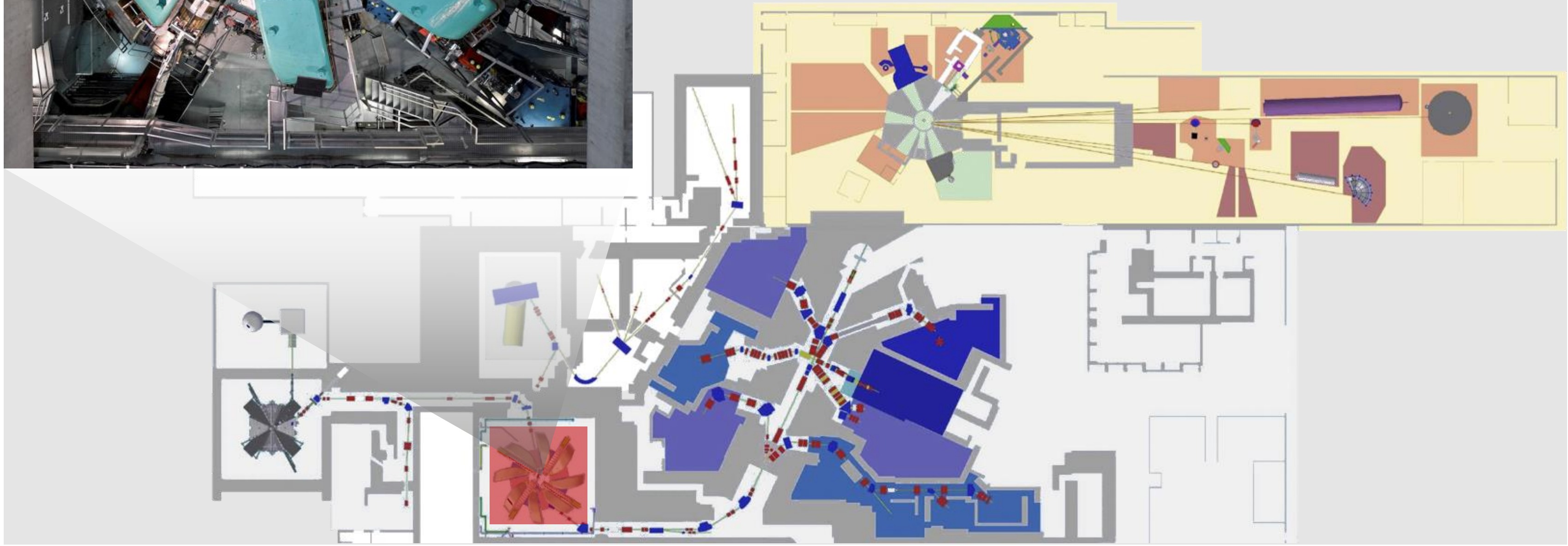
Jean-Pierre Revol, pDriver-Workshop 2016

*C. Rubbia et al, CERN/AT/95-44 (ET)

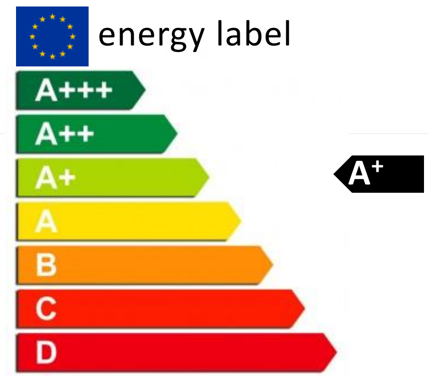
High Intensity Proton Accelerator Facility



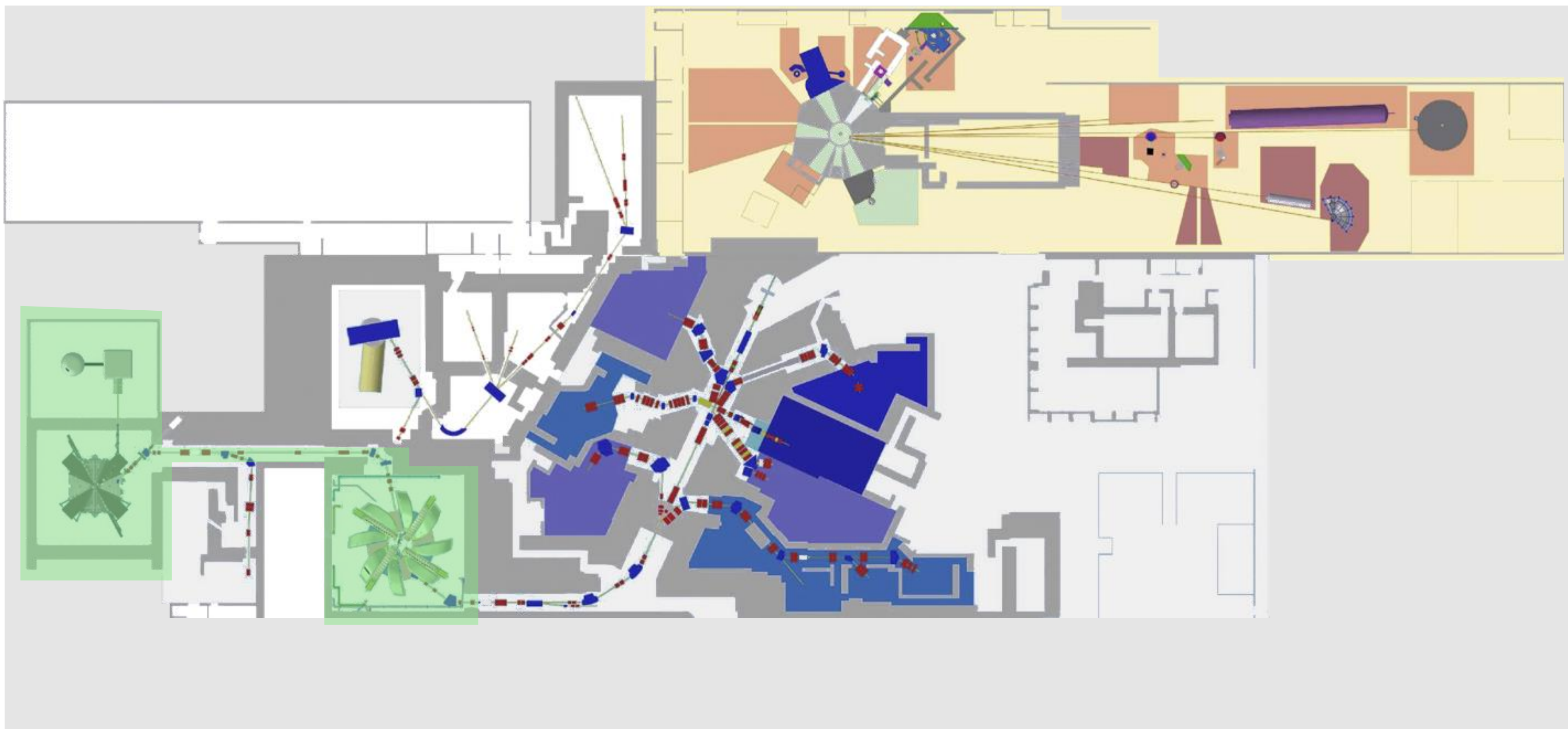
Ring Cyclotron: 590 MeV
1.4 MW beam power (2.4 mA)
186 turns
8 sector magnets



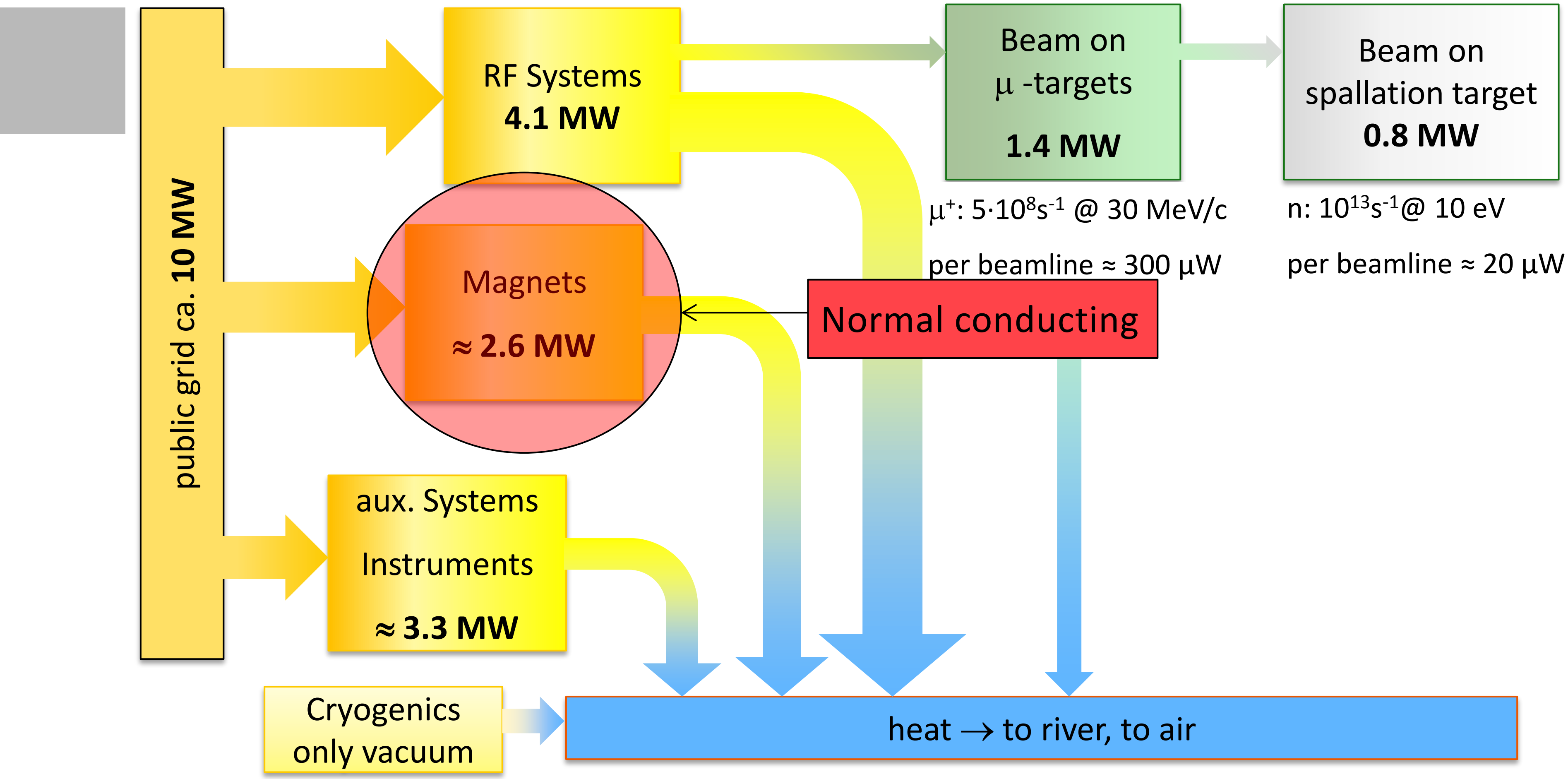
Overall Efficiency



Total power consumption:	10 MW
Beam Power:	1.4 MW
Efficiency:	14%
Just the accelerator:	**18%** (8 MW)



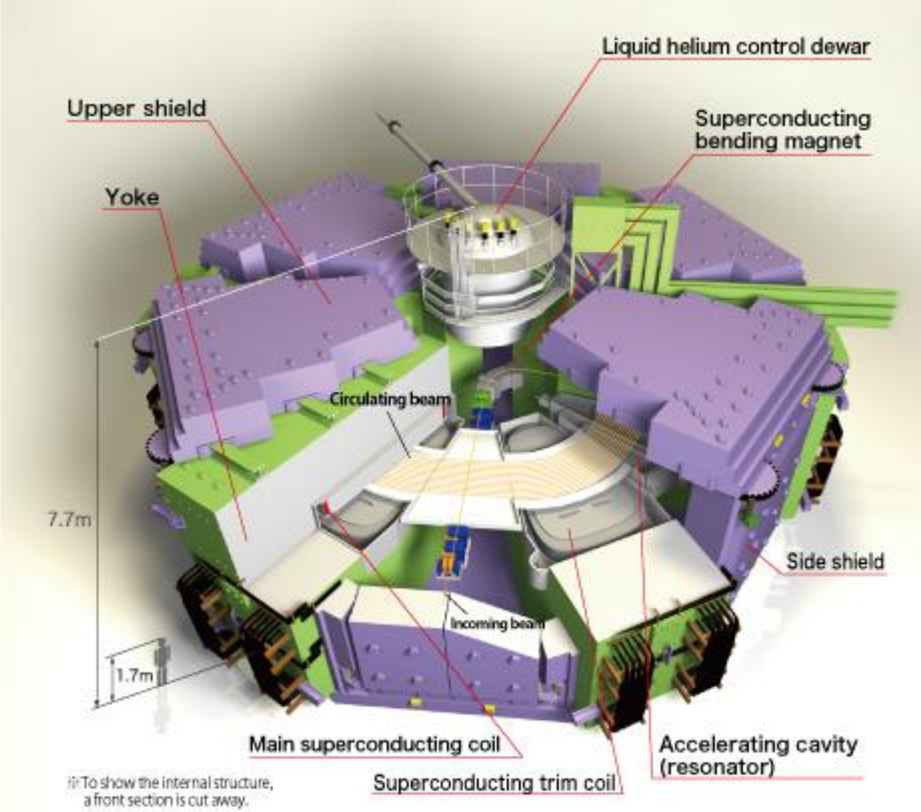
Grid to Beam Power



Potential Optimizations for Cyclotrons

RIKEN Superconducting Ring Cyclotron

Superconducting magnets
- **Lower energy consumption**



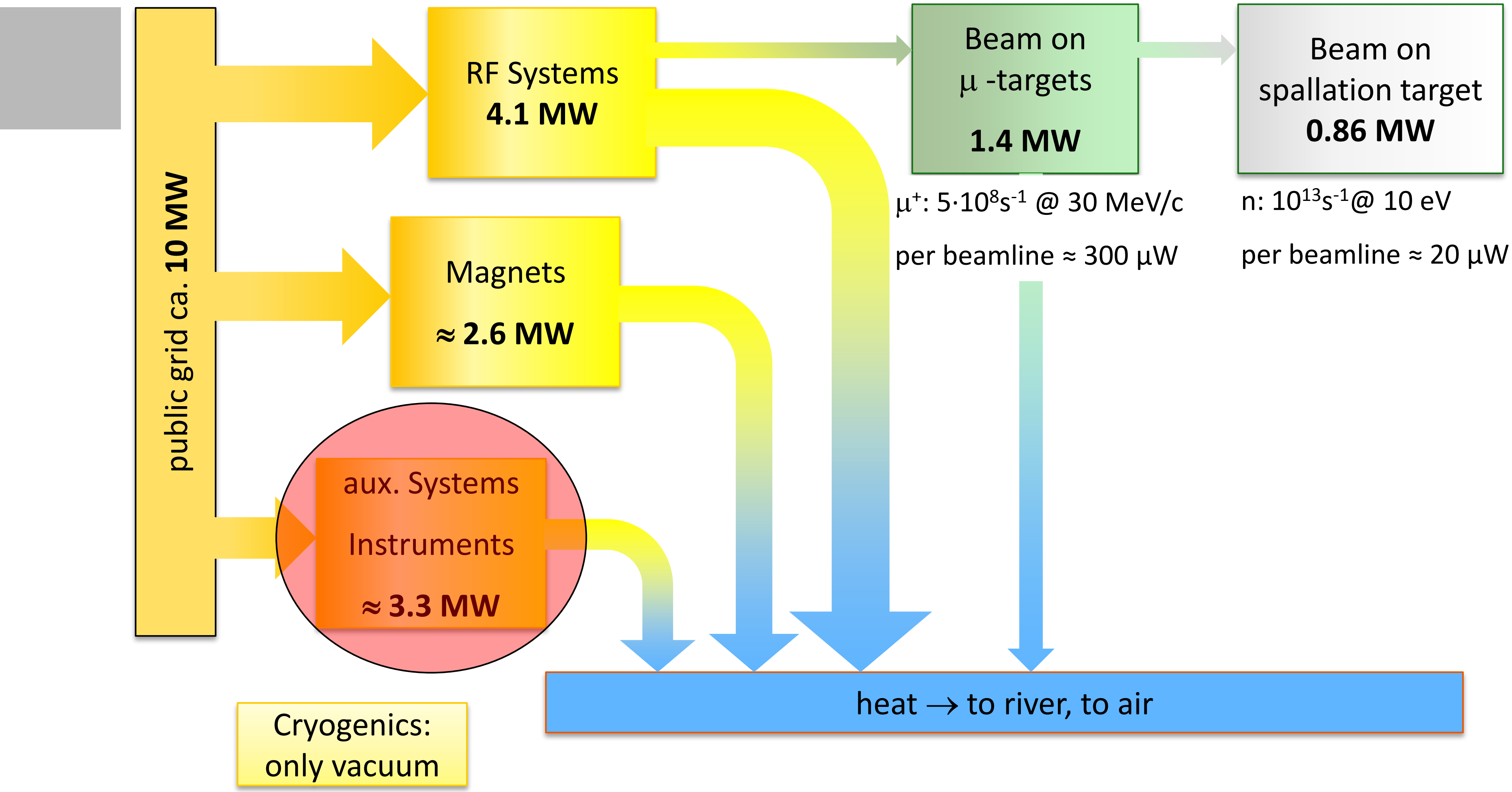
Utilization:
Acceleration of a broad spectrum of ions up to Uranium

K = 2600 MeV
- 350/400 MeV per nucleon
- 6 superconducting sector magnets
- 8 Tm bending power (3.8 T)
- 4 RF resonators
- RF frequency 18-38 MHz
- Injection and extraction elements
- 19 m diameter
- 8 m height
- 8300 t total weight

650 kW for magnets/cryogenics

15 MW total power consumption
Hiroki Okuno priv. comm.

Grid to Beam Power



Cooling Circuit Efficiency

Office
heating

Connected wattage 2 MW

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

Operating load:

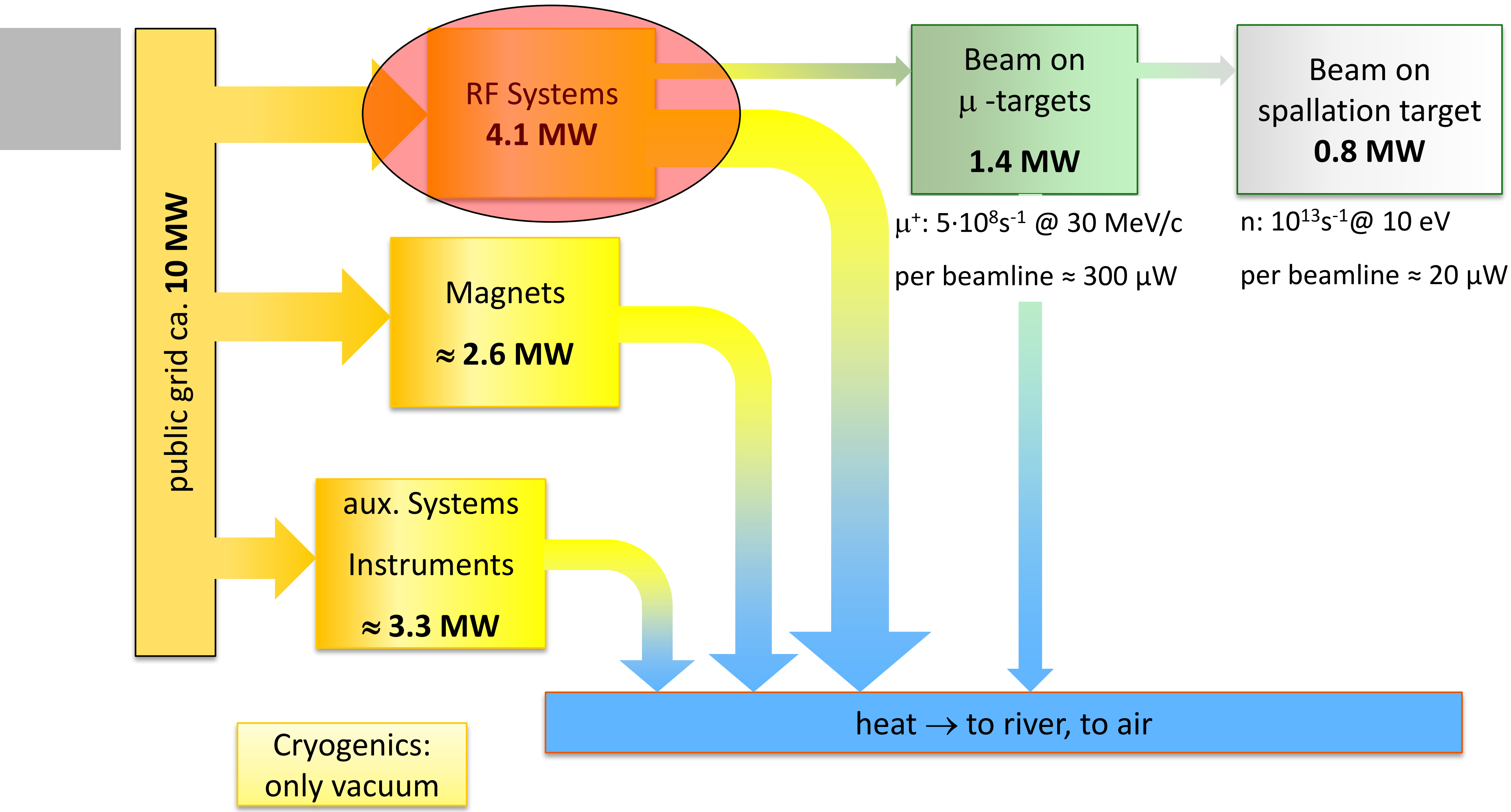
- Primary circuit 0.3 MW
- Secondary circuit 0.25 MW

Overall efficiency: 94%

Improvement:

- Energy recovery
- 3360 MWh recovered in 2015

Grid to Beam Power



Efficiency of the RF System

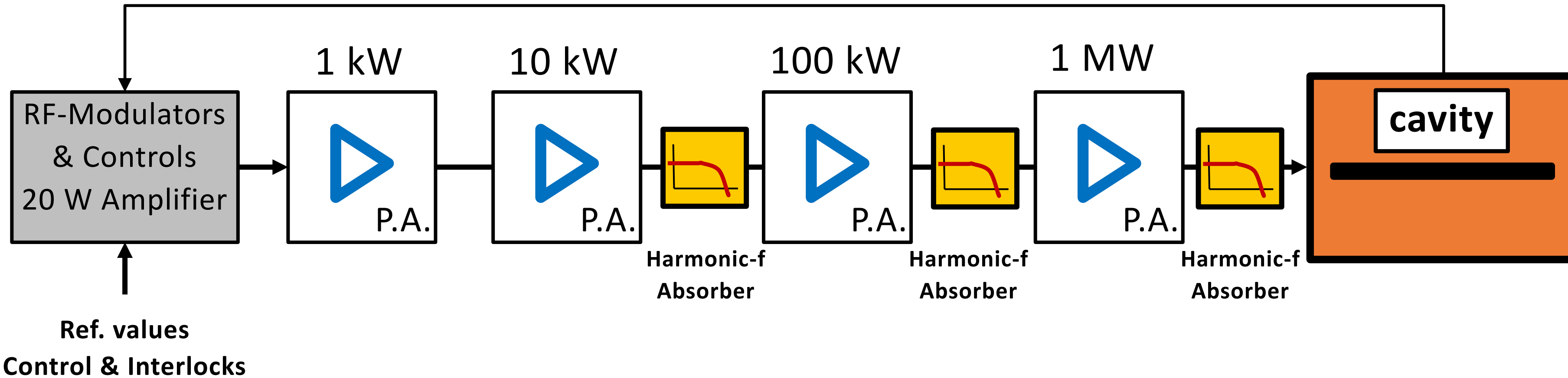
- Transfer of up to **400 kW power to the beam** per cavity
- f = 50.6 MHz
- U_{max} = 1.2 MV/p (0.85 MV/p at present)
- Q = $4.8 \cdot 10^4$

Inside the resonator

hydraulic tuning devices (5x)

Amplifier Chain for one Copper Cavity

4-stage power amplifier chain with power Tetrode Tubes

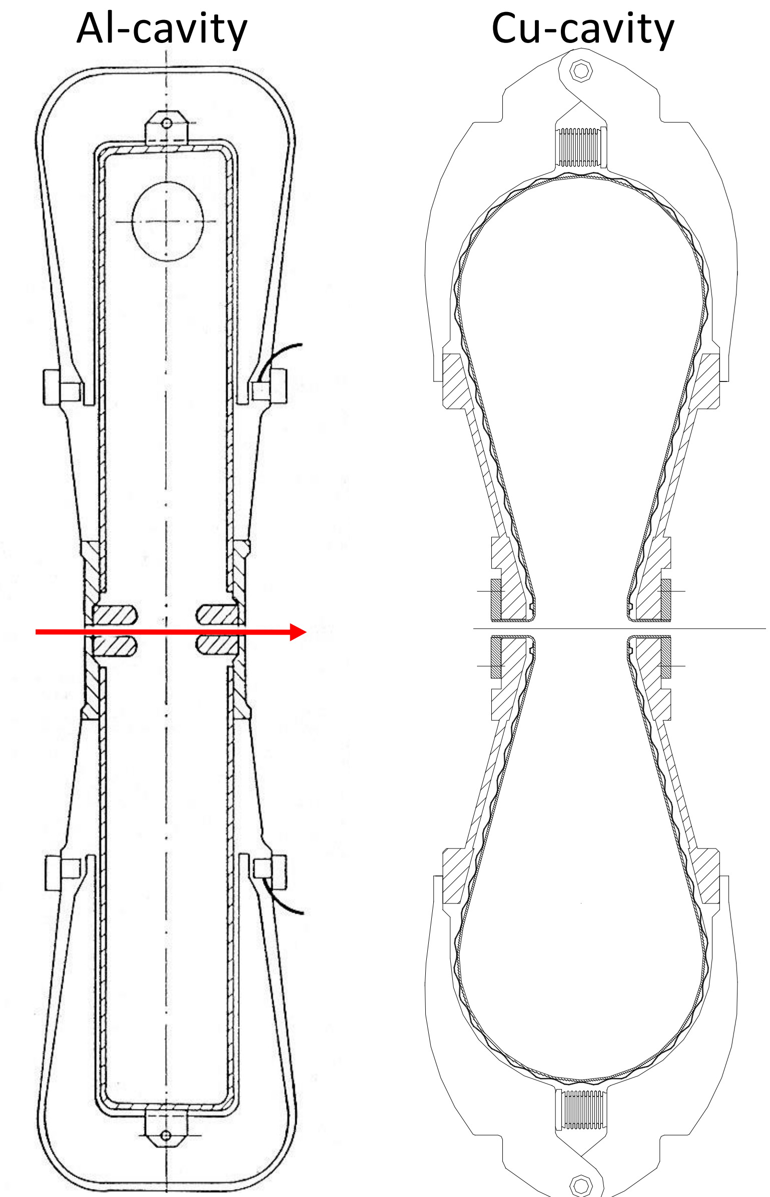


Wall plug to beam efficiency:

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

M. Schneider, PSI

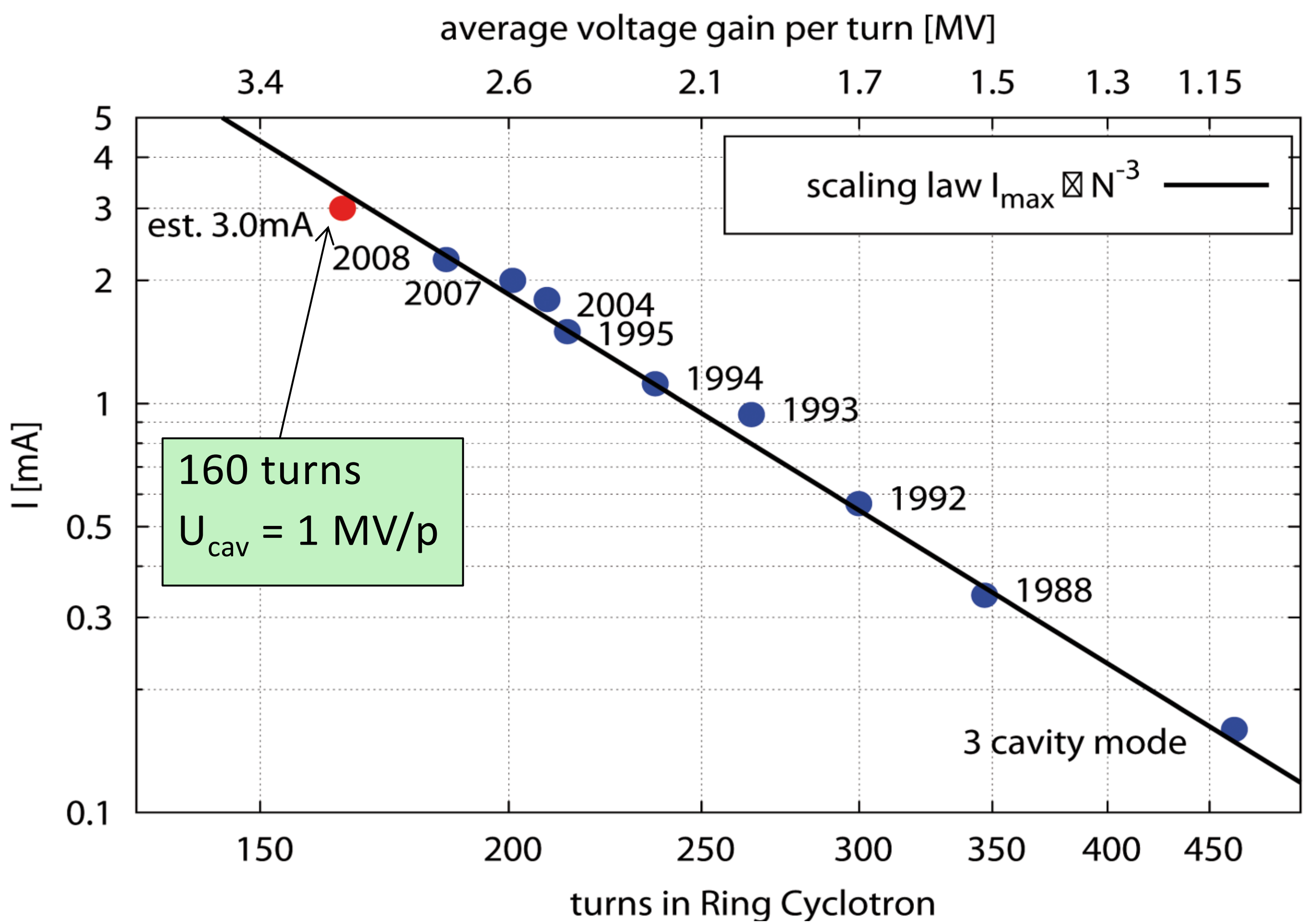
Cyclotron Cavities



	Al-Cavity	Cu-Cavity
Frequency	50.6 MHz	50.6 MHz
Voltage	750 kV_p	>1 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

History of the Beam Power at PSI

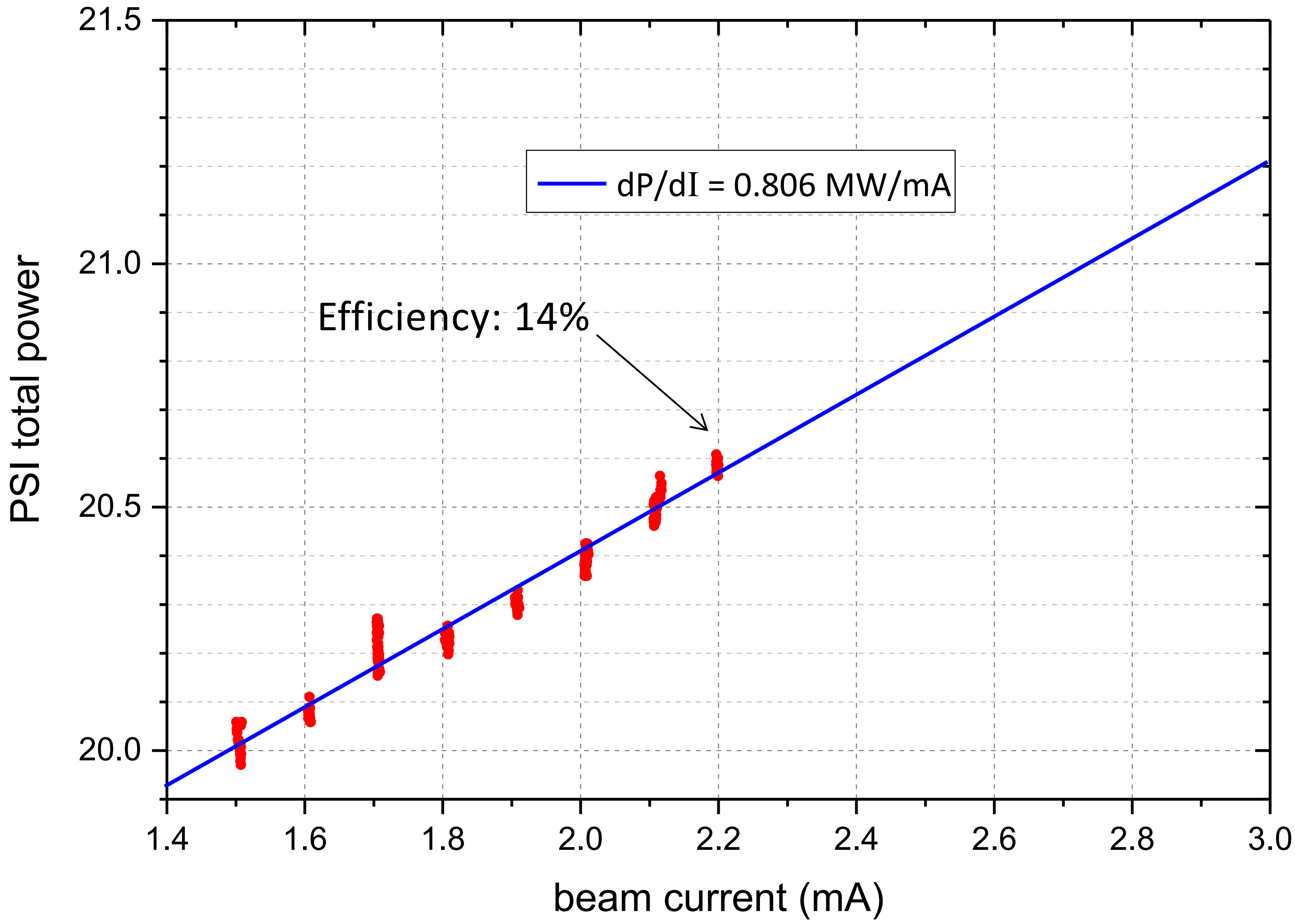


W. Joho

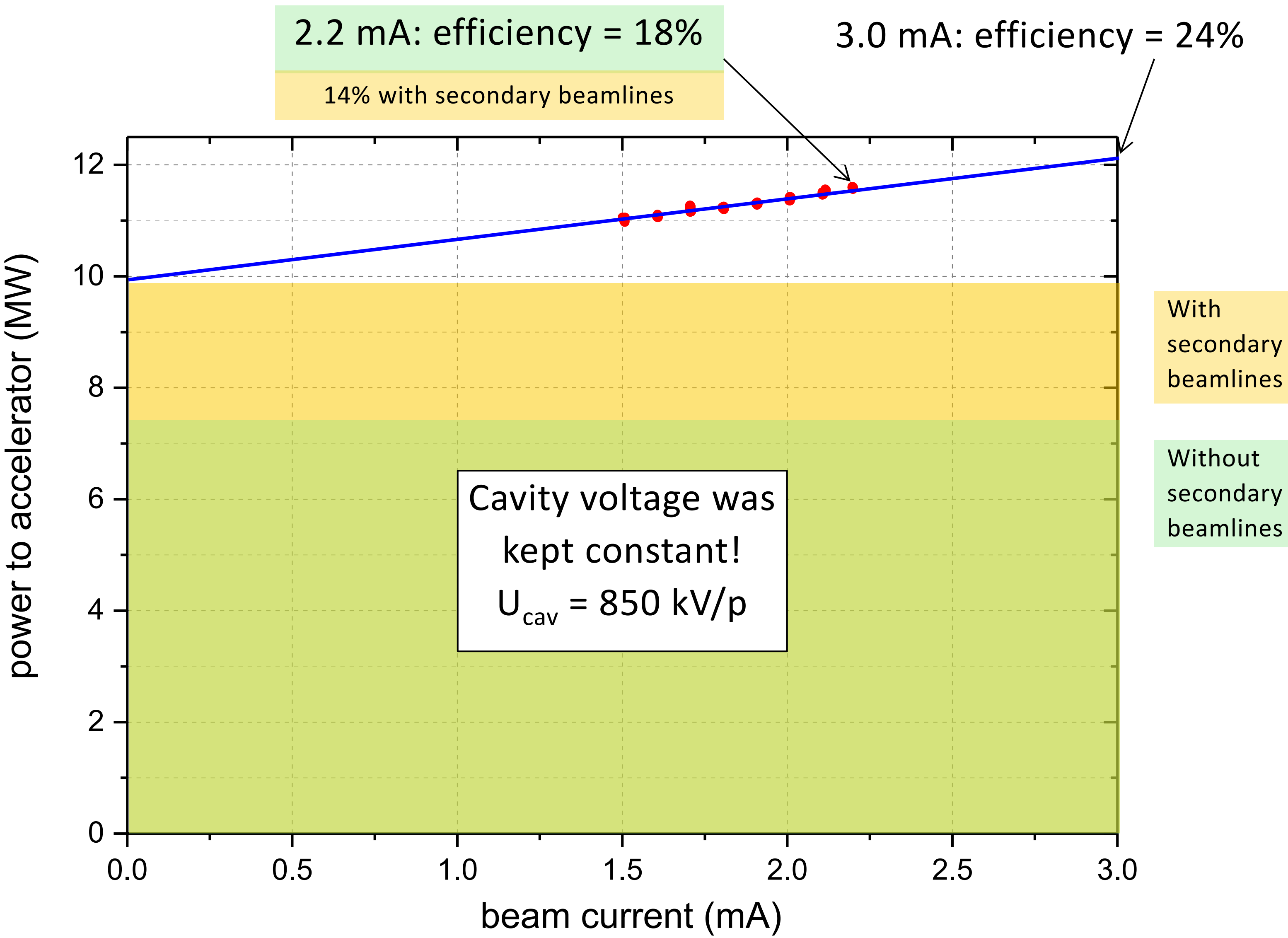
Losses scale with
- (turn separation at the extraction)$^{-1}$ $\propto$ **N**
- Charge density in the cyclotron $\propto$ **N**
- Acceleration time $\propto$ **N**

Grid to Beam Power Conversion

Efficiency apparently scales with beam power



Grid to Beam Power Conversion



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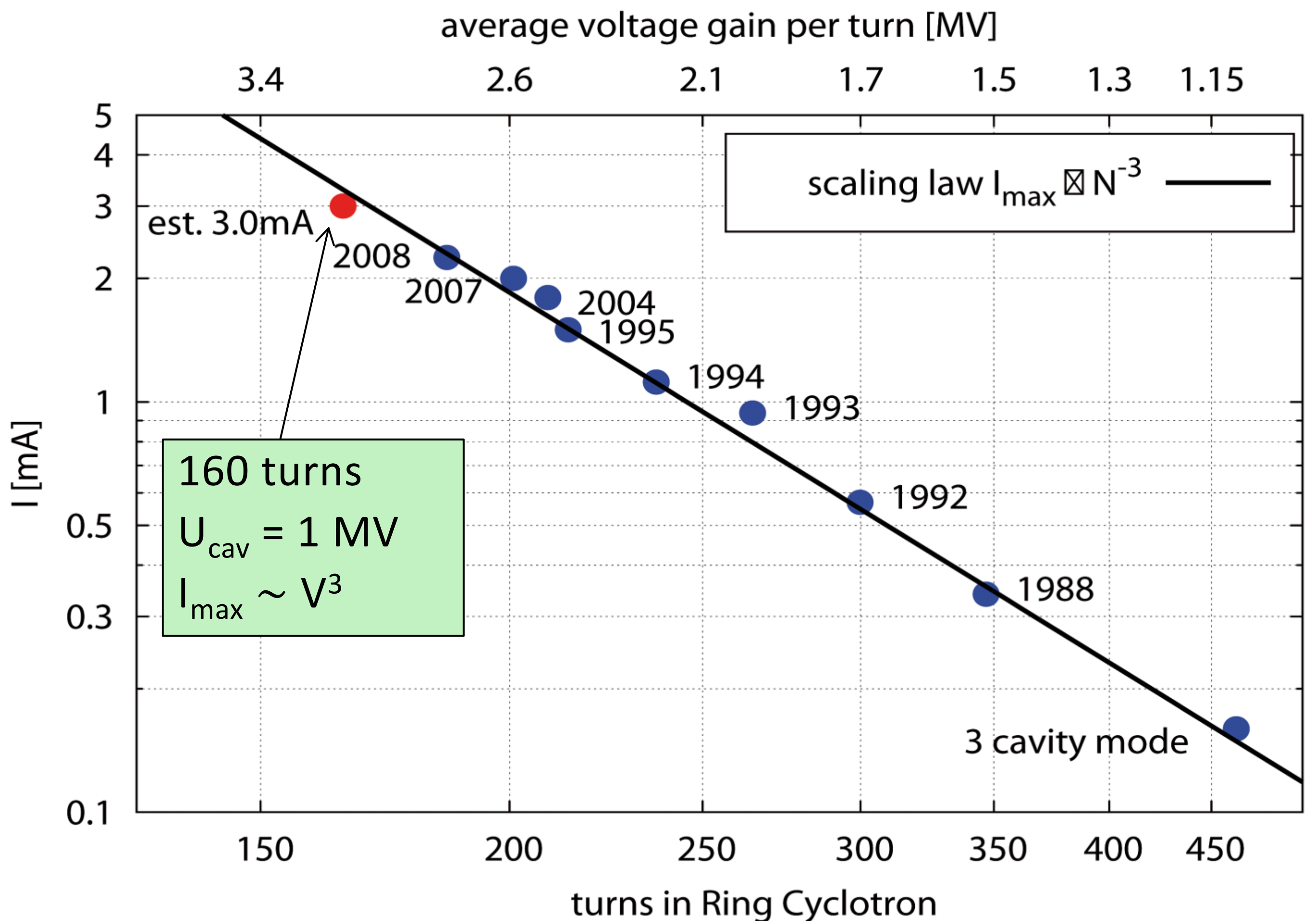

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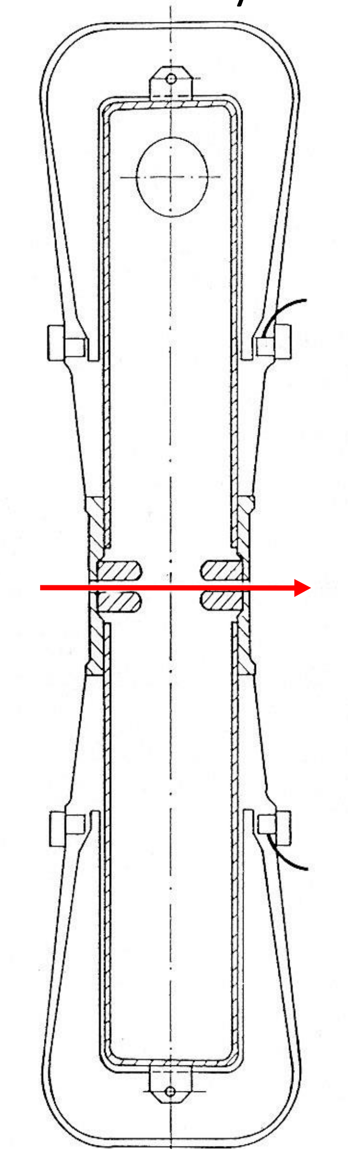
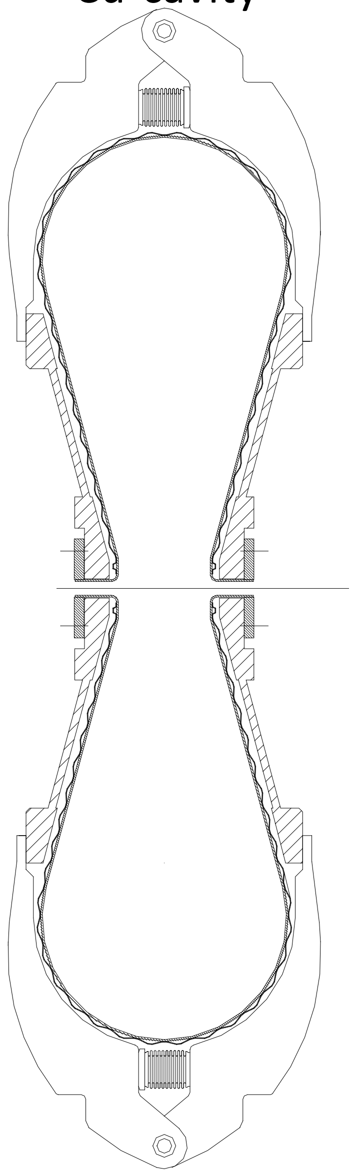
Cyclotron Cavities

Al-cavity



Cu-cavity



Ohmic losses:

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

Efficiency and Beam Power

$$\eta_{acc} = \frac{P_{beam}}{P_{loss} + P_{beam} / \eta_{RF} + P_{aux}}$$

$$P_{beam} = I_{\max} E_{kin} / q$$

$$I_{\max} \approx \frac{1}{n^3}$$

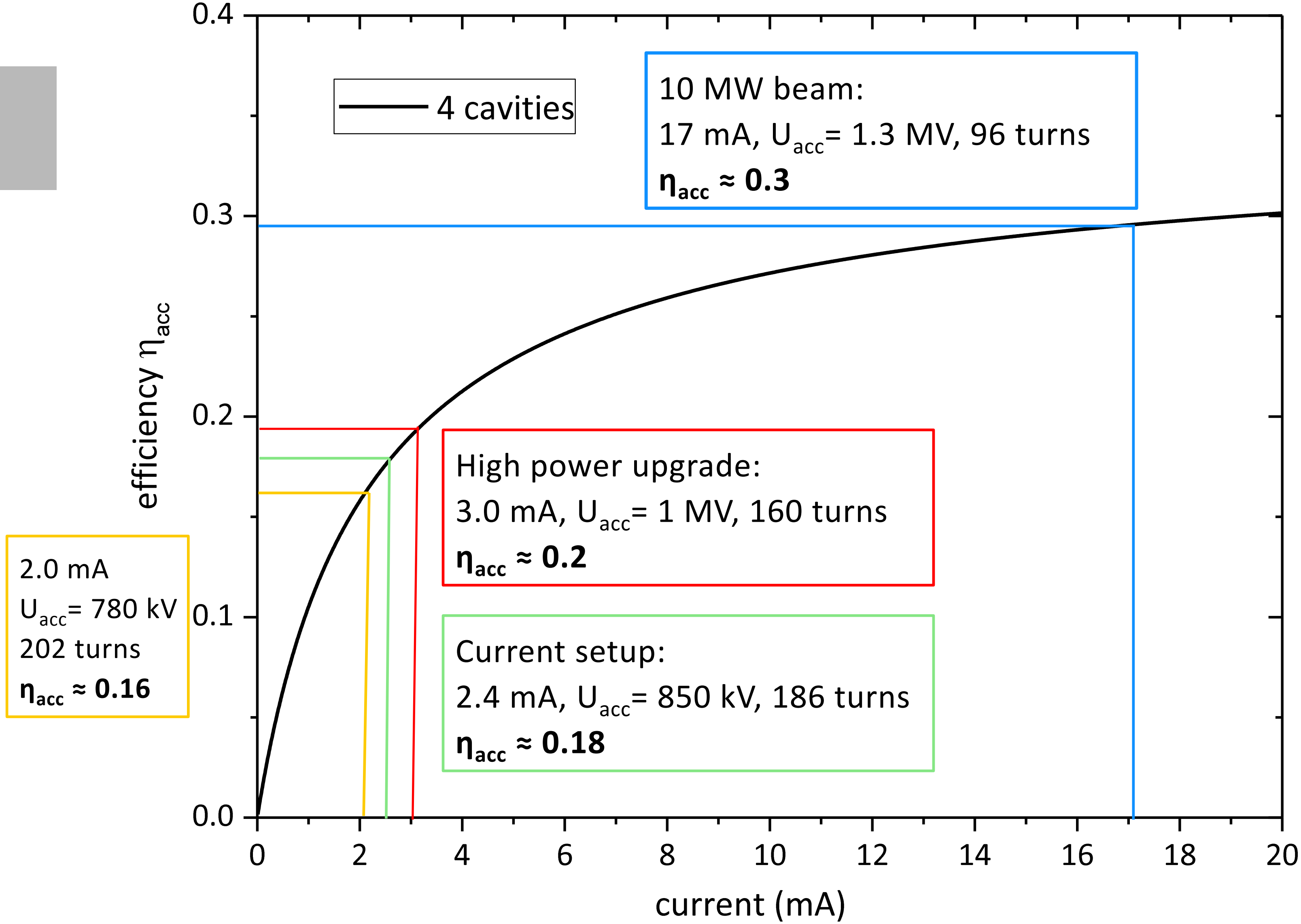
$$I_{\max} = \frac{c V_{acc}^3}{E_{kin}^3 / q^3}$$

$$V_{acc} = E_{kin} / q \cdot \sqrt[3]{I_{\max} / c}$$

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

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

Efficiency and Beam Power



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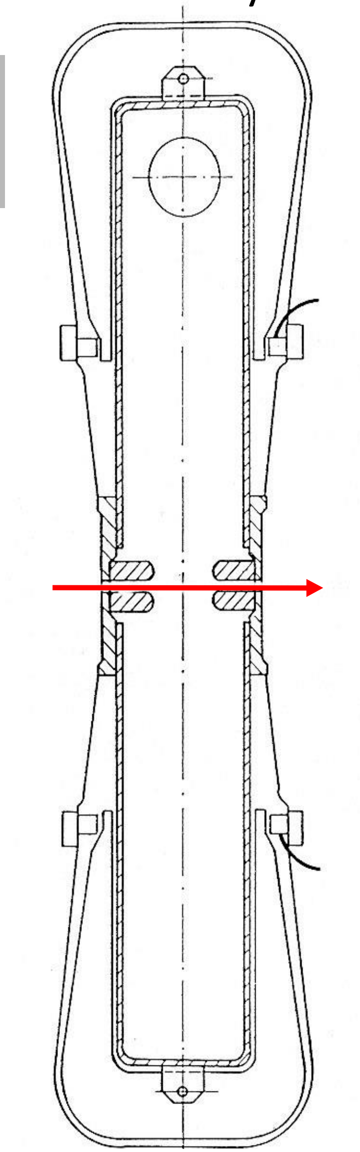

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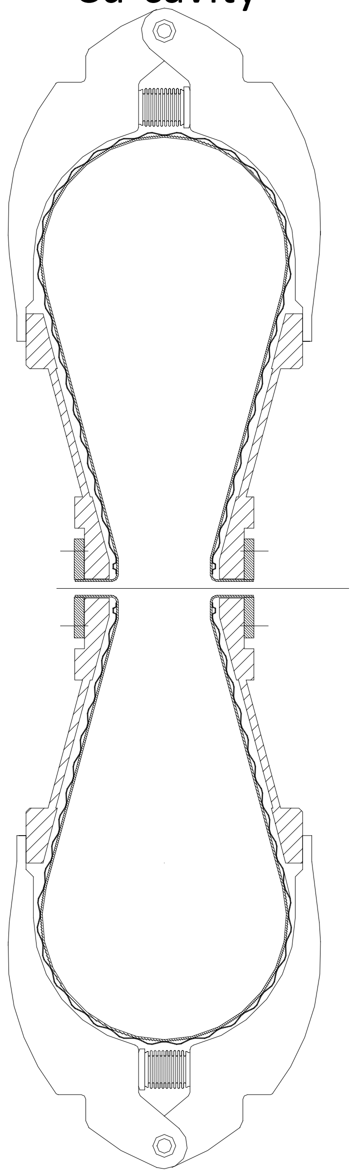


Ohmic losses:

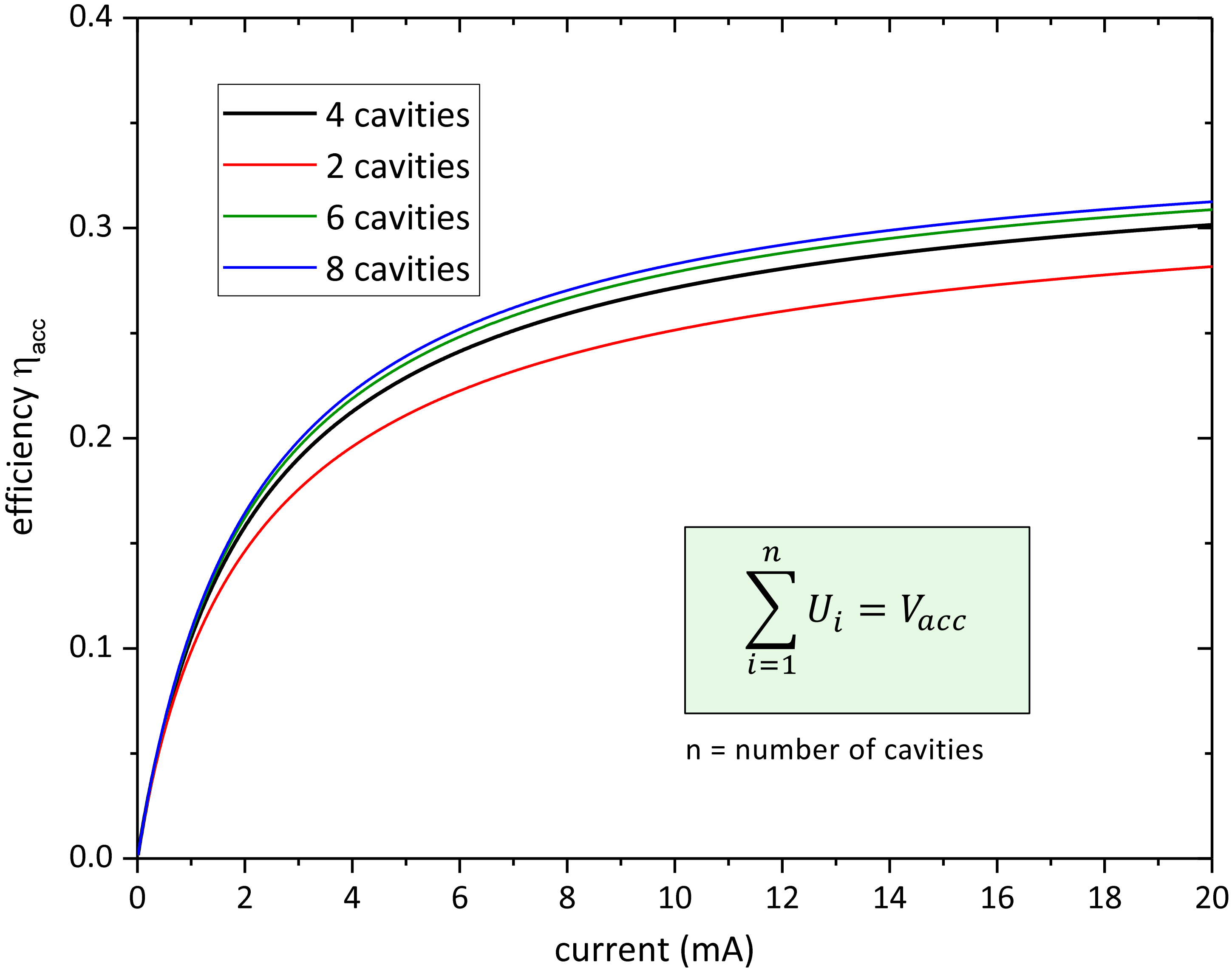
$$P_{loss} = \frac{|V_{acc}|^2}{2 \cdot R}$$

→ to improve the efficiency for a given gap voltage the shunt impedance ***R*** must be optimized

$$\frac{R}{Q} = \frac{|V_{acc}|^2}{4\pi f W} = \sqrt{\frac{L}{C}}$$

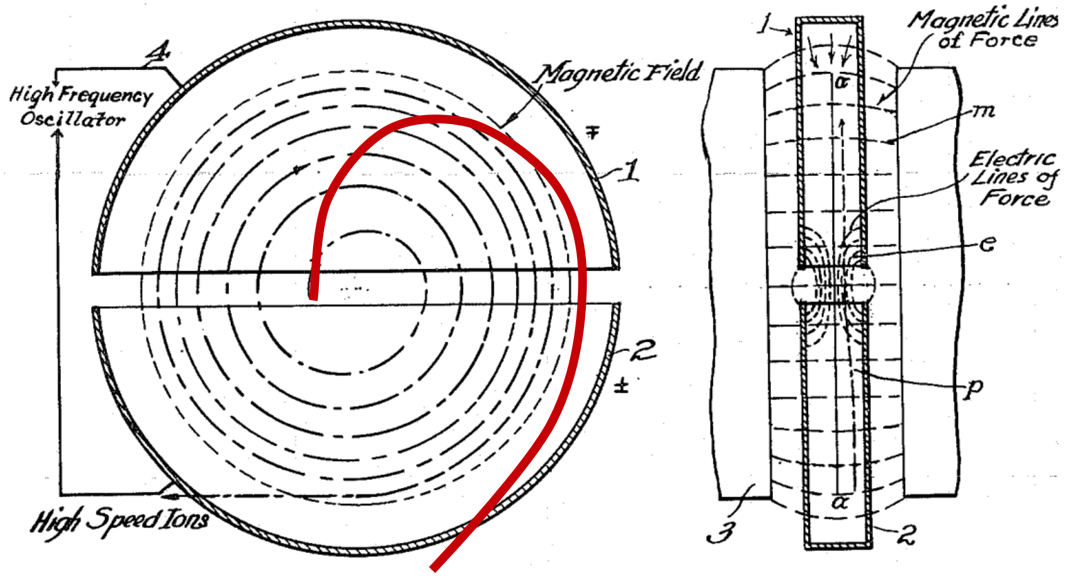
→ Depends only on geometry!

Efficiency and Beam Power

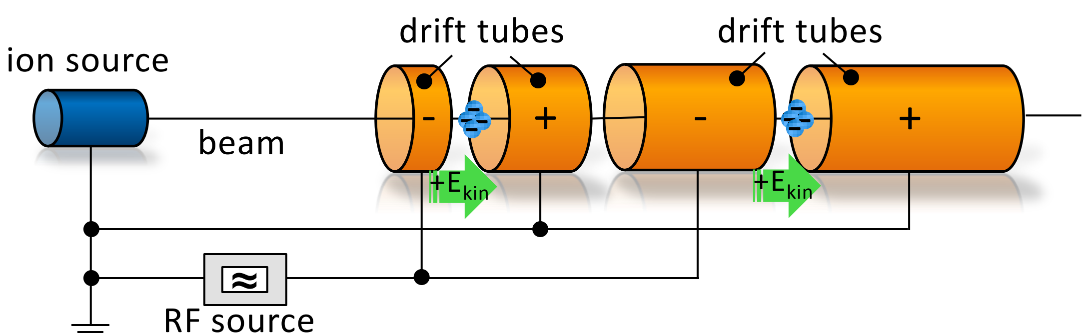


Cyclotron Efficiency

1929: E.O. Lawrence, Berkley



inspired by Rolf Widerøe



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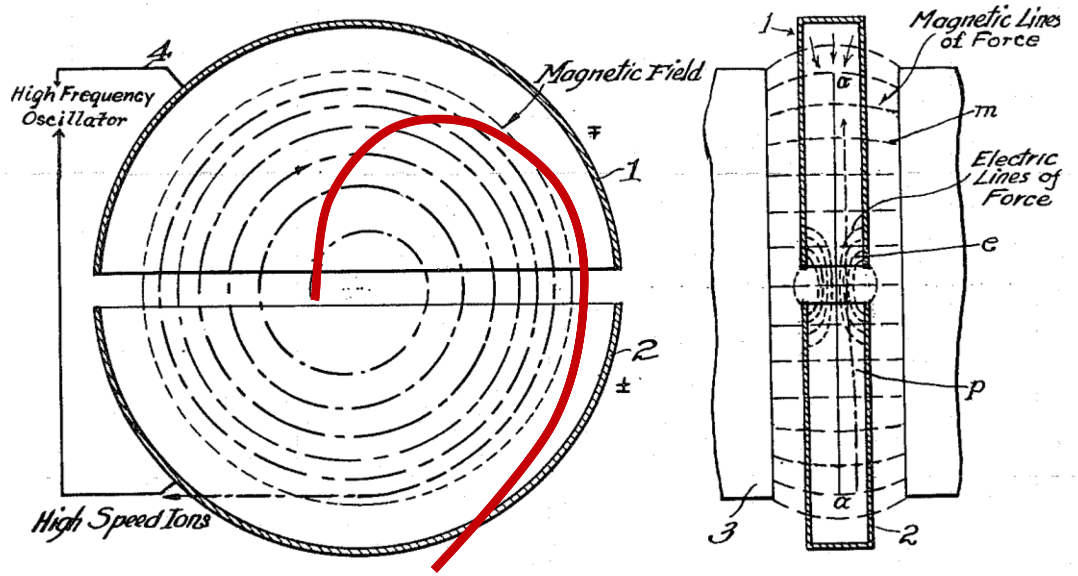
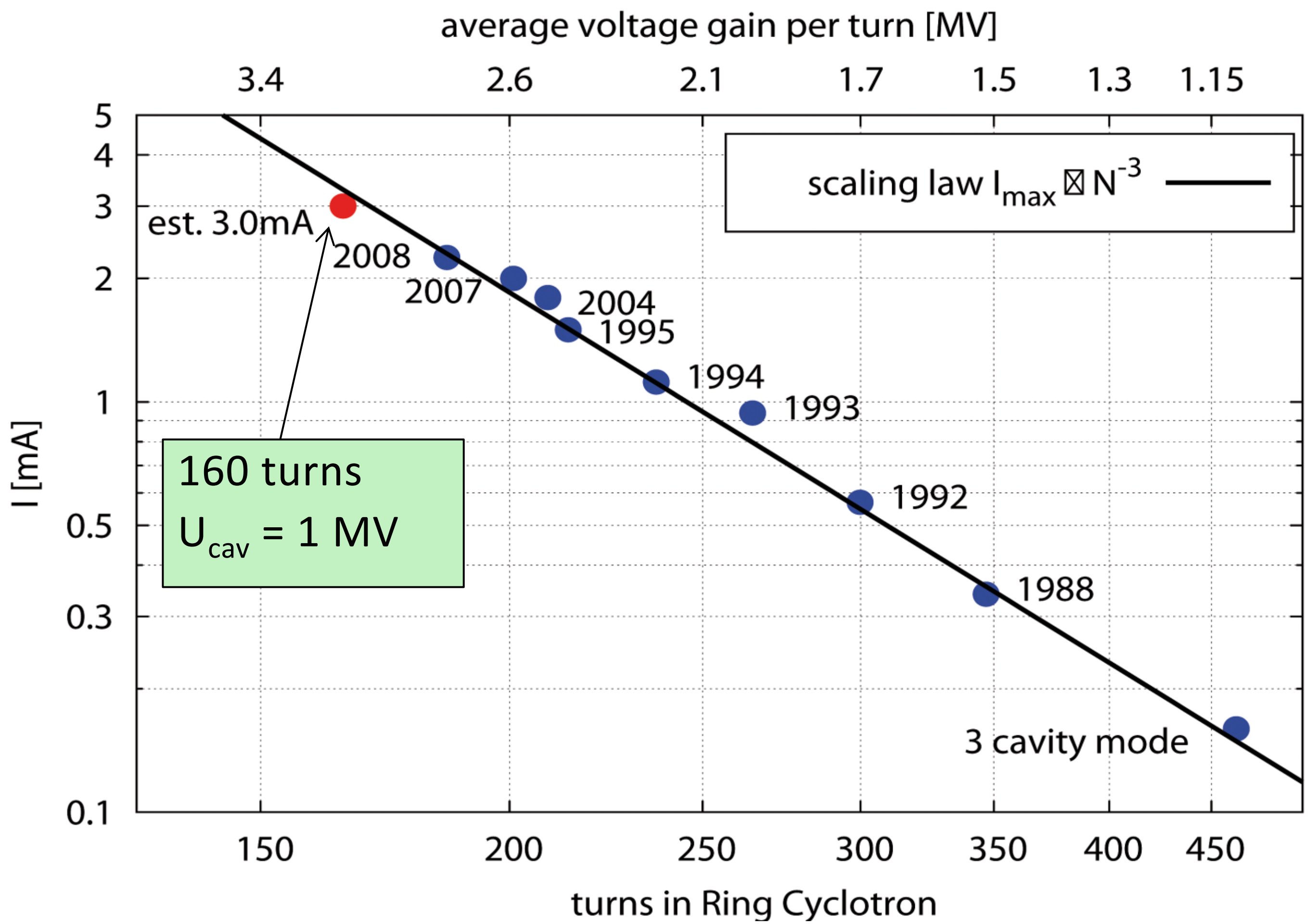


inspired by Rolf Widerøe

Talk by Mike Seidel

FRB01: Cyclotrons and Superconducting Linacs as High Intensity Driver Accelerators

History of the Beam Power at PSI



W. Joho

Losses scale with

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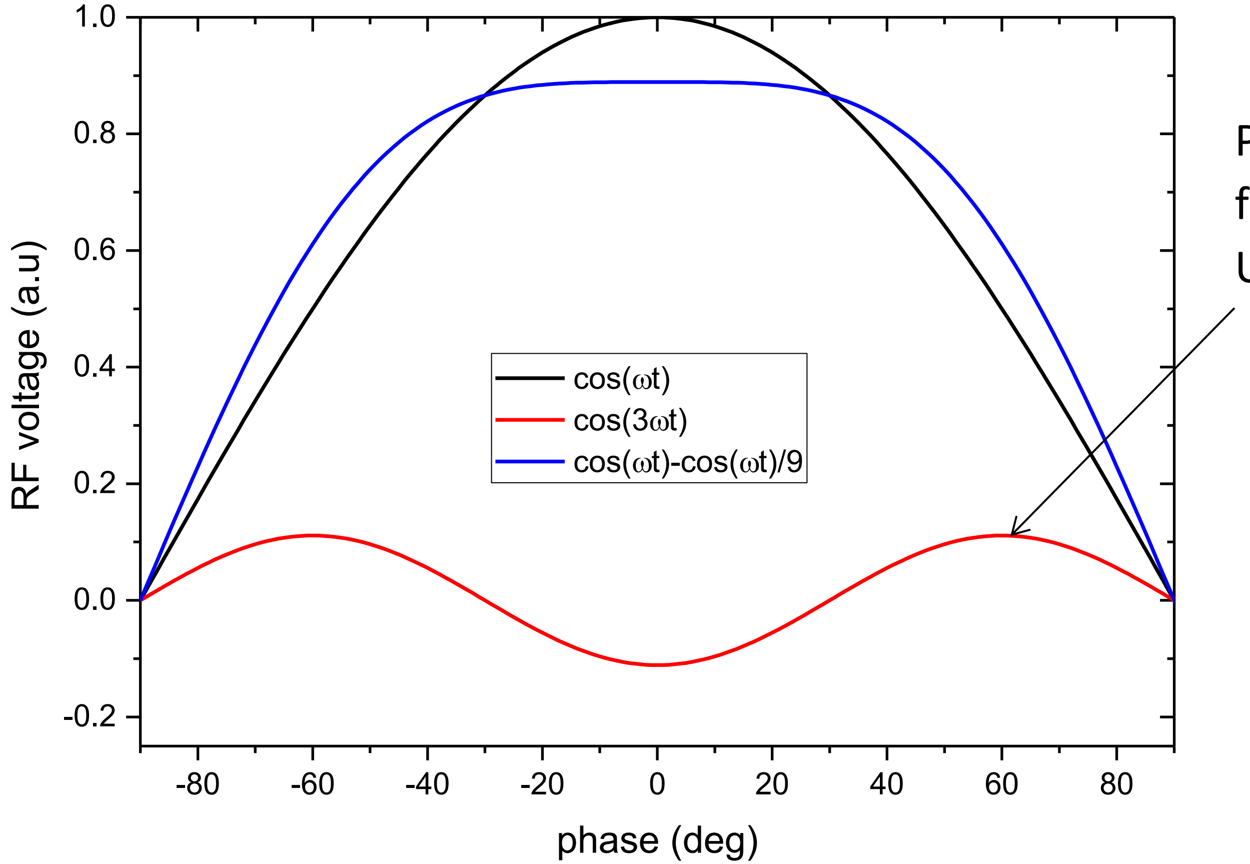
Longitudinal Dynamics

- variation of accelerating voltage over the bunch length **increases energy spread**
- thus a third harmonic flattop resonator is used to **compensate the curvature** of the resonator voltage w.r.t. time
- optimum condition: $U_{\text{tot}} = U_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$



PSI:

f = 150 MHZ

U_p = 550 kV

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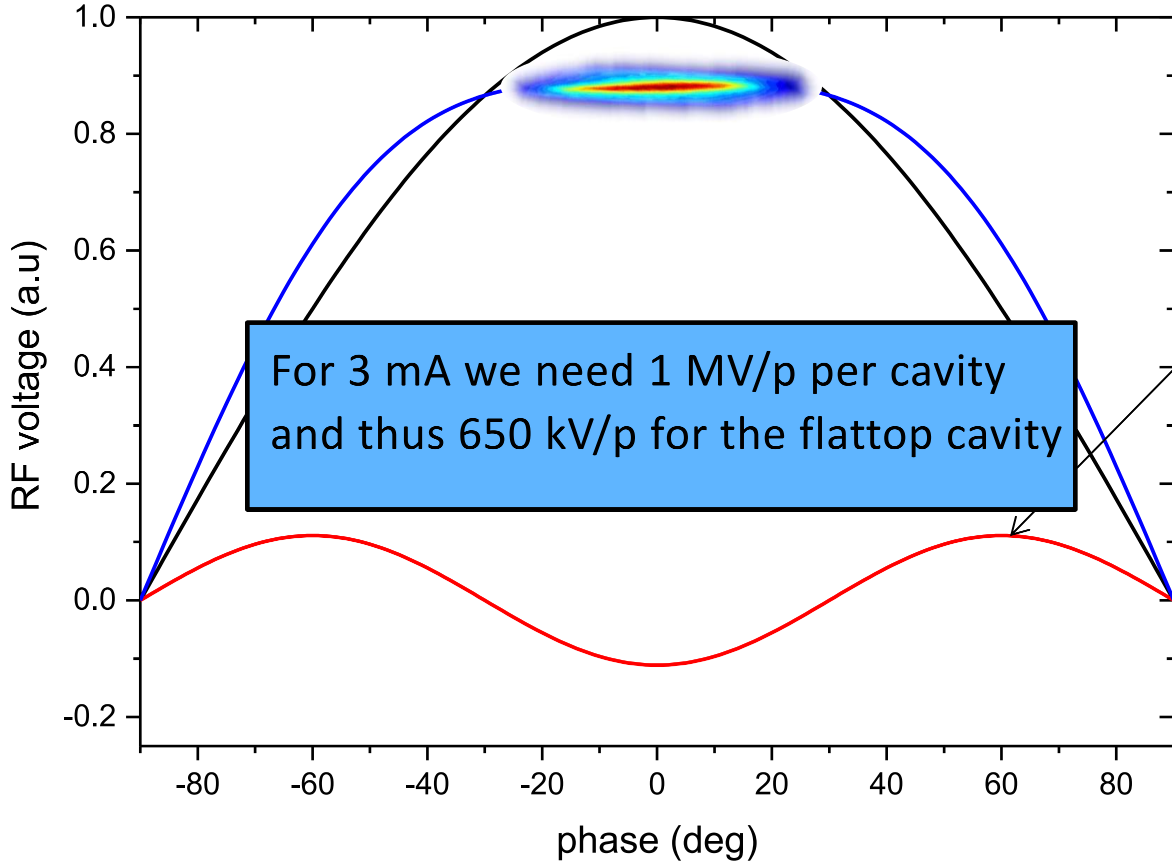

PSI:

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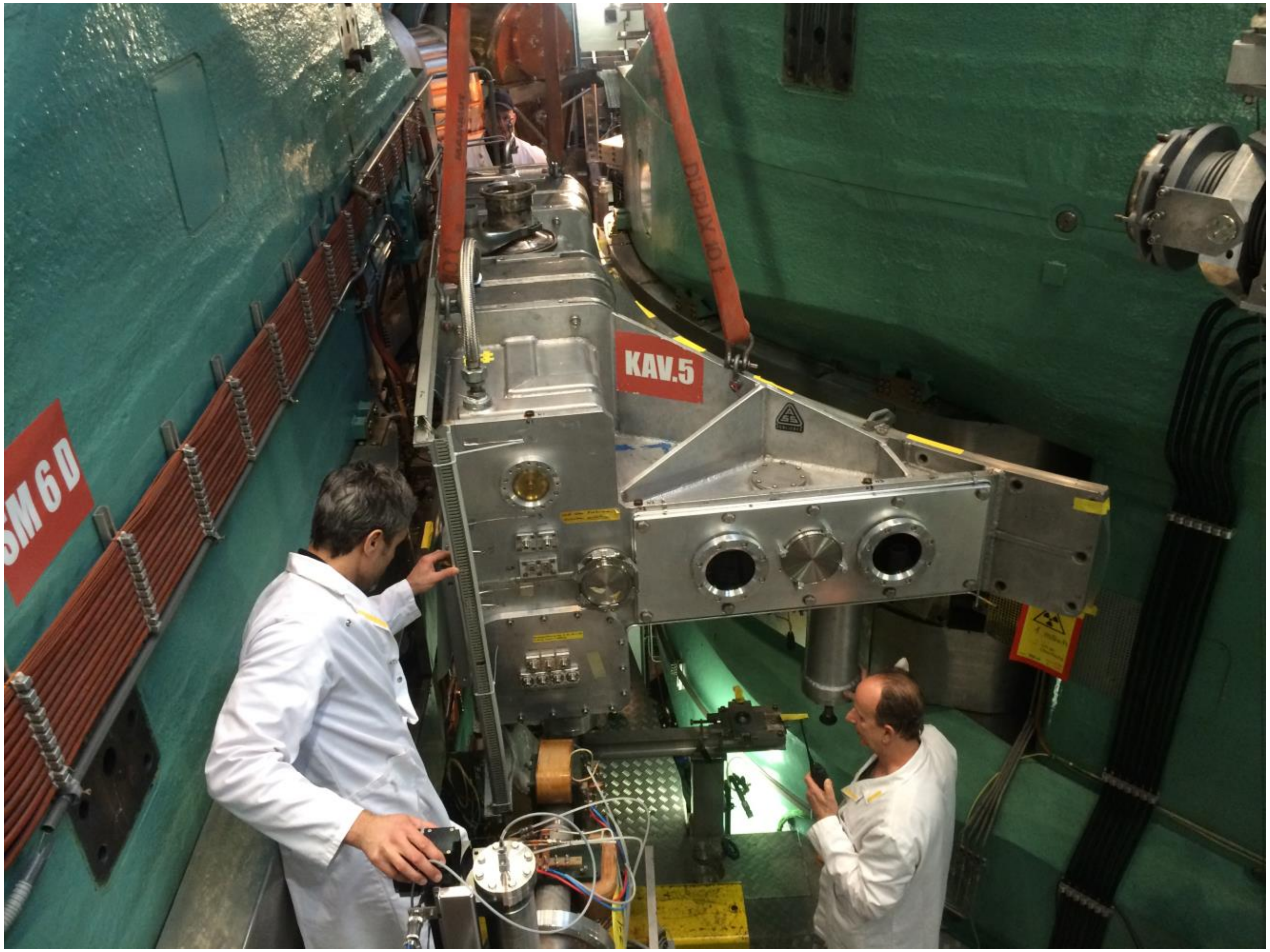
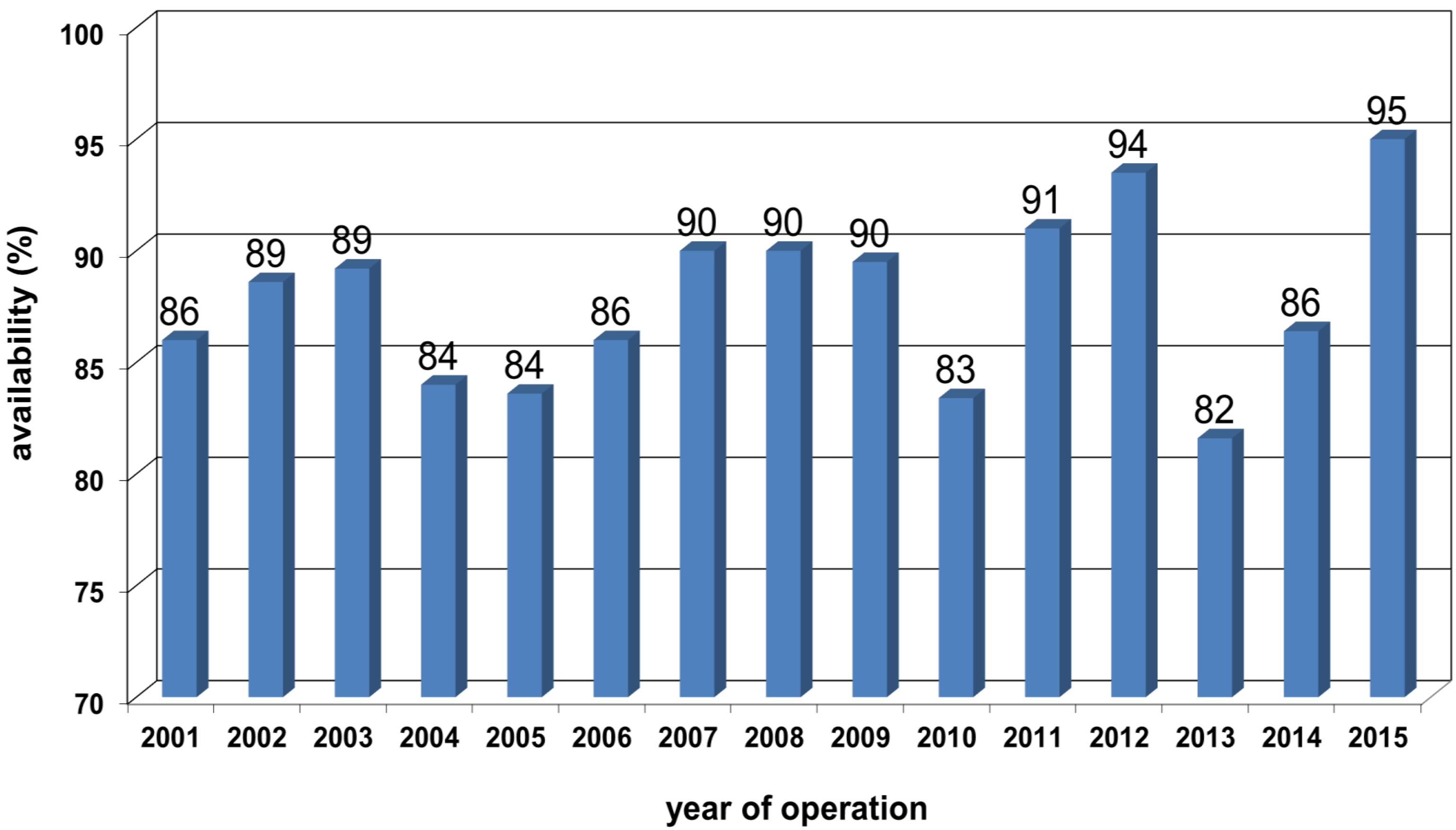
150 MHz Flattop Cavity

Limited to 550 keV

- New cavity (design)
- New RF-amplifiers



Availability and Efficiency



Availability has an impact on the efficiency. Especially if systems are running without beam!

Power Saving at PSI

Duration of outages

	2014 (86%)	2015 (95%)	causes
t < 5 min	≈ 141 h	≈ 64 h	mostly discharges
t < 30 min	≈ 42 h	≈ 30 h	control system, RF, operation
t > 30 min	≈ 408 h	≈ 180 h	targets, infrastructure, magnets, ...

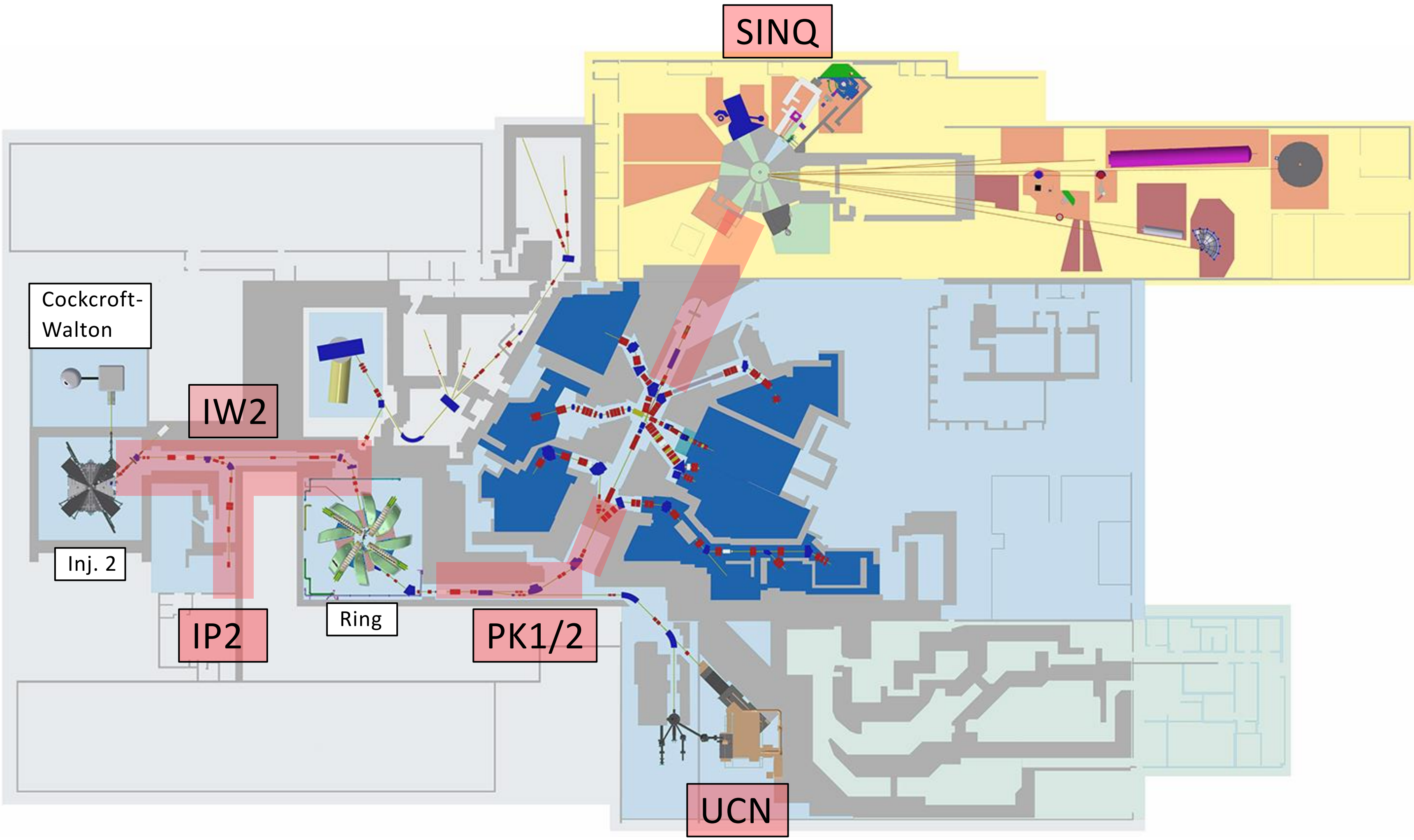
Power needed without beam (8.5 MW):

4.1 MW for RF -> can be switched off (for t > 2h)

2.6 MW for all magnets -> main magnets are usually not switched off

1.8 MW for beamline magnets -> can be switched off (250 magnets)

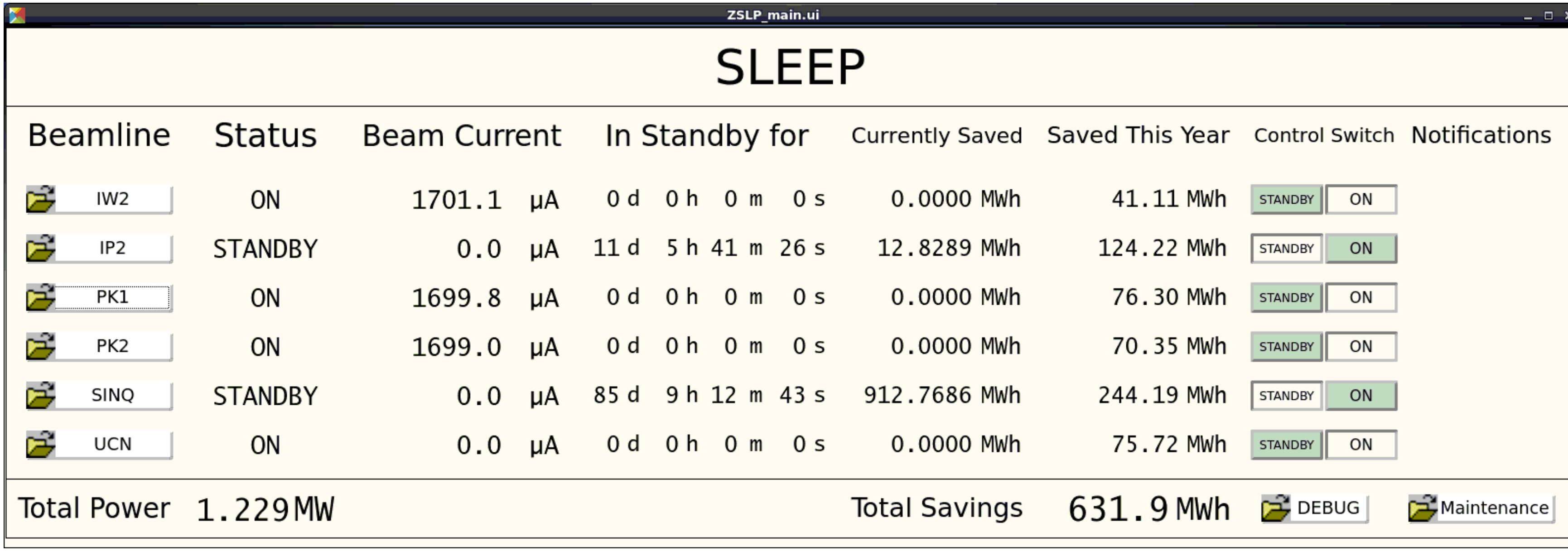
Power Saving at PSI



Sleep at PSI

https://www.pinterest.com/

System for Lucrative Energy Economization in Proton accelerators



Beamline	Status	Beam Current	In Standby for	Currently Saved	Saved This Year	Control Switch	Notifications
IW2	ON	1701.1 μA	0 d 0 h 0 m 0 s	0.0000 MWh	41.11 MWh	STANDBY ON	
IP2	STANDBY	0.0 μA	11 d 5 h 41 m 26 s	12.8289 MWh	124.22 MWh	STANDBY ON	
PK1	ON	1699.8 μA	0 d 0 h 0 m 0 s	0.0000 MWh	76.30 MWh	STANDBY ON	
PK2	ON	1699.0 μA	0 d 0 h 0 m 0 s	0.0000 MWh	70.35 MWh	STANDBY ON	
SINQ	STANDBY	0.0 μA	85 d 9 h 12 m 43 s	912.7686 MWh	244.19 MWh	STANDBY ON	
UCN	ON	0.0 μA	0 d 0 h 0 m 0 s	0.0000 MWh	75.72 MWh	STANDBY ON	

Total Power 1.229 MW — Total Savings 631.9 MWh — DEBUG — Maintenance

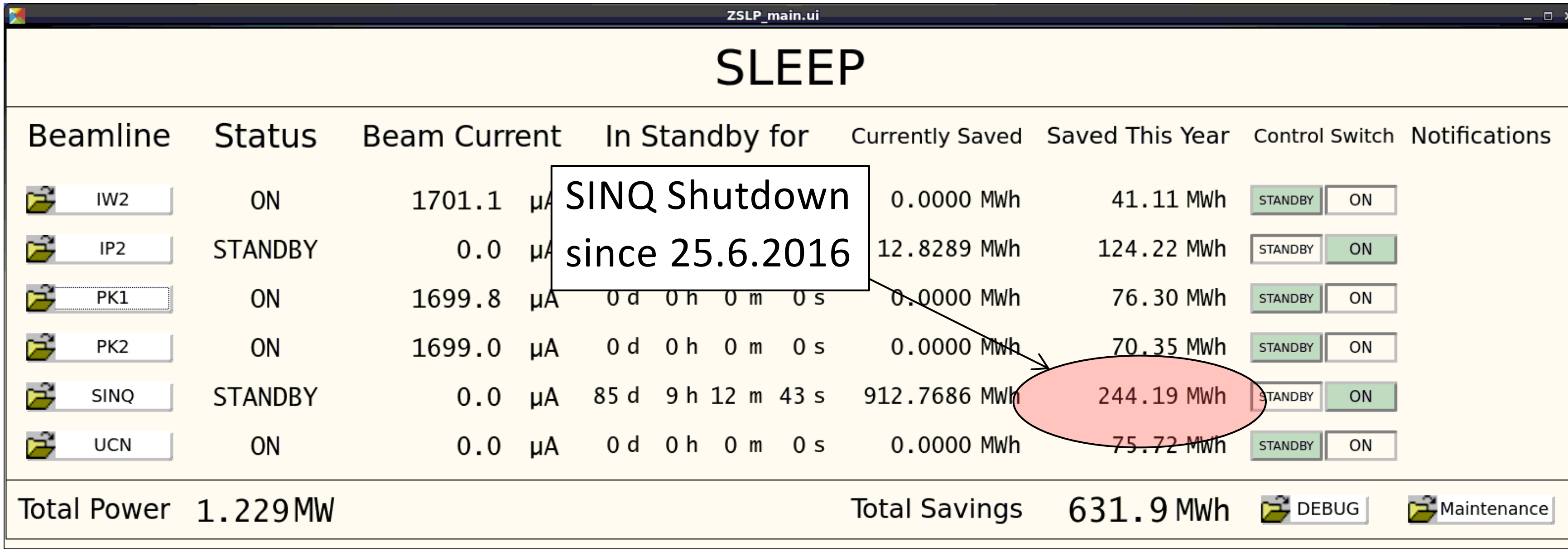
A. Kovach, A. Parfenova, Operations PSI

Similar to a Start-Stop system in cars

Sleep at PSI

https://www.pinterest.com/

System for Lucrative Energy Economization in Proton accelerators



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Total Power 1.229 MW — Total Savings 631.9 MWh — DEBUG — Maintenance

A. Kovach, A. Parfenova, Operations PSI

Similar to a Start-Stop system in cars

Conclusions

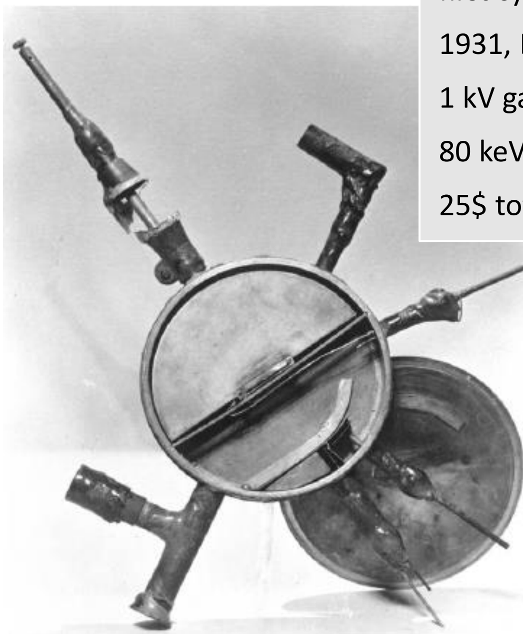
- **Cyclotrons represent one of the most efficient accelerator type**
  - Energy and cost efficient (compact, multiple use of the acceleration voltage)
  - Operational parameters have a strong impact on the efficiency (pulsed, CW, ...)
  - RF dominates the efficiency
  - Increasing the beam power "apparently" increases the energy efficiency
  - Could meet ADS requirements
    - Existing facilities could reach 25% already, ADS desires 20-40%
    - low loss extraction possible
  - **Up to now, no machine has been designed for maximum energy efficiency**

Improvements (specific for each design):

- Machine design (more cavities, no injector?)
- SC-magnets, permanent magnets, magnet cooling
- Optimize grid to RF power conversion
  - cavity design
  - DC-RF: klystrons (90% C. Lingwood et al), solid state (55%)
    magnetrons claim 85% (B. Chase, pdriver'16)
- Conventional systems (buildings, cryo systems, heat recovery, energy management)
- Targets, neutron guides, moderators, treatment facilities...

Don't forget costs, feasibility, and reliability

Thank you for your Attention



first cyclotron:

1931, Berkeley

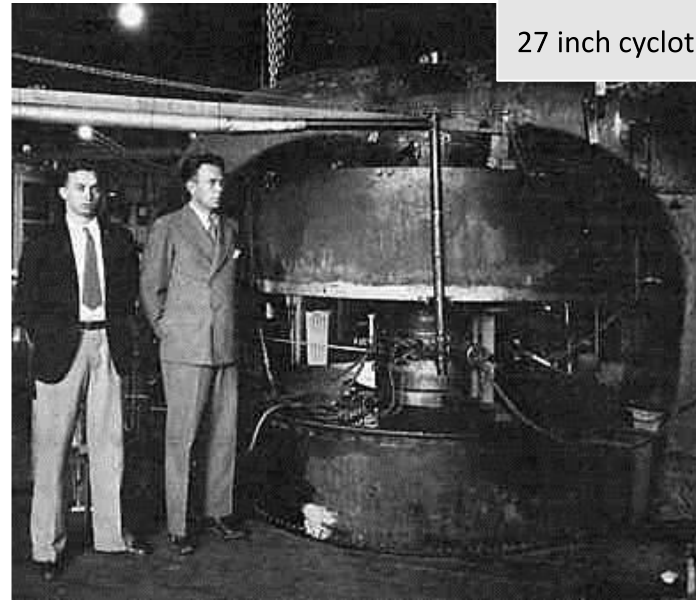
1 kV gap voltage

80 keV protons

25$ total cost

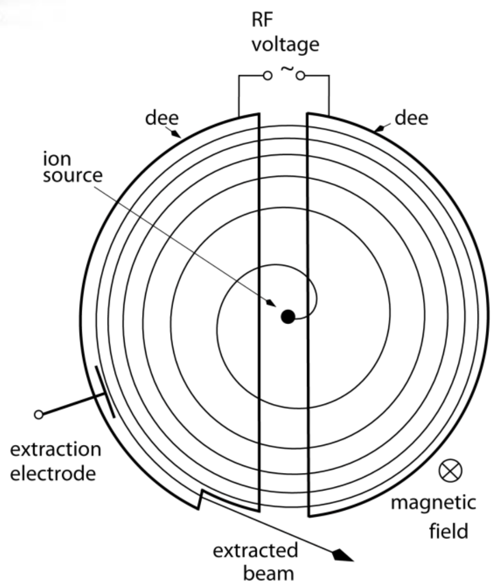
Lawrence & Livingston

27 inch cyclotron



Powerfull concept:

- ✓ Simplicity
- ✓ CW operation
- ✓ Multiple usage of accelerating voltage



Two capacitive electrodes (Dees) two gaps per turn

Internal ion source

Homogeneous B field

Constant revolution time for low energies ($\gamma \approx 1$)