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PSI

Joachim Grillenberger :: Large Research Facilities :: Paul Scherrer Institute

High Intensity Proton Accelerator Status and Development

Festive Symposium for the 50th Anniversary

Contains tobacco depictions and references to alcohol

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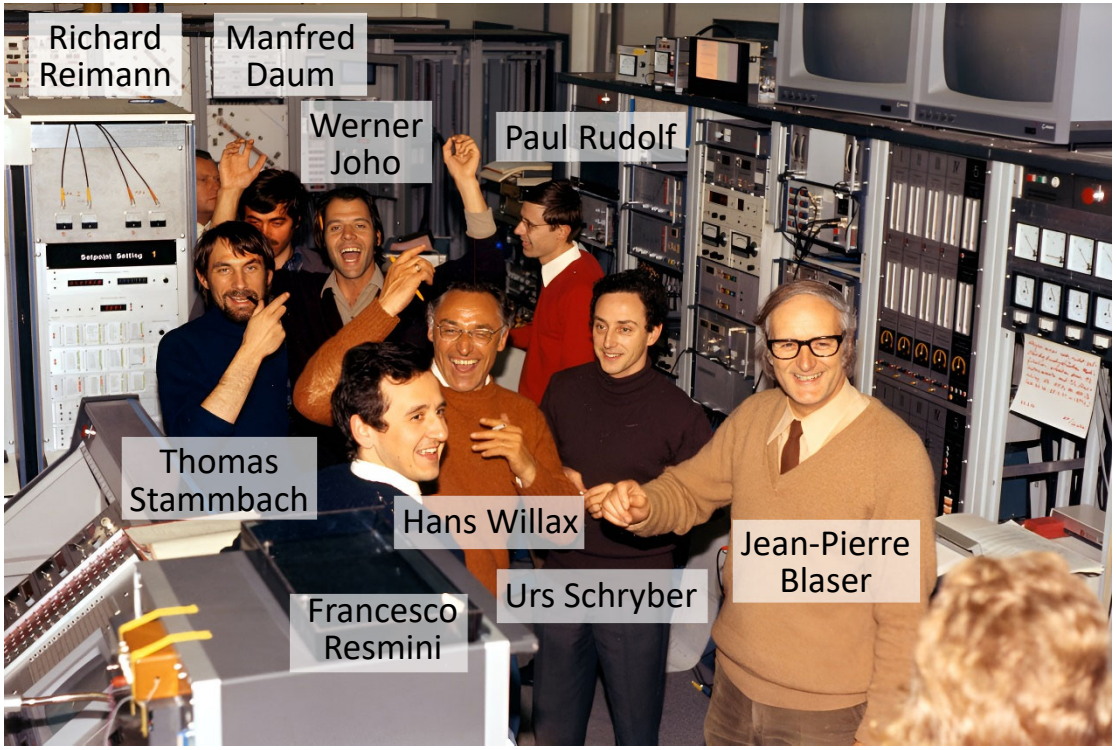
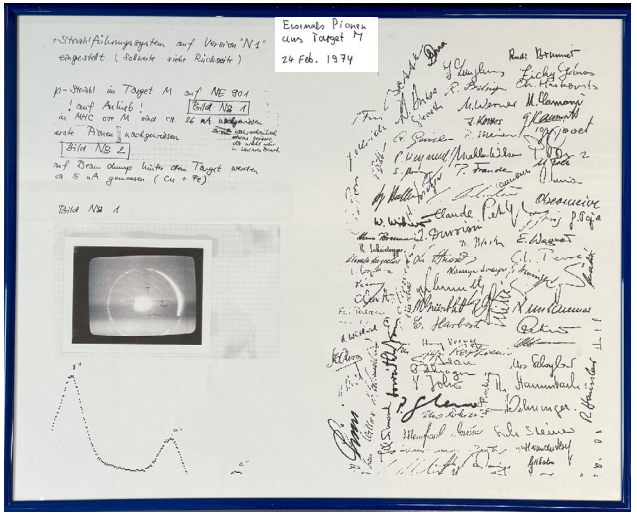
First Pions

24. February 1974 0:40h





The first 590 MeV protons were extracted on the

18th of January 1974

Adam, Joho, Schryber, Stammbach

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Pioneering Innovation

Reenacted Scene

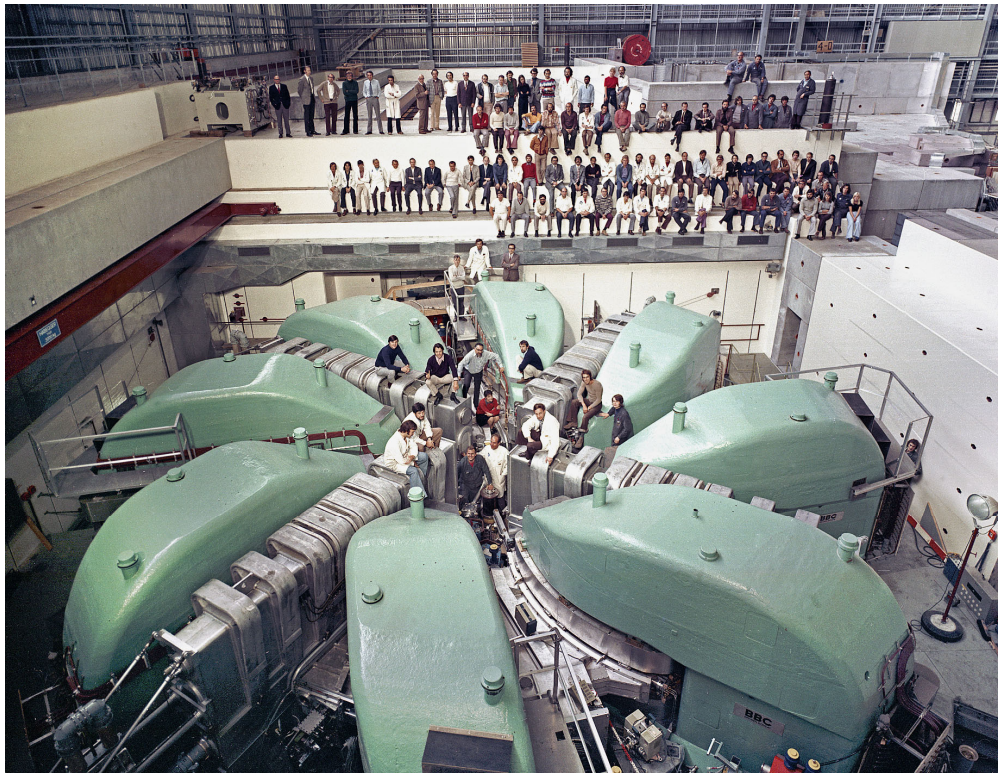
60 MeV, 20 μA

In 1959, **Jean-Pierre Blaser** assumes leadership of the Cyclotron Planning group. **Hans Willax** is part of it.

We owe it to Jean-Pierre Blaser's vision and Hans Willax' intriguing concept that we are now operating a megawatt facility…

LORDS AND LADIES OF THE RING

1973: RIGHT BEFORE COMMISSIONING



…and of course to the over 120 people involved in the design and the construction of the **Isochronous Ring Cyclotron** with

- 8 Sector magnets
- 4 accelerating cavities

↓

- higher acceleration
- distinct turn separation
- electrostatic extraction channel
- **less losses, higher extraction rate**
- **higher beam current**

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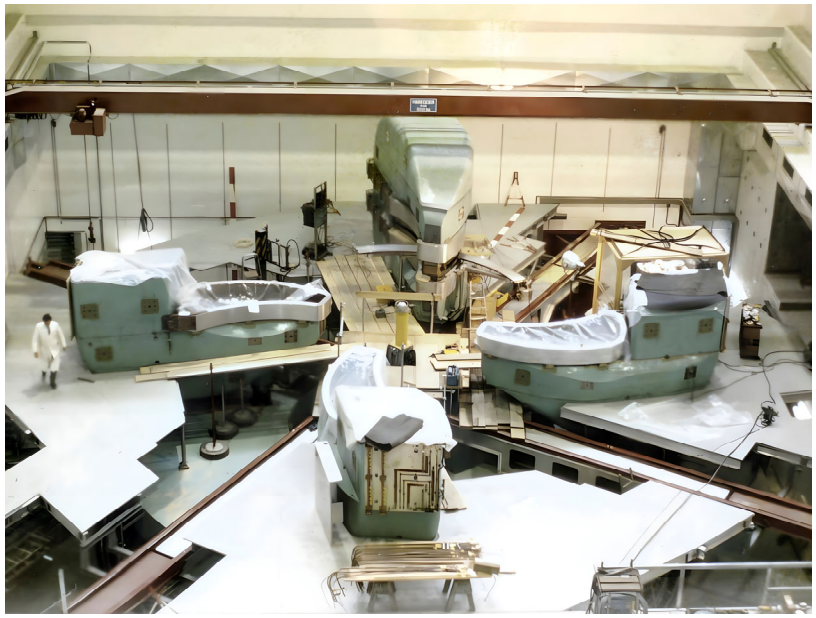
Forging the Future

Last Minute Decisions

One of 8 sector magnets
1968

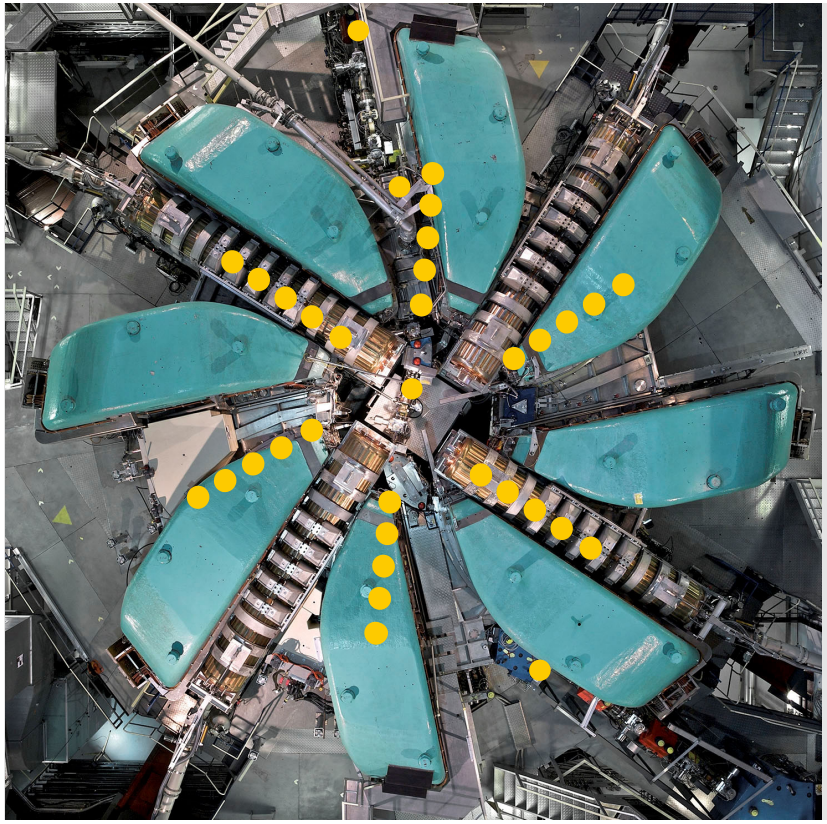
First aluminum cavity
1971



Ring cyclotron bunker
1972

Last minute decision: Let's go from 500 to 590 MeV!

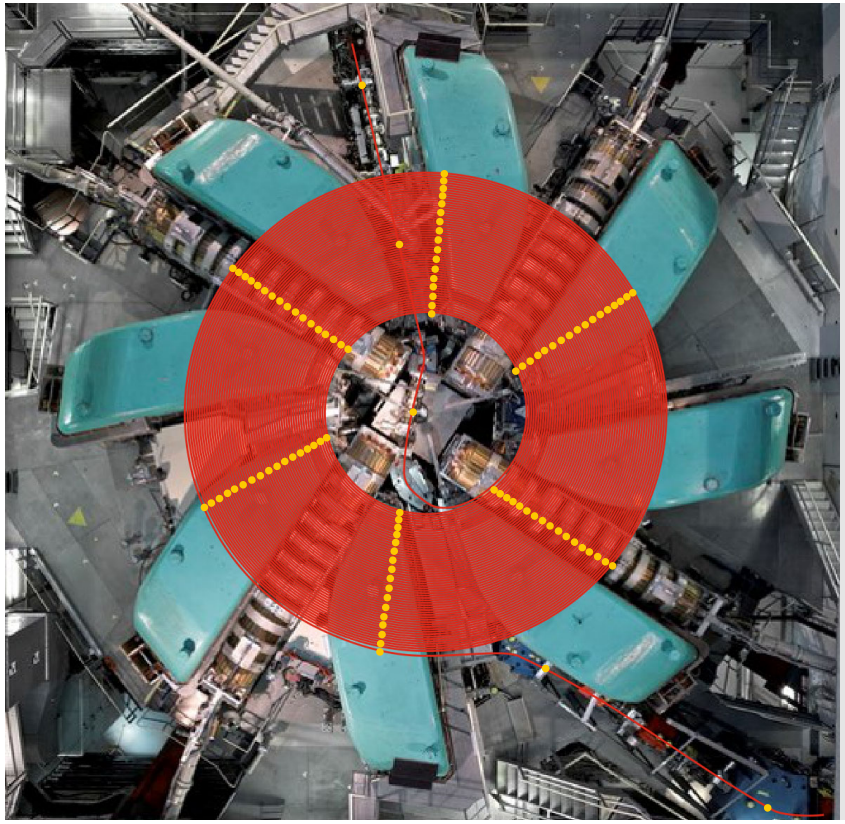
The PSI Ring Cyclotron



Injection energy:	72 MeV
Extraction energy:	590 MeV
Magnetic Field:	1.5 – 2.1 T
Cavity voltage:	850 kVp
Frequency:	50 MHz
Max. beam current:	**2.4 mA**
Beam power:	**1.42 MW**

The PSI Ring Cyclotron

What does this square do?



Energy gain per turn: 2.9 MeV

Number of turns:

$$\frac{590\ MeV - 72\ MeV}{2.9\ MeV} \approx \mathbf{180}$$

Time for the protons to pass through the Ring: **22 µs**

The Power of the Ring

The protons cover a distance of 4 km, reaching 80% of the speed of light.
This is **240 000 km/s or 6 times around the earth in one second.**

2.4 mA ≙ $1.5 \cdot 10^{16}$ protons/s ≈

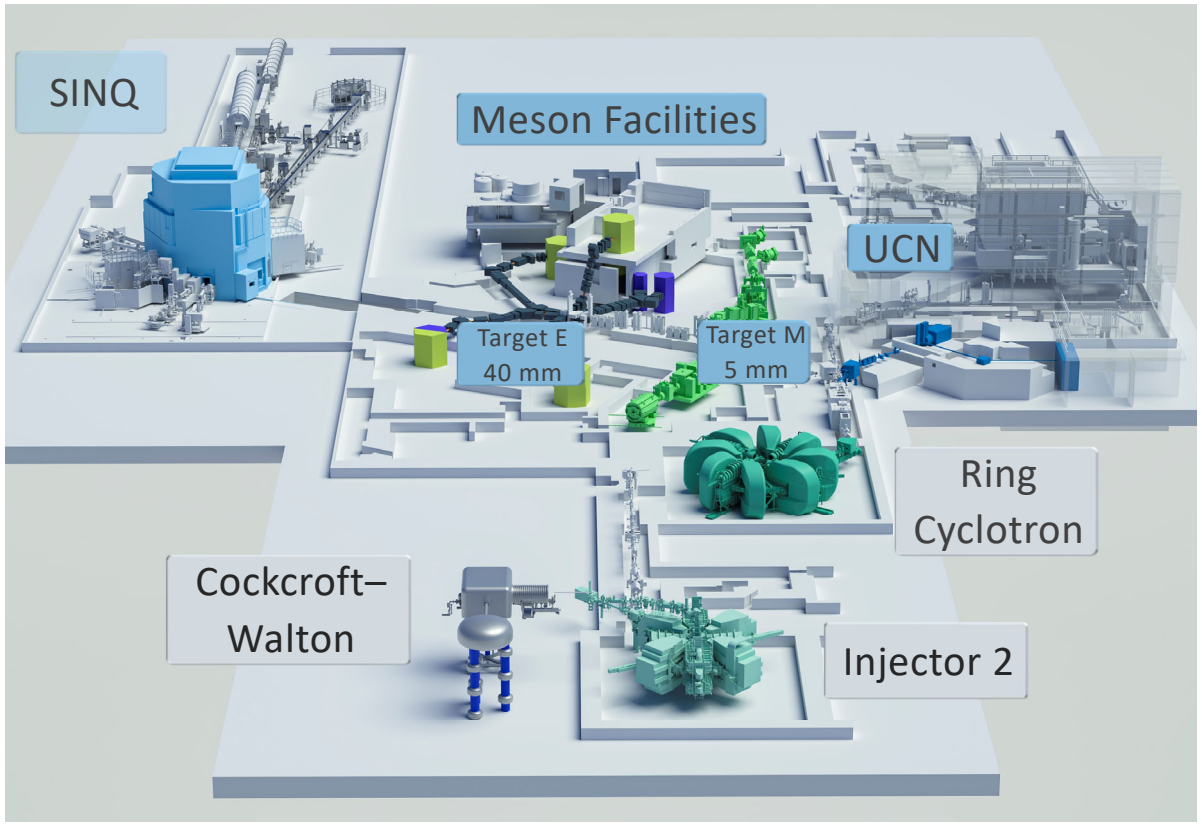
$3 \cdot 10^{23}$ protons/year ≙ 0.5 g of H_2

Beam Power:

590 MV · 2.4 mA = **1.4 MW** ≙ **1900 hp**

melts 1kg of steel in 10 ms

High Intensity Proton Accelerator Facility



Average Beam Time:
≈ 5000 h per year

Cockcroft–Walton
870 keV, 30 mA

Injector 2
72 MeV, 2.7 mA

Ring
590 MeV, 2.4 mA

Accumulated Charge
≈ 10 Ah per year

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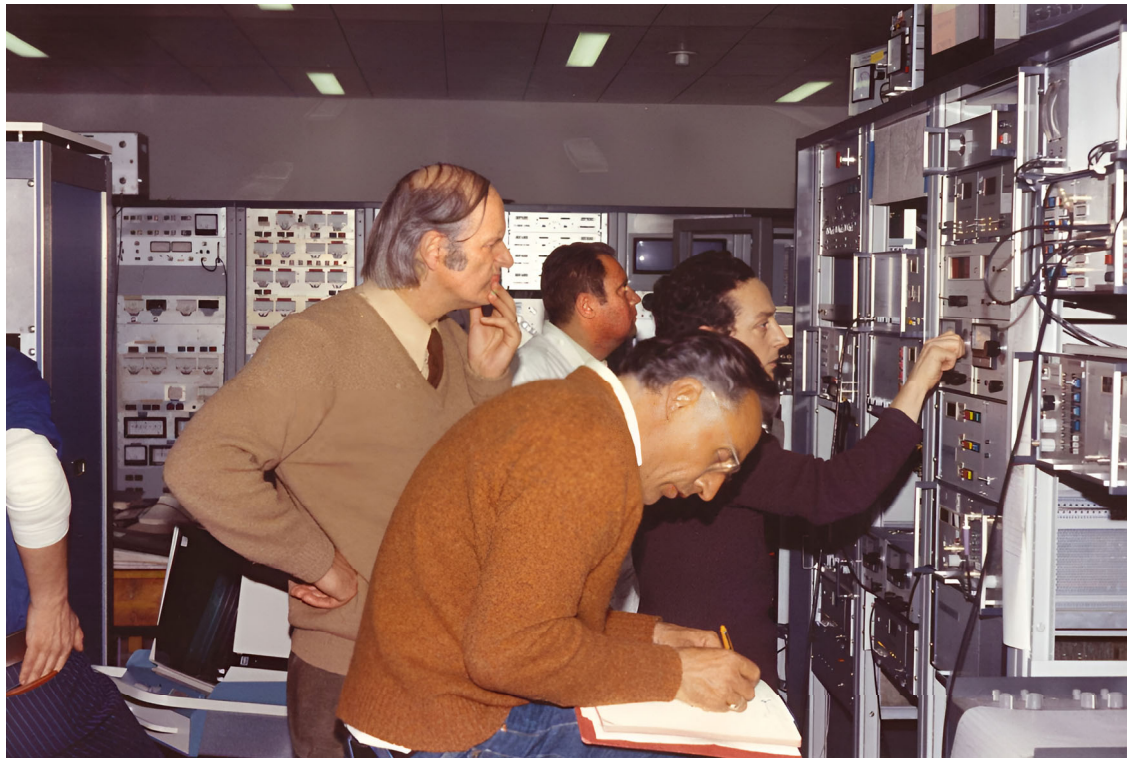
How to Reach a Megawatt

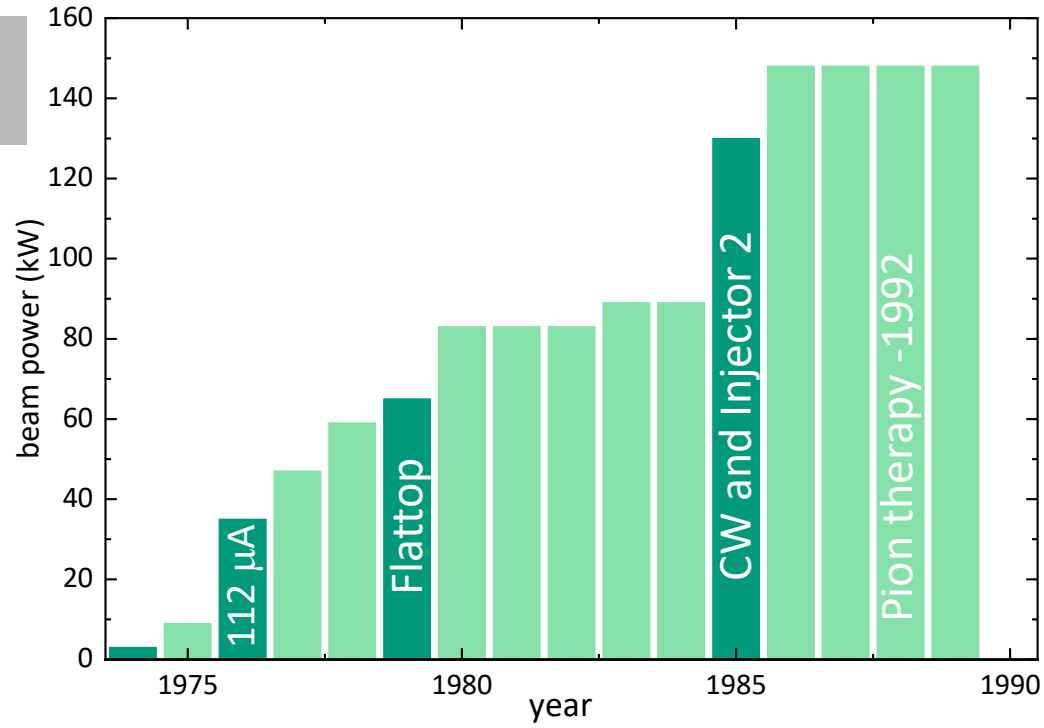
Knowledge, Diligence and Ambition



The original design goal was **100 μA** or **60 kW**.
This was deemed utterly ambitious.

Things are only impossible until they are not.

History of the Beam Power



1974: 25 µA (Commissioning)

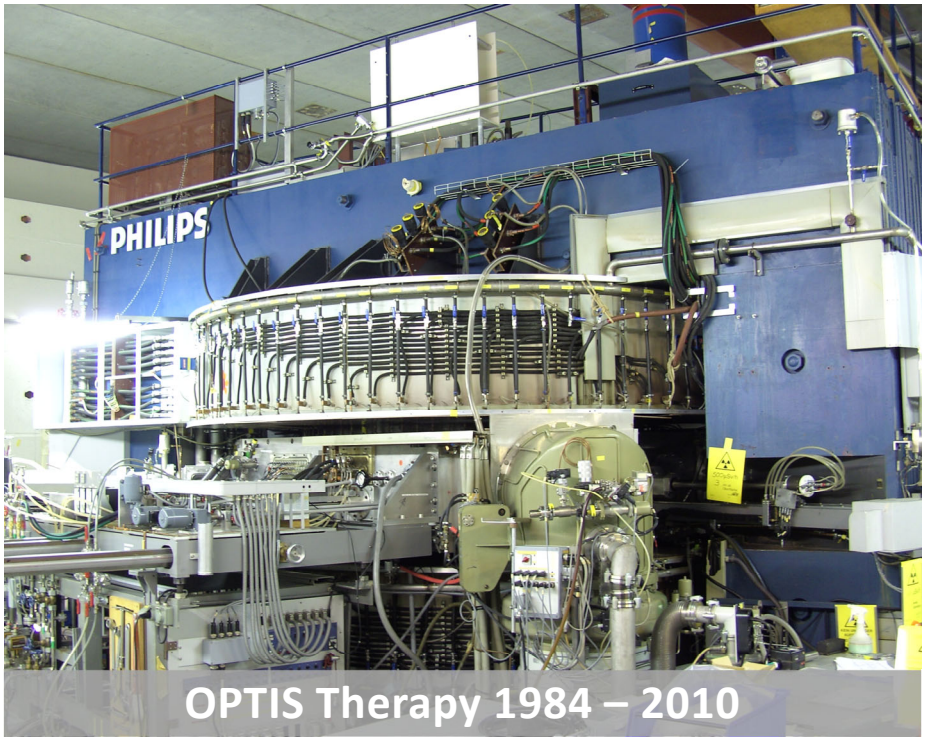
1976: **112 µA** design value reached
extraction efficiency **99.9%**
2–4 mA considered feasible

1979: Flattop (1/10 of losses)

1985: **250 µA**
Injector 2 Commissioning

1990: **High-Power Upgrade**
Targets: Daniela

Injector 1
A Versatile Bottleneck



OPTIS Therapy 1984 – 2010

Thomas Stammbach manages to tune Injector 1 to an extraction efficiency of 95% instead of 70%

Still: I_{max} < 200 μA (Injector I)

Proposal for new pre-accelerators

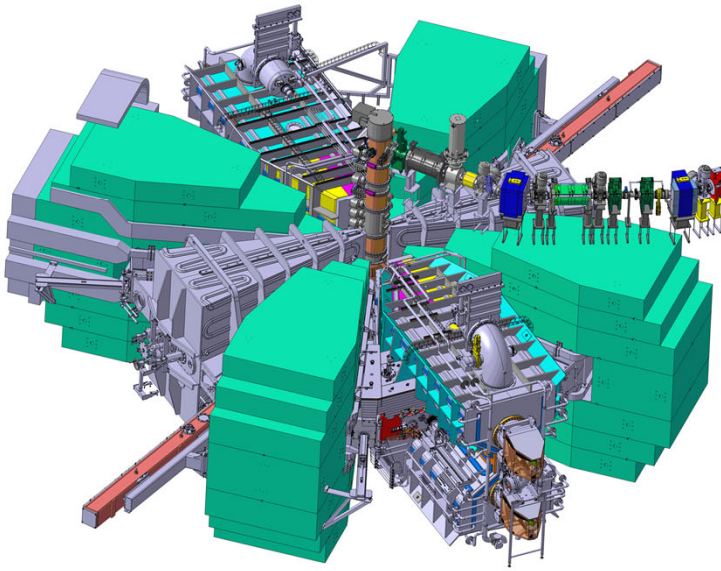
- Cockcroft-Walton
- Injector 2 cyclotron

Design study 1972, approved 1978
Project leader: Urs Schryber

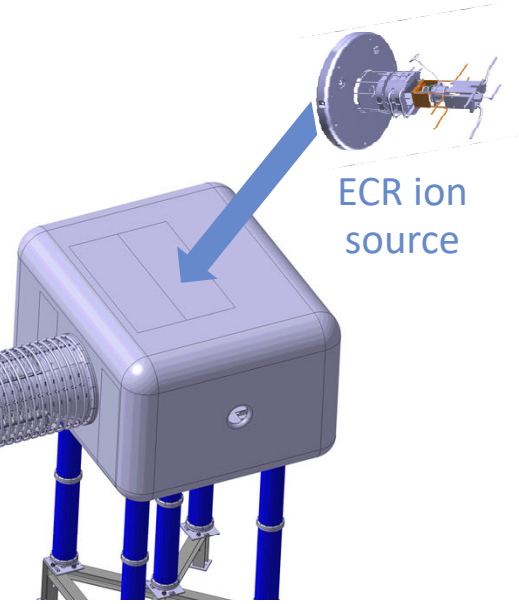
The New Pre-Accelerators

Commissioning 1985

Injector 2: 4 sectors, 4 resonators,
higher acceleration ⟹ higher current



72 MeV, 2.7 mA



Cockcroft–Walton: reliable, efficient
870 keV, 10 mA

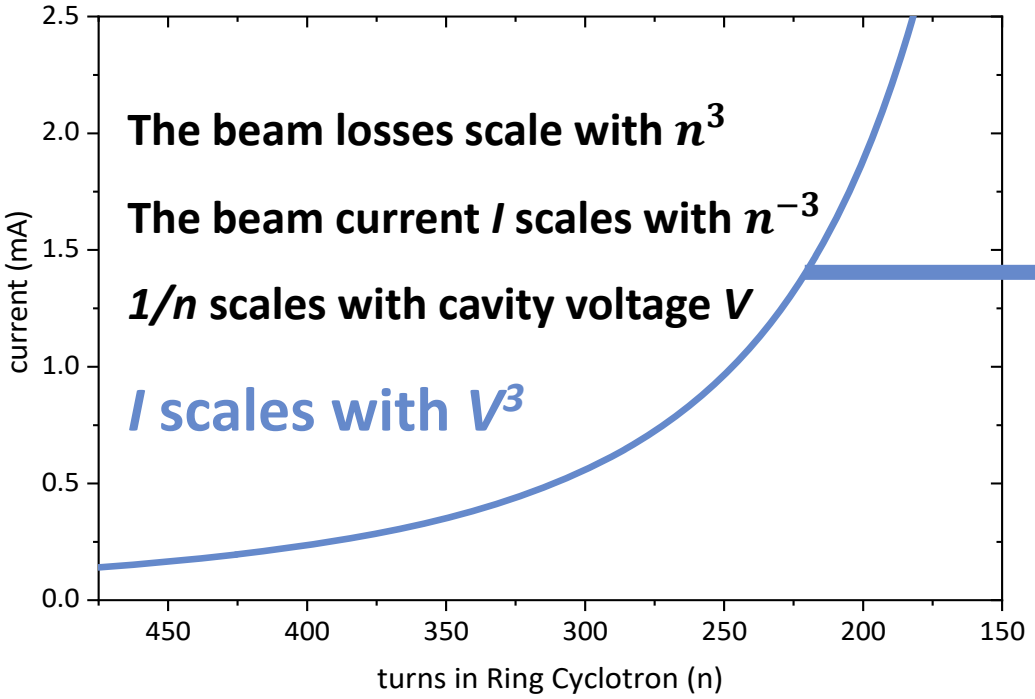
1990 → **Start of High Power Upgrade**
New targets, components, ….

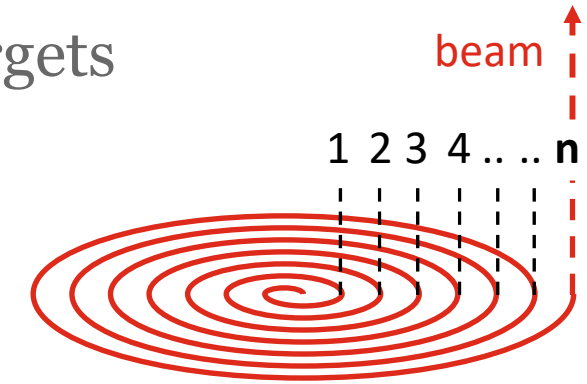
1990: New Injector, New Targets

New Target: 3 mA

The beam current is limited by proton losses

1981 Werner Joho formulates his empirical law:





Strategy:

Reduce the number of turns **n**

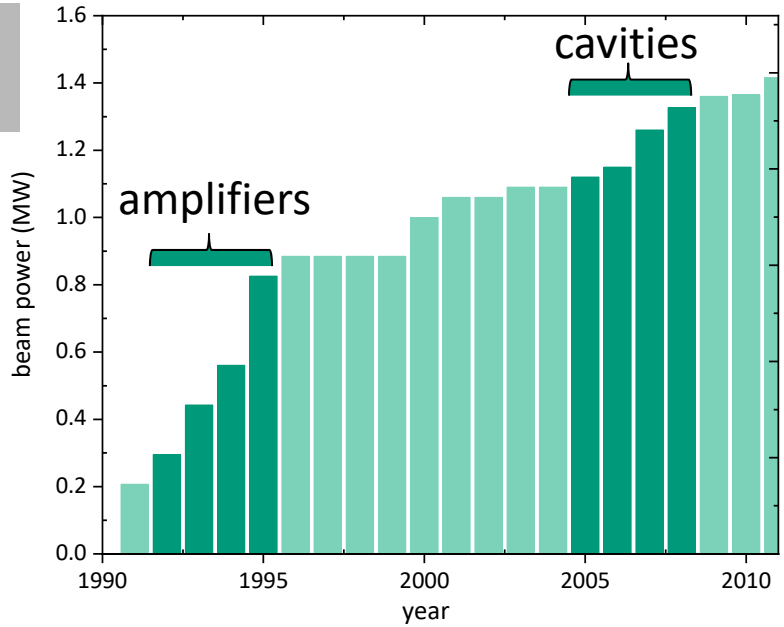
⟹ **Increase cavity voltage**

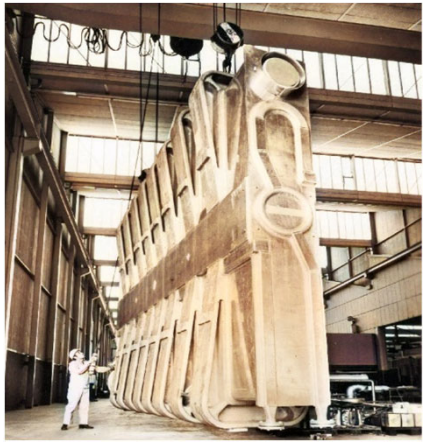
⟹ More powerful amplifiers (1992–1995)

⟹ More powerful cavities (2005-2008)

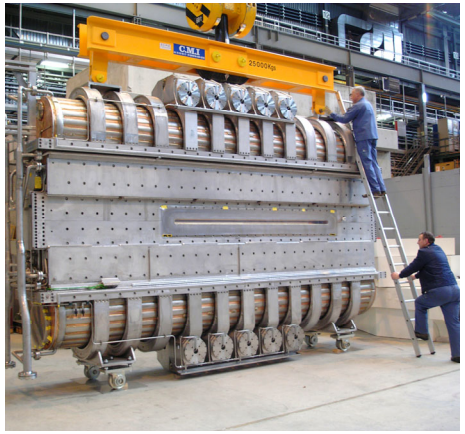
High Power Upgrade

Still Frequently Discussed





Maximum voltage:
700 kV



Higher voltage of 850 kV
(up to 1.4 MV)

RF – Upgrades → Higher energy gain per turn, less turns ⟹ **less losses**

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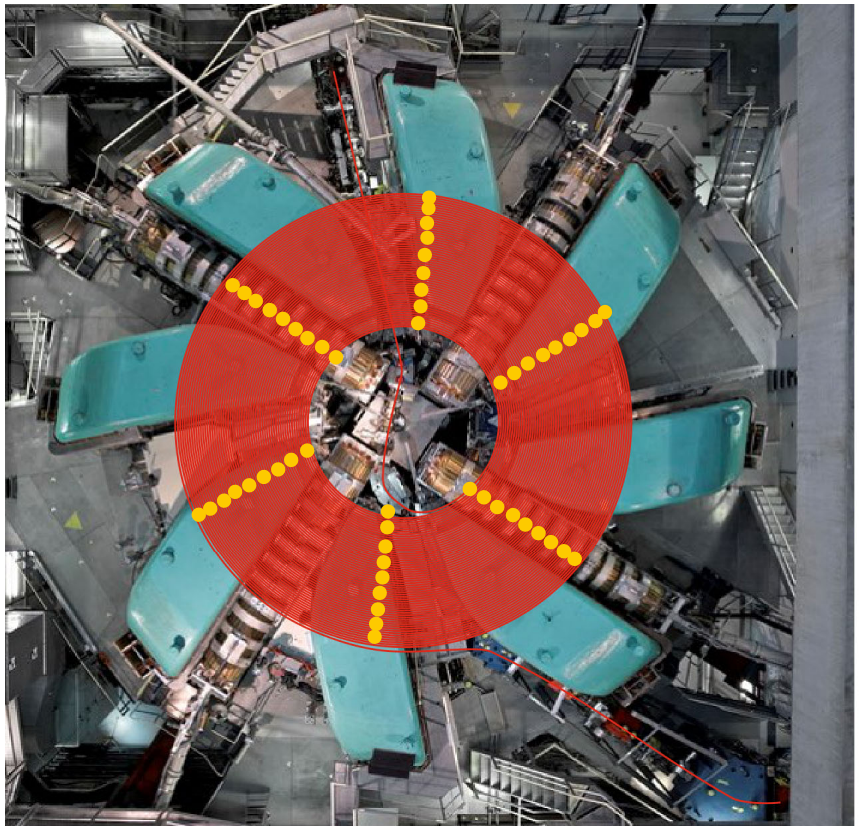
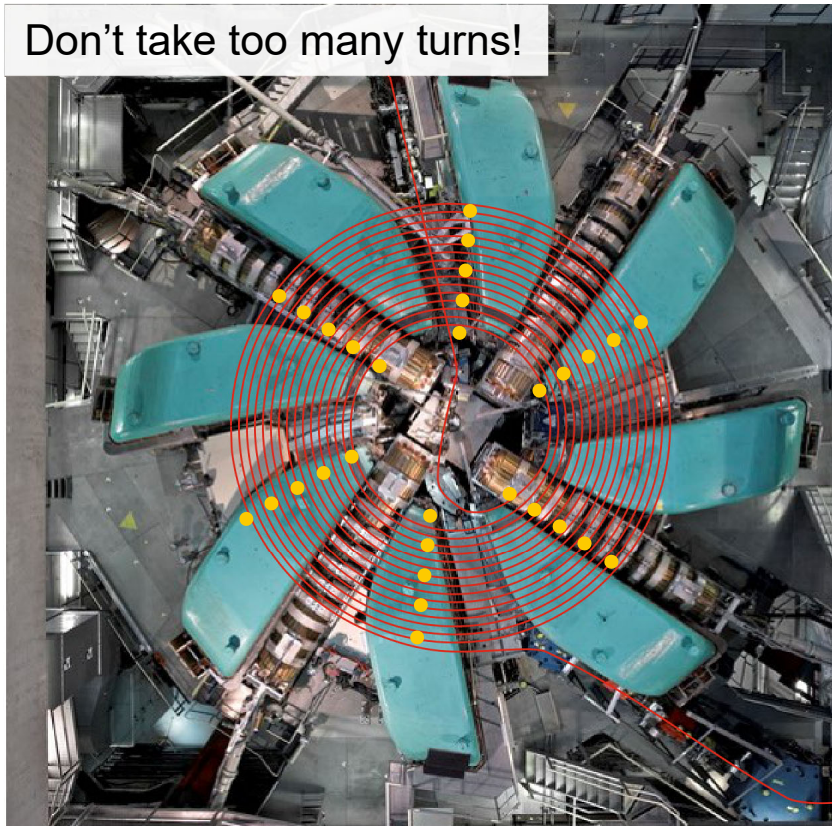
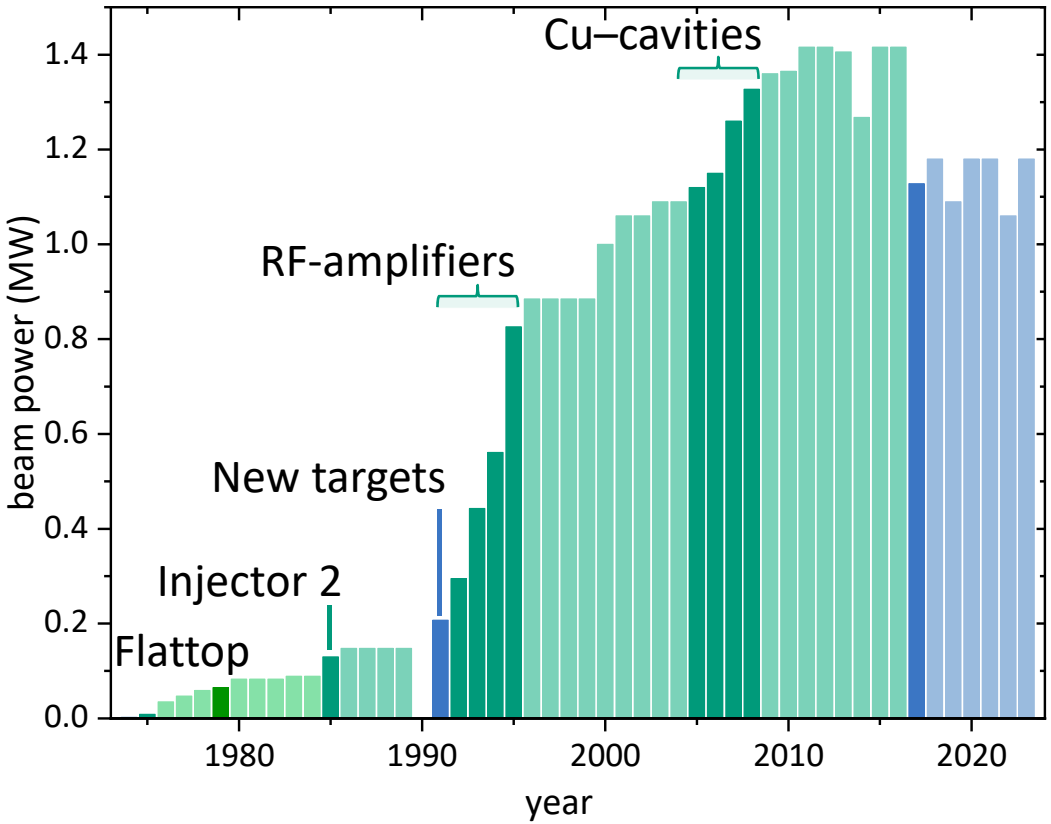
Enhanced Acceleration

Less Flight Time, Better Turn Separation, Less charge density

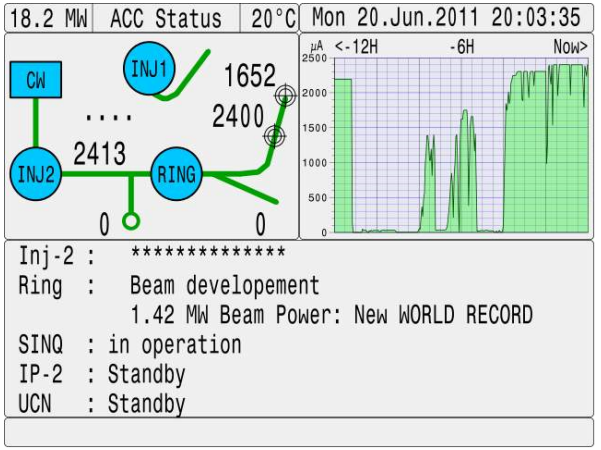




History of the Beam Power



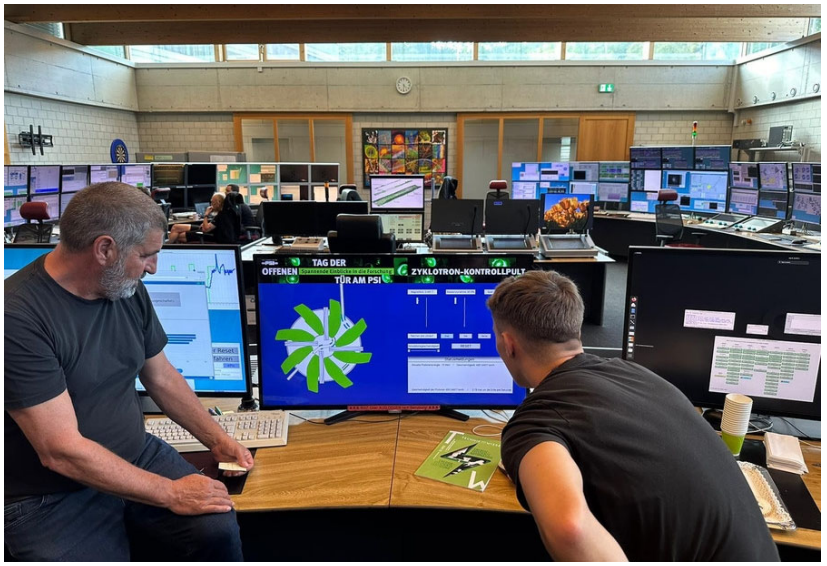
2011: Most powerful accelerator



2017: reduced power operation
upgrades, Cov19, energy crisis, ...

Knowledge, Experience, Intuition, Motivation

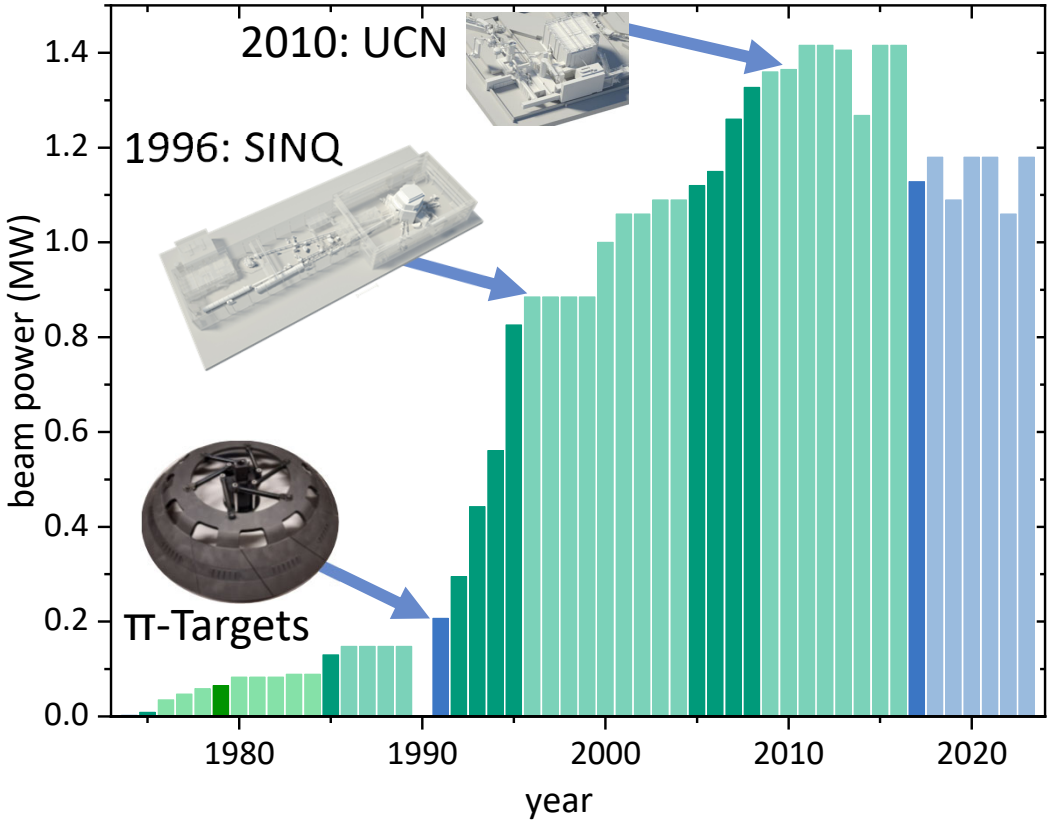
Original control room



New control room with windows and Linux

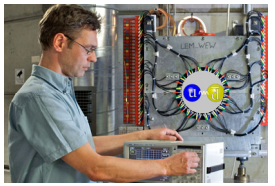
Flair is what marks the difference between artistry and mere competence: The operators not only push the machine to its peak performance but also ensure stable 24/7 operation.

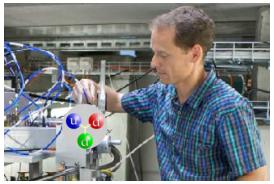
The Sources of Science



Users are concerned about secondary particle rates

- The rate of usable muons is the highest worldwide

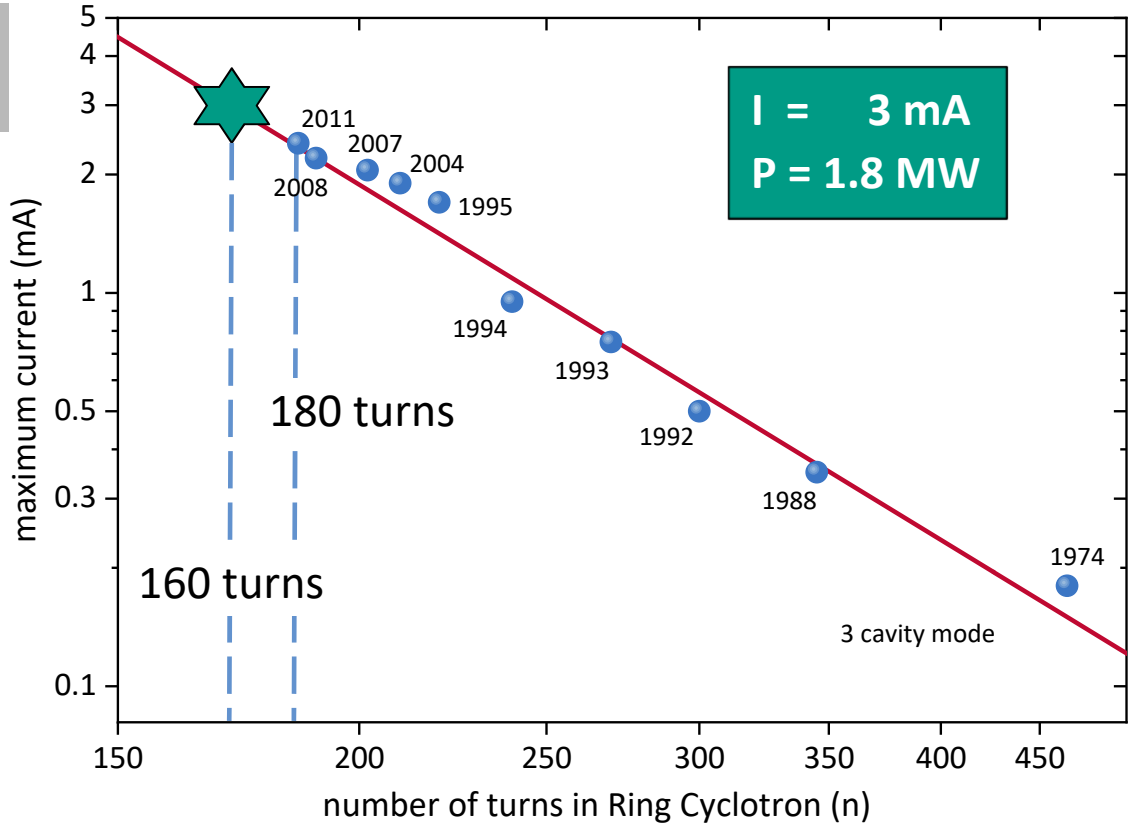




- In the ‘90s the proton current is high enough for neutron spallation sources.

⟹ 1996 SINQ (1st of its kind)
⟹ 2010 UCN

The Ultimate Goal

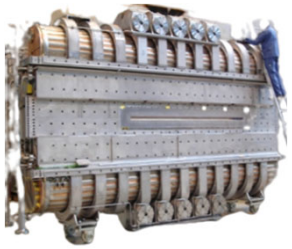


$I_{max} \sim V^3$

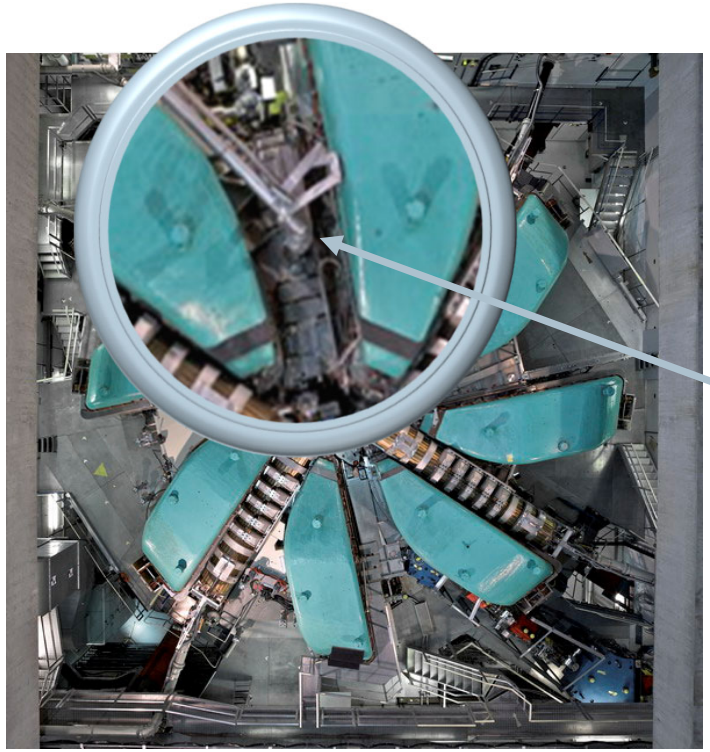
V(2.4 mA) ≈ 850 kV

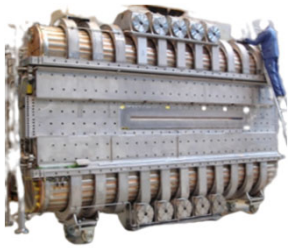
V(3.0 mA) ≈ 1000 kV

.....per cavity



Is the Ring Prepared for 3 mA?





***V* (3.0 mA) ≈ 1000 kV**

Amplifiers at their limit!

3rd harmonic «flattop» cavity

Frequency: 150 MHz

Peak voltage: **550 kV**

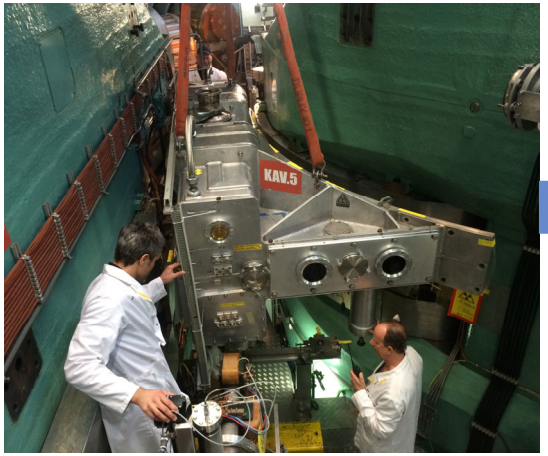
LIMIT

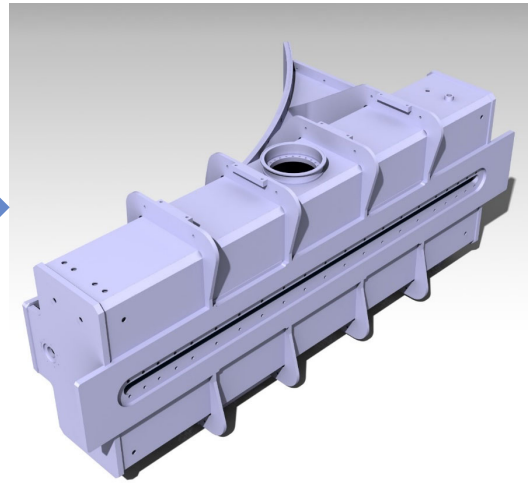
New Ring Flattop Cavity

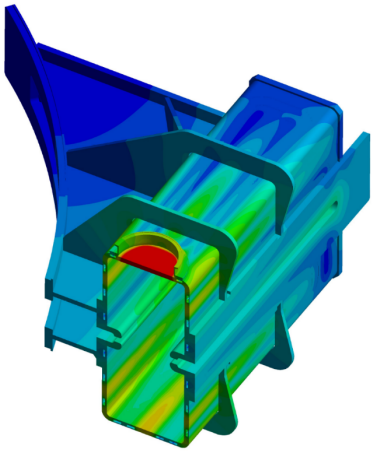
Maintaining Bunch Democracy

For 3 mA we need 650 kV $\Longleftrightarrow$ $V_{\mathrm{tot}} = V_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$

- new flattop
- new amplifiers





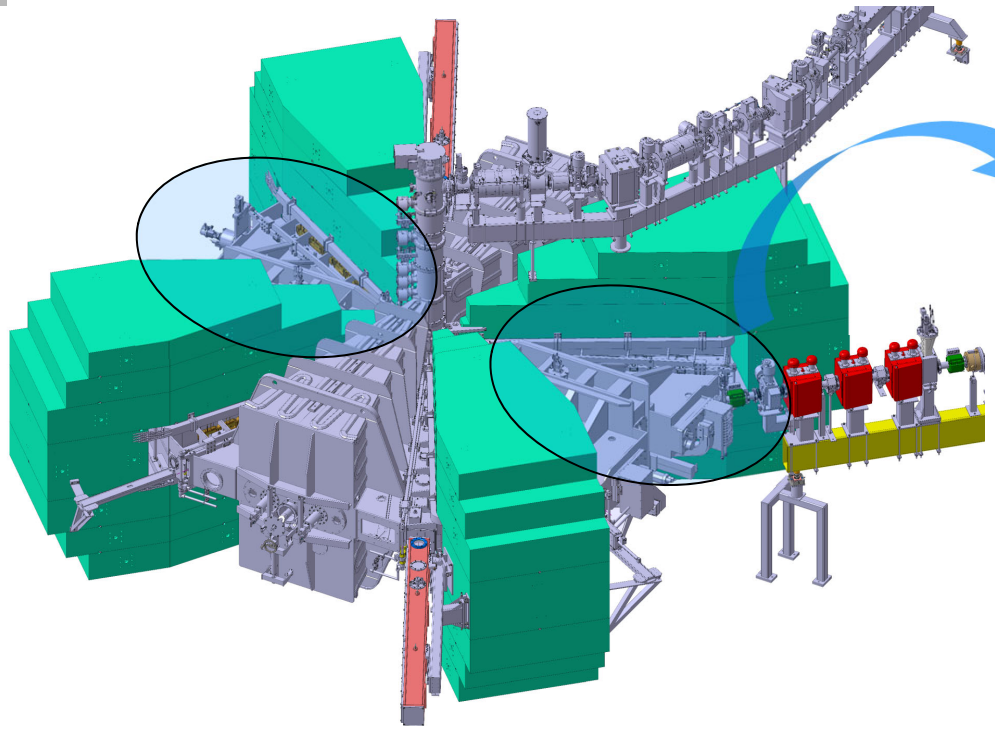


New flattop design for V > 650 kV

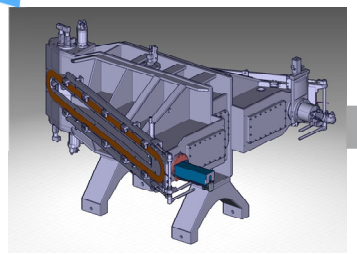
Injector 2–Upgrade

Goals: Increase beam current to **3 mA** **currently I_{max} = 2.7 mA**

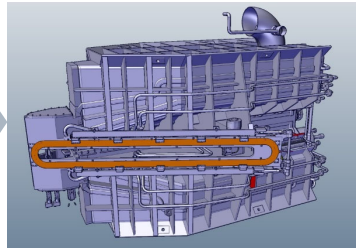
Reduce number of turns ⇒ **Less losses**



Strategy: Replace flattops with more powerfull accelerating resonators



150 MHz, 40 kV



50 MHz, 400 kV

60 instead of 80 turns ⇒ 3.0 mA

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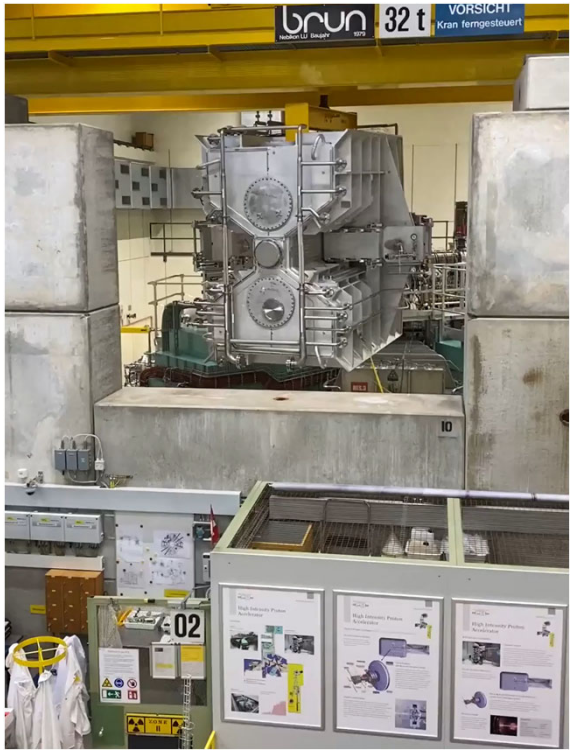
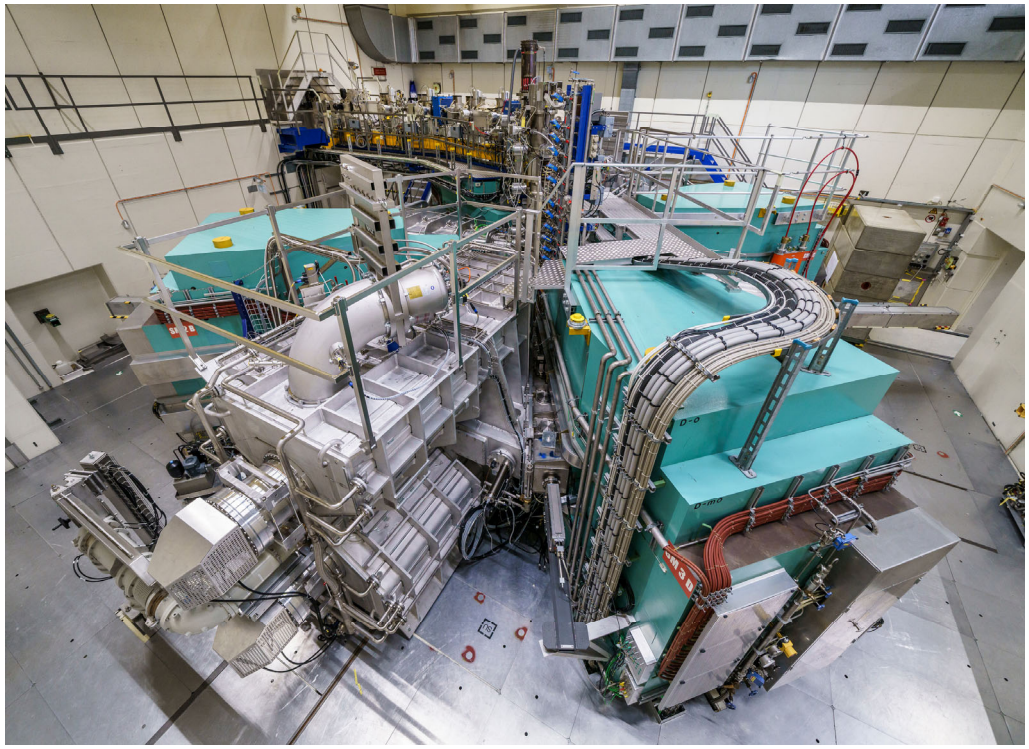
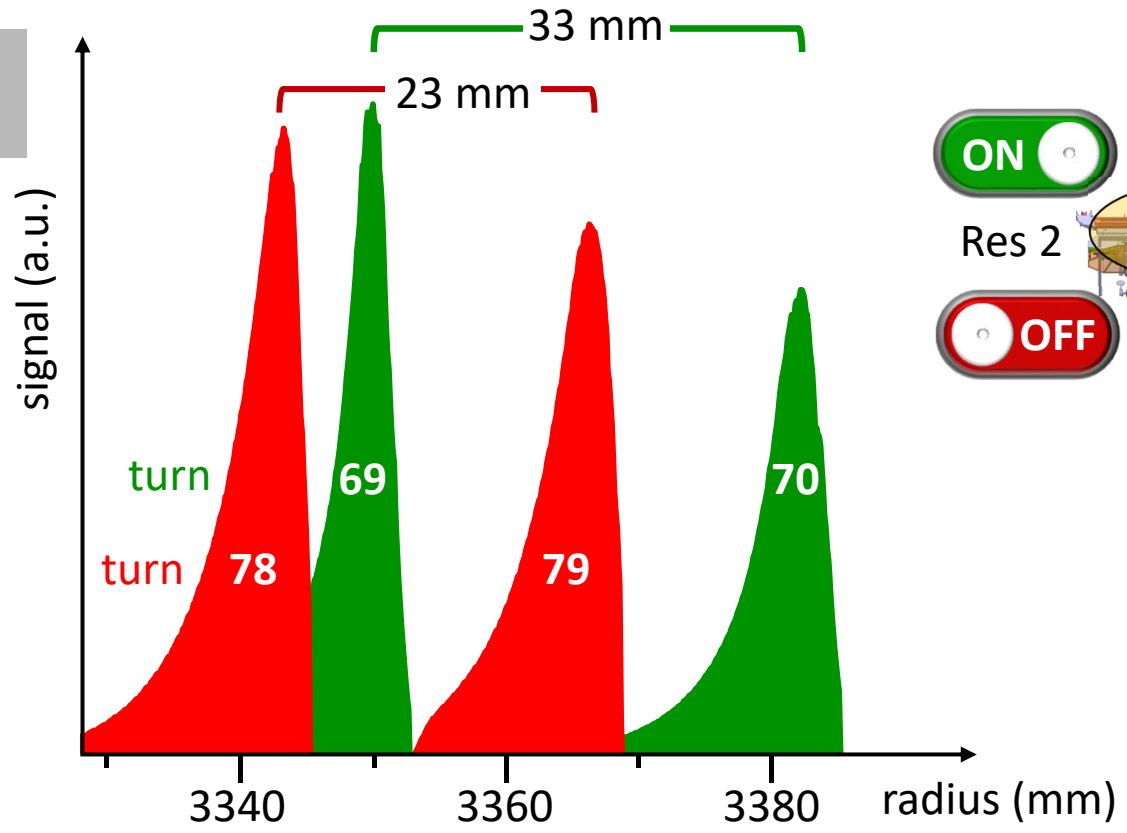
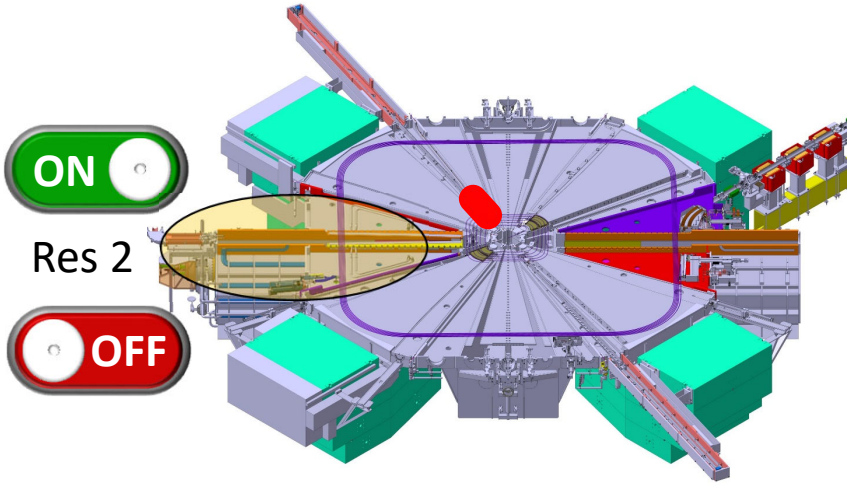
The Installation
2018 and 2024





The Result – Illustrative Dipiction





Enhanced turn separation

Less turns ⟹ less losses

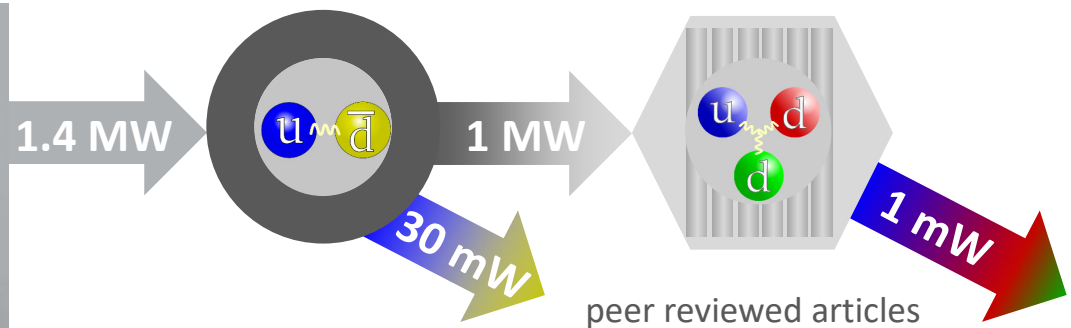
2023: Resonator 2

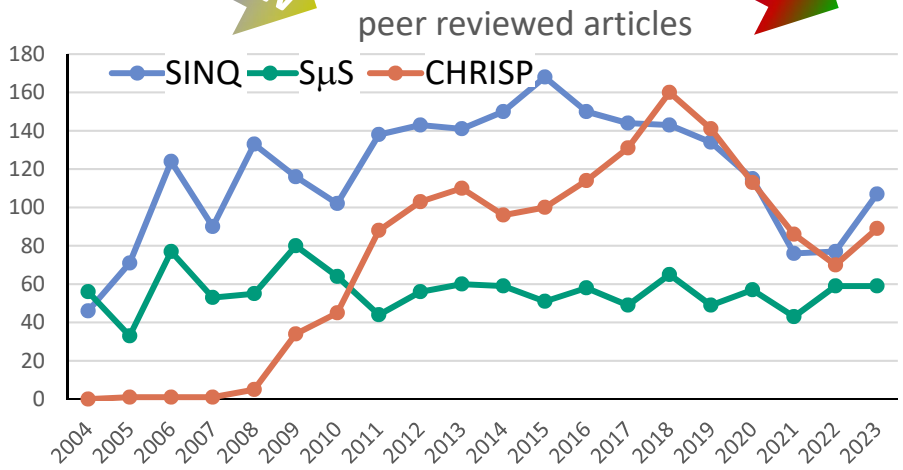
2024: Resonator 4

2025: Amplifiers 1&3

How Much Power is too Much?
How Far Do We Go?

More beam power, more secondary particles ⟹ more power from the grid!

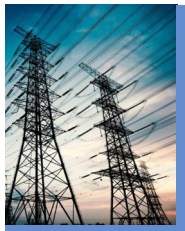




Optimizing targets and instruments can increase the secondary particle yield by orders of magnitude…

…but the accelerator is the leverage.

The Balance of Power



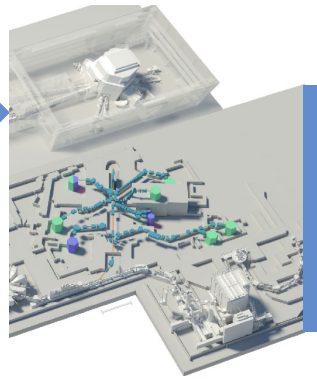
10 MW

5 MW

3 MW

2 MW

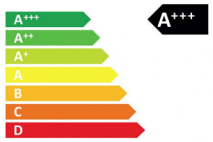
Beam: **1.4 MW**



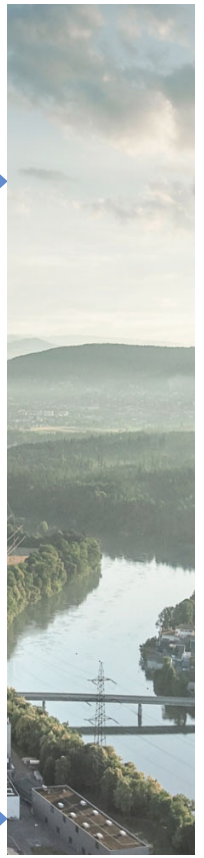
Efficiency =

$$\frac{1.4\ \text{MW}}{10\ \text{MW}} = 14\%$$

World record!

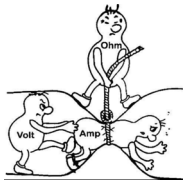


District heating 2 MW



Cyclotron Efficiency

Higher Precision on the Fast Track



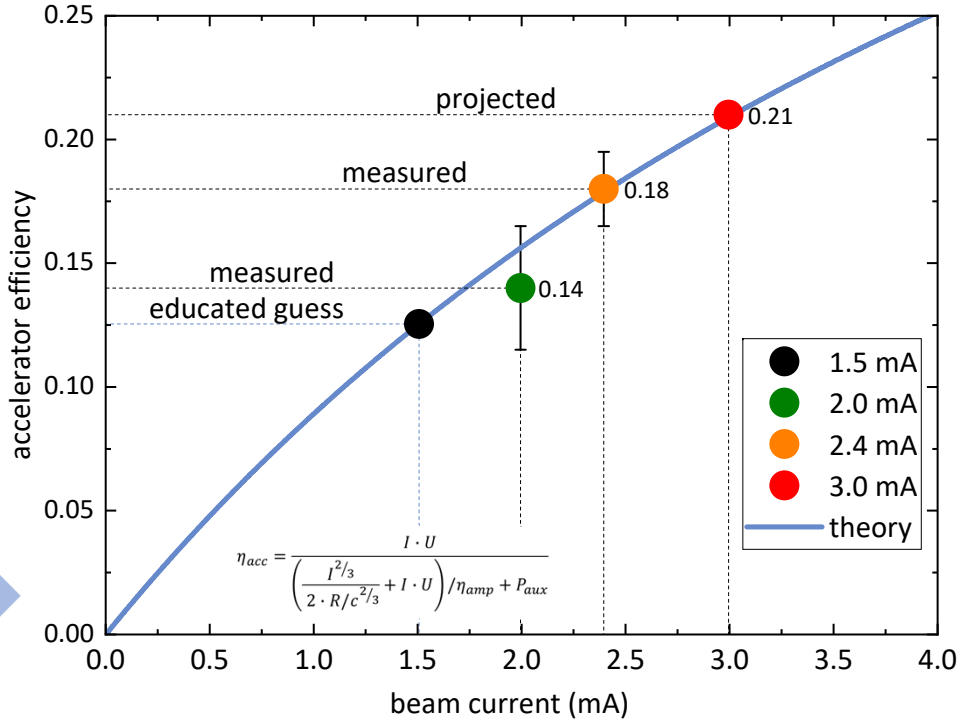
Efficiency:

$$\eta = \frac{P_{beam}}{P_{grid}} = \frac{U \cdot I}{P_{grid}}$$

$$P_{grid} \sim U \cdot I + P_{base} + \frac{V^2}{2 \cdot R}$$

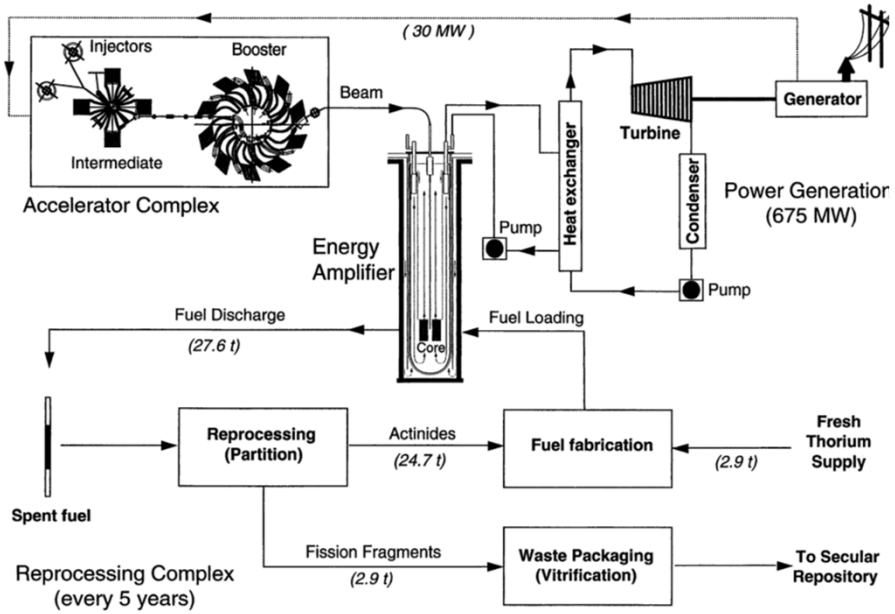
$$I \sim V^3$$

Efficiency increases with beam current!

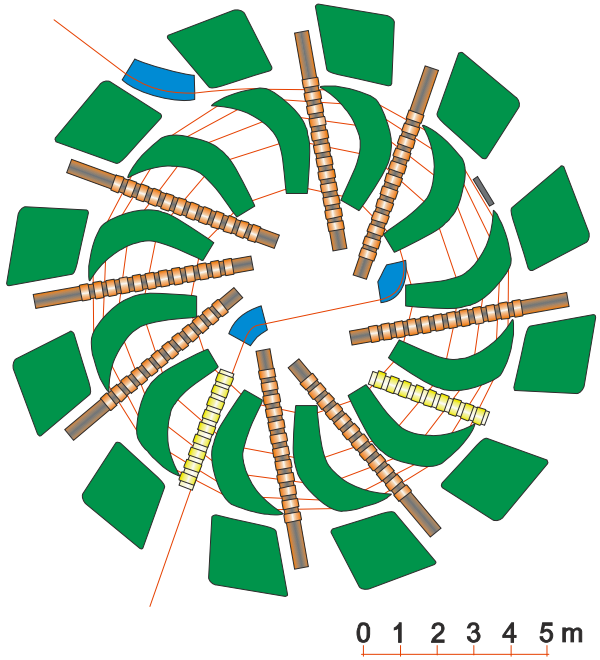


Cyclotrons for Accelerator Driven Systems

The energy efficiency is specifically important within the context of **Accelerator Driven Systems**



C. Rubbia et al. Report CERN-AT-95-44



10 MW Dream Machine (1 GeV, 10 mA)

Th. Stammbach et al. NIM B 113 (1996) I-7

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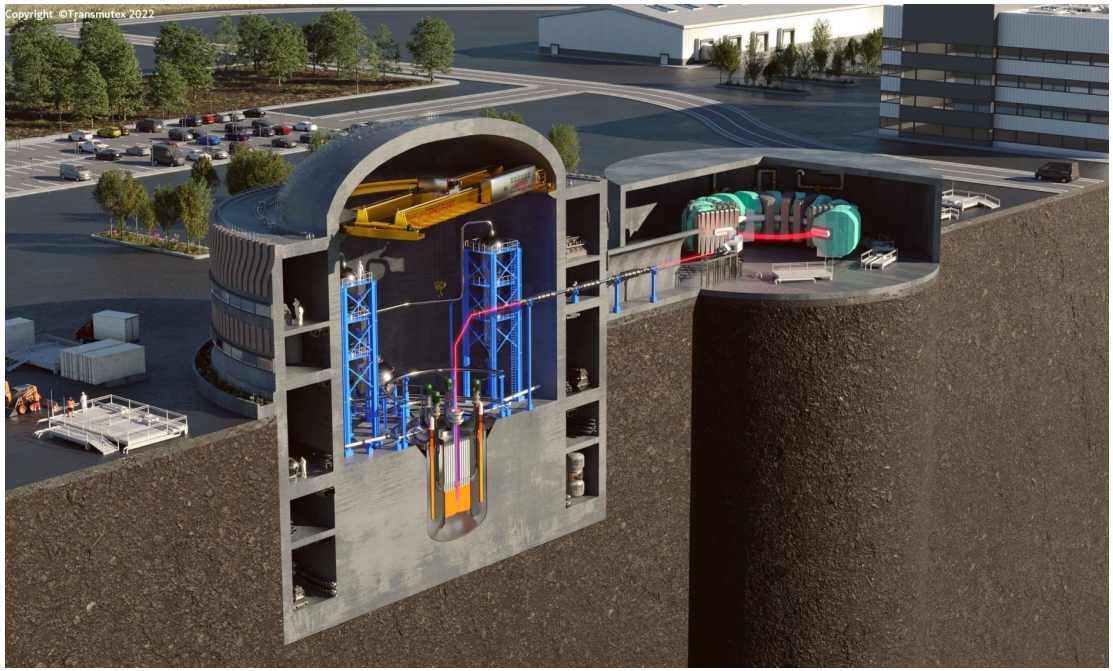
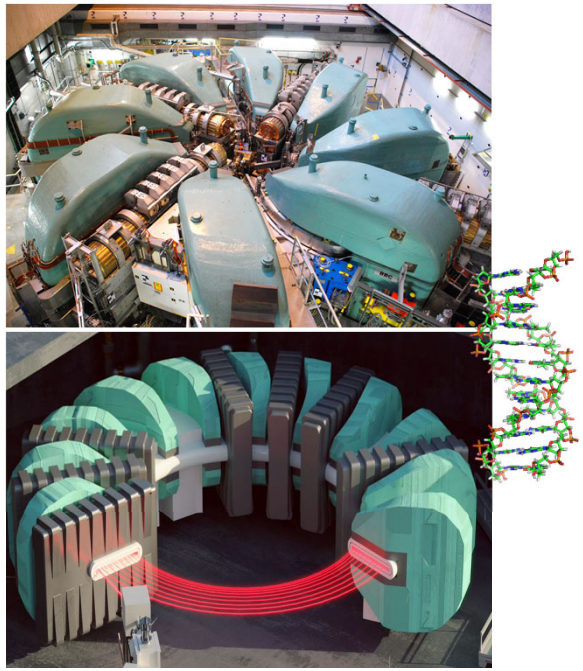
Cyclotrons for Accelerator Driven Systems

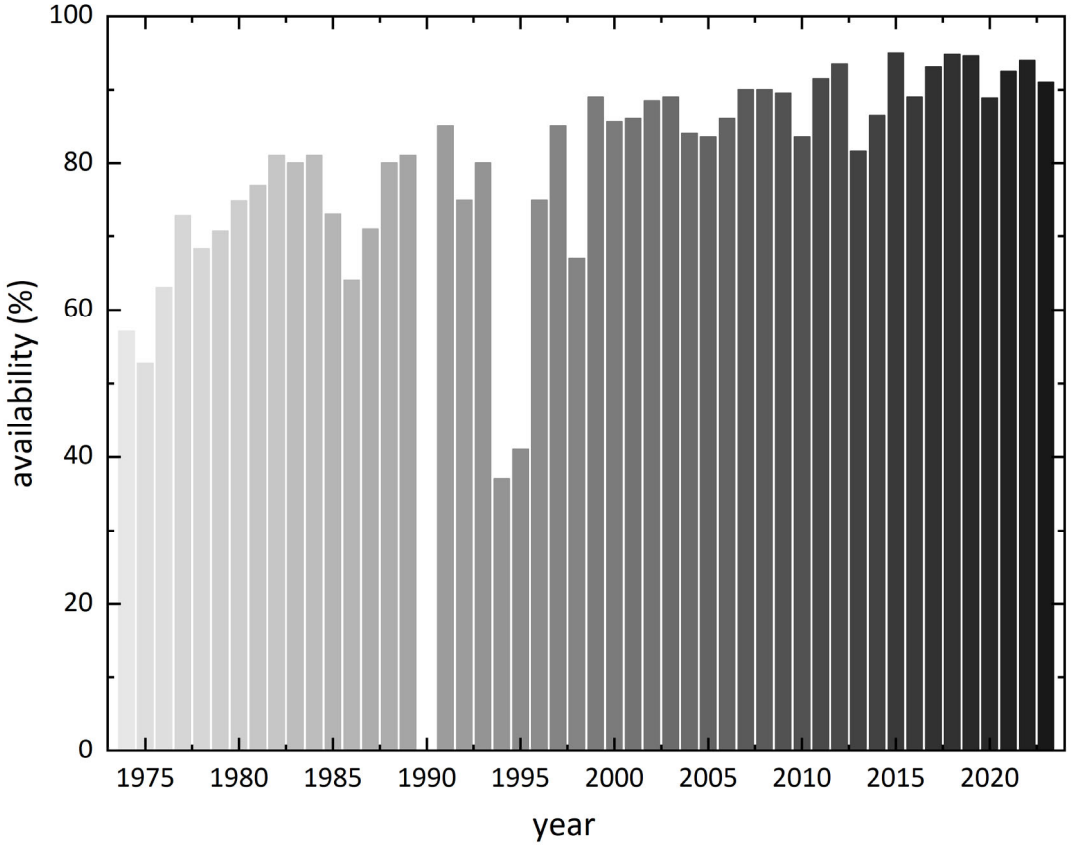
Power Generation with a Thorium Subcritical Device

Up to now, there is no MW–accelerator with a higher energy efficiency.





History of the Availability



Beam availability is of utmost importance, especially for the upcoming projects.

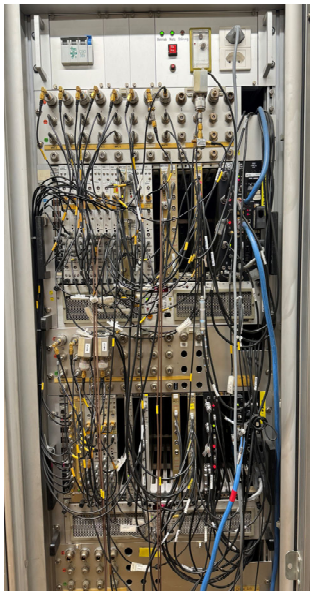
Average: 90%
Maximum: 95%

Prior to upgrading, it is imperative to refurbish outdated systems!

Just paint won't help!

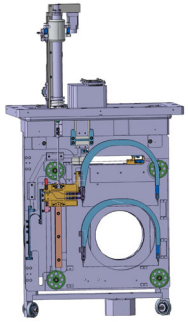
10 Year Upgrade Plan
Embracing the Next 2 Decades

Control system

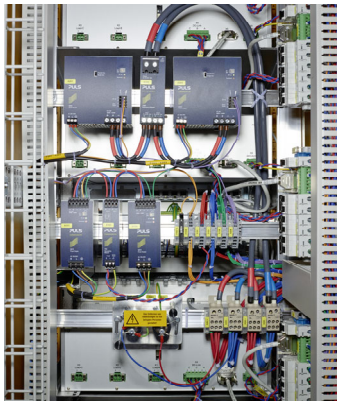


Magnets

Components



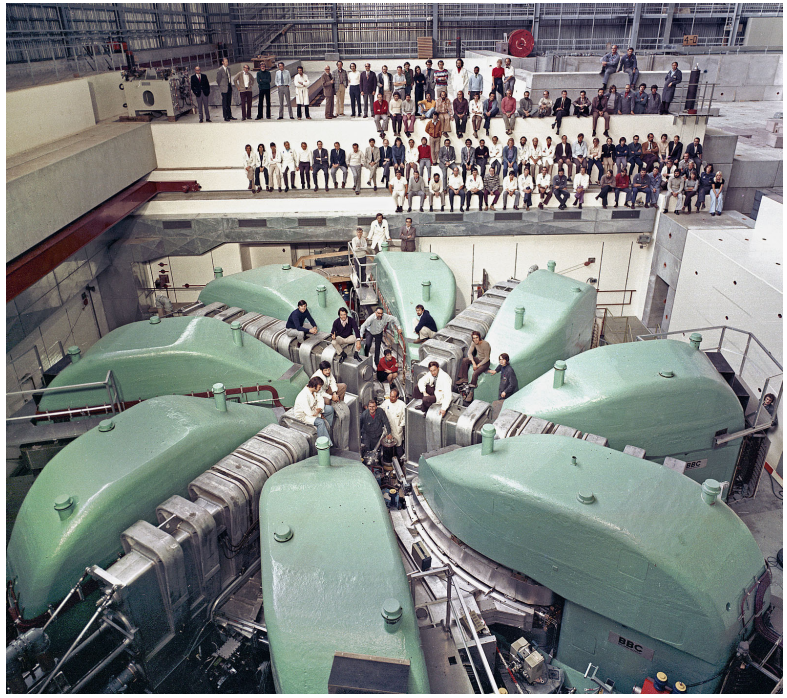
Infrastructure



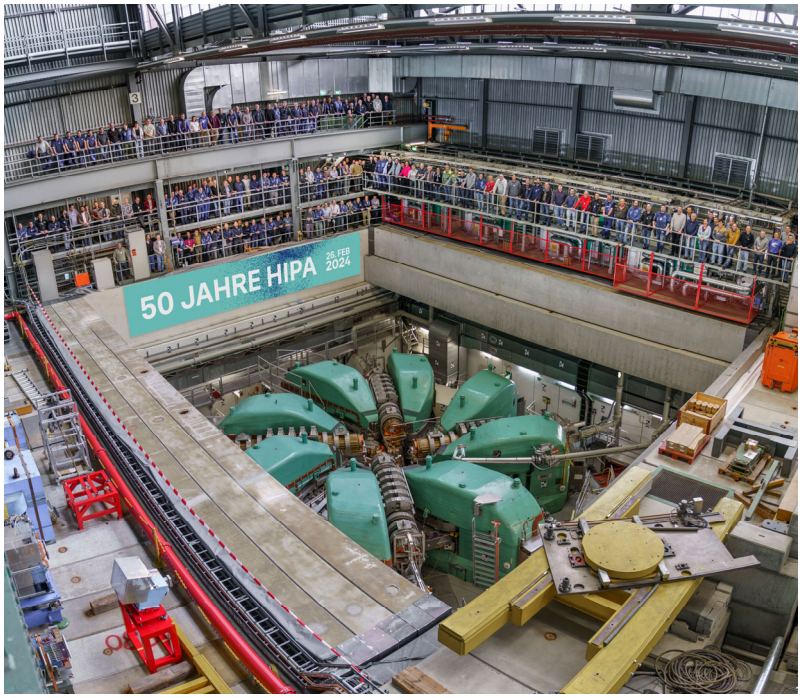
Electronics, Software, Magnets, Cooling, RF, Vacuum, Diagnostics, Power Supplies, Collimators, Targets, you name it….

It’s ALL About People!

The Backbone of Success



Thank you for the invaluable legacy you've bestowed upon us!



Gratitude to our team for safeguarding this legacy and driving its evolution!

PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

My thanks go to

- My colleagues
- your attention

Material:
layouts: C. Sattler, M. Dzambegovic
n^{-3}: W. Joho
Flattop: J.Y. Raguin, E. Solodko
Space Charge: S. Adam, S. Warren

Without Jean-Pierre Blaser's Vision there would be no
Particle Physics, Material Science, Neutron Sources, Proton Therapy, Isotope Production, SLS, SwissFEL, Park Innovaare

Construction site in Villigen. An option was Hönggerberg. The final decision to opt for Villigen was mainly based on the proximity to EIR with its essential infrastructure.