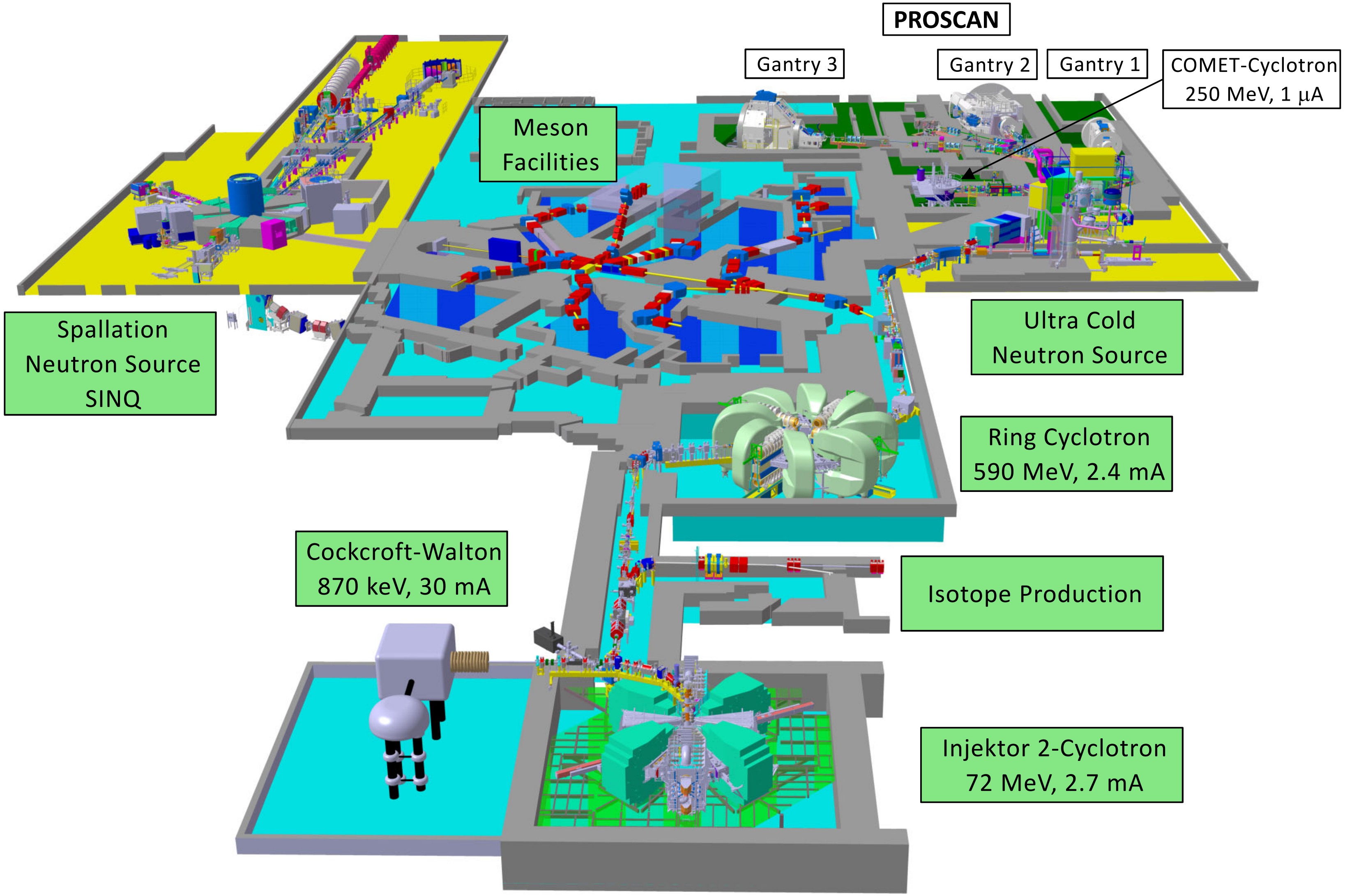
Joachim Grillenberger :: Head of Proton Facilities :: Paul Scherrer Institute

The High Intensity Proton Accelerator Facility
Past, Present, Projects

Snowmass'21 Workshop on High Power Cyclotrons

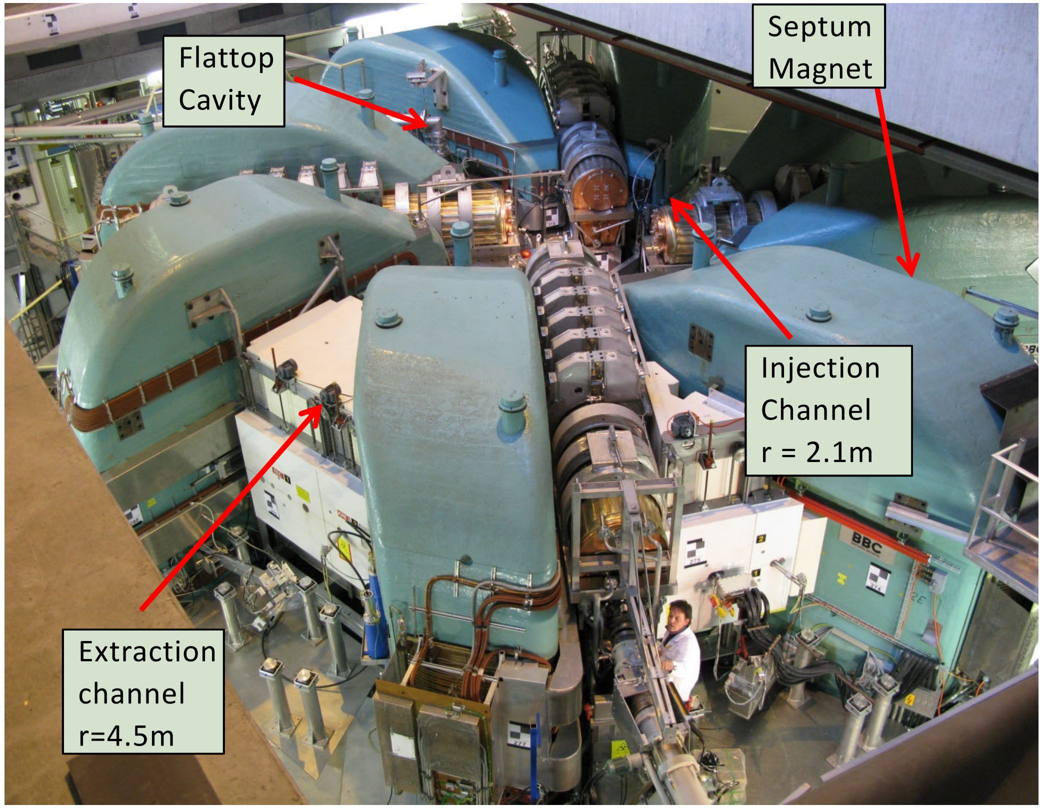
High Intensity Proton Accelerator Facility



The PSI Ring-Cyclotron

in operation since 47 years (19.2.1974 first muons)

- 8 Sector magnets:	0.6 – 0.9 T
- Magnet weight:	250 tons
- 4 cavities (50.63 MHz):	850 kVp
- 1 Flat-Top (150 MHz):	550 kVp
- harmonic number:	6
- beam energy:	**72 → 590 MeV**
- beam current max.:	**2.4 mA**
- operating current:	**2.2 mA**
- extraction radius:	4.5 m
- number of turns:	186
- relative Losses: (at 2.4 mA)	**1..2·10^{-4}**

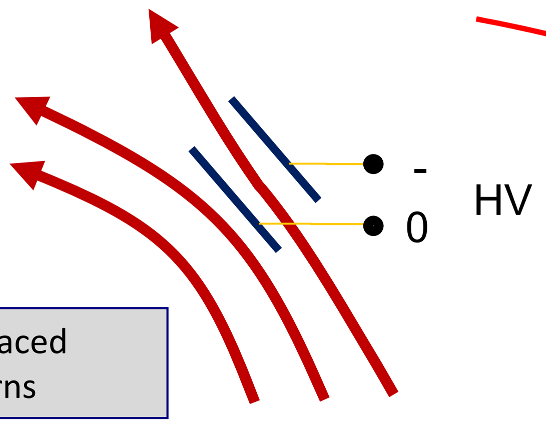


Beam power: 590 MV × 2.4 mA = 1.42 MW

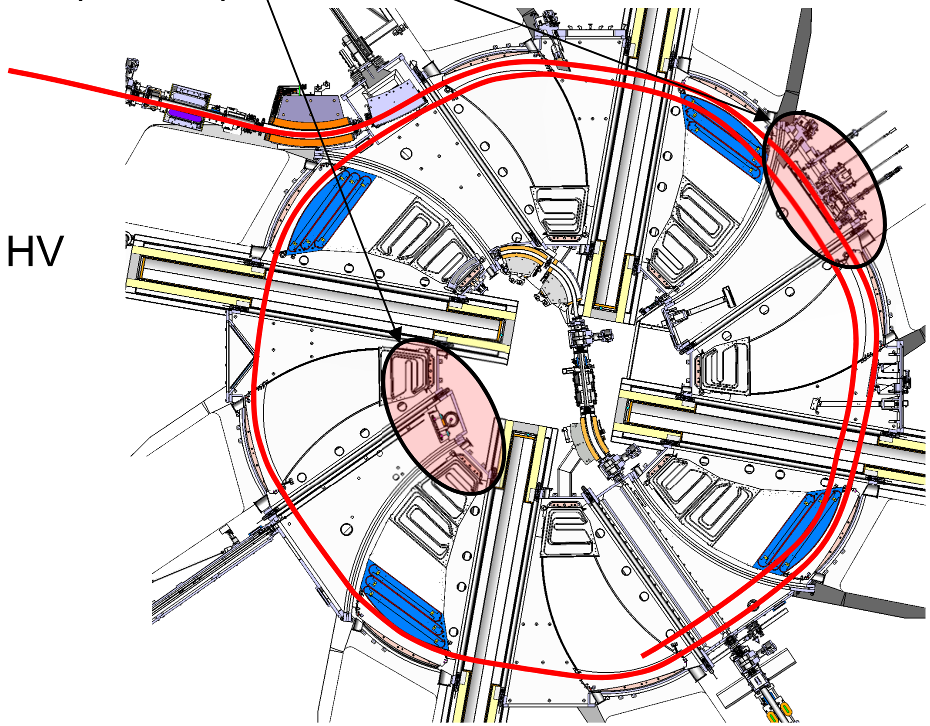
Single Turn Extraction

Electrostatic Deflection

- Electrostatic extraction channel (142 kV)
- Electrostatic injection channel (133 kV)



Electrode placed between turns

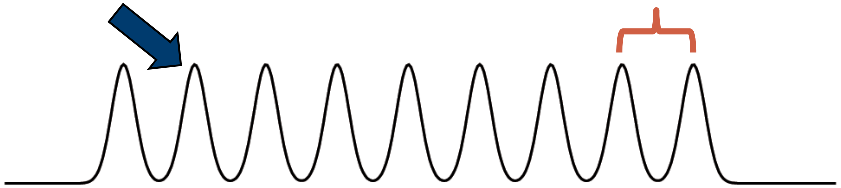


Extraction is a notorious problem in circular accelerators...
I'd stick to it…

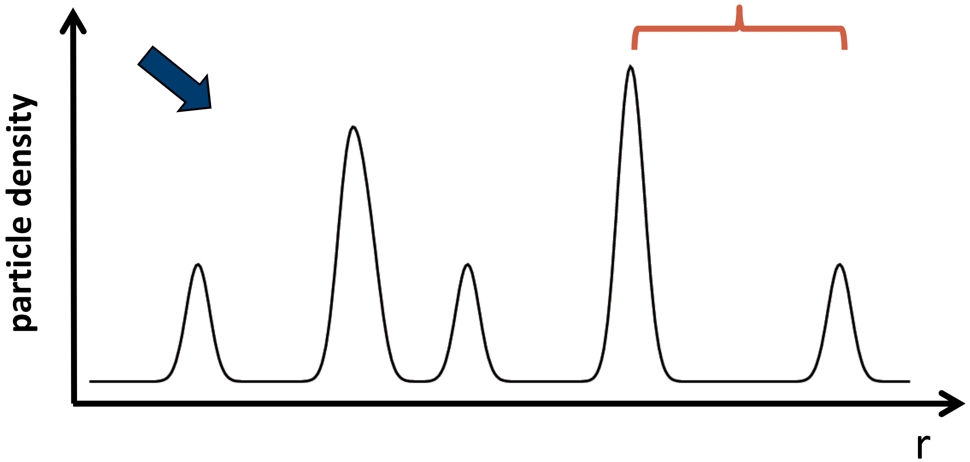
Extraction with off-center orbits

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)



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



History of the Facility

Original proposal (1963)[1]
- Facility for the production of π-mesons and muons
- Driven by a proton accelerator (E_{kin} > 450 MeV)
- Beam current: tens of microamperes
- Extraction rate > 50%

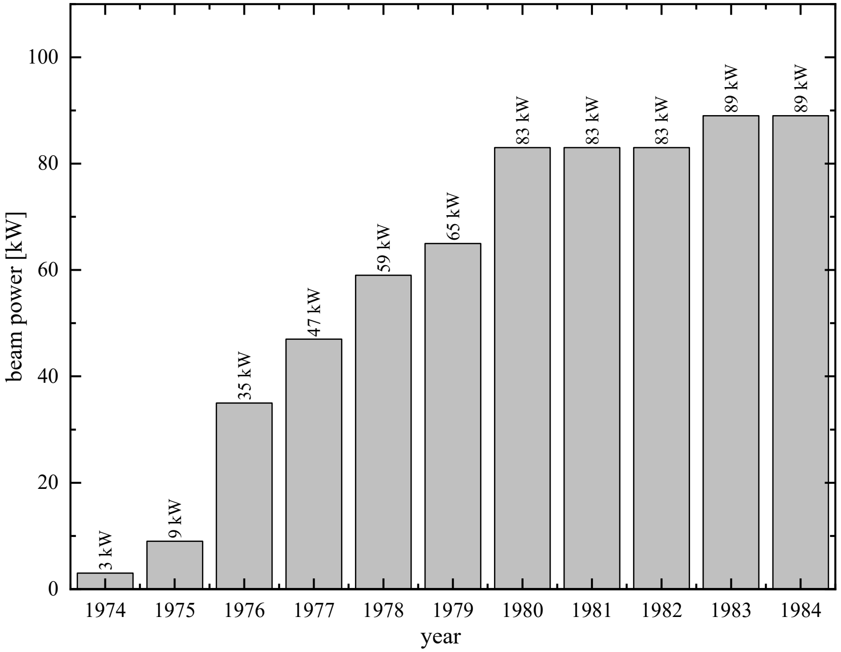
Final design (1969)[2]
- Isochronous sector cyclotron (8 magnets, 4 cavities)
- E_{kin} = 590 MeV
- Beam current > 100 μA
- Pre-accelerator Philips cyclotron (72 MeV)

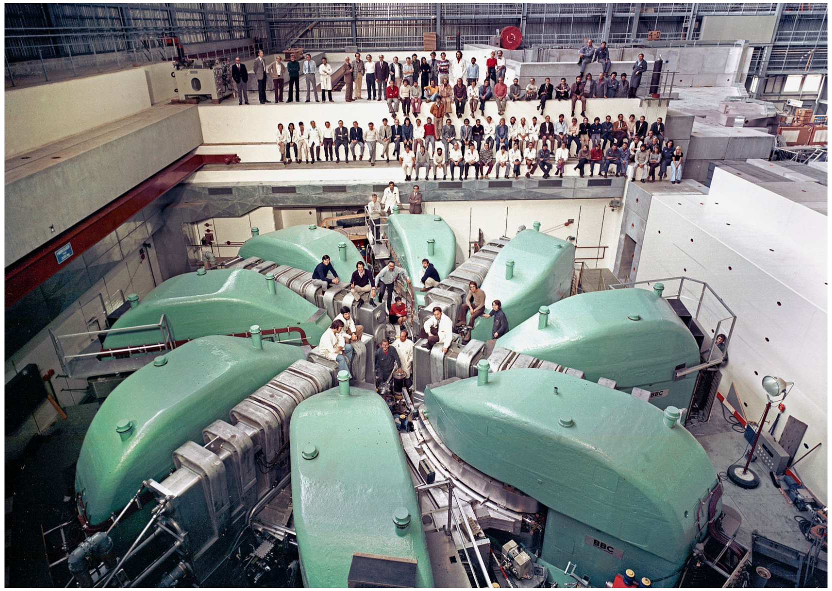
Comissioning in 1974 with up to 25 μA

[1]H. A. Willax,Proposal for a 500 MeV isochronous cyclotron with ring magnet, In F. Howard363and N. Vogt-Nilsen, eds.,CERN Report 63-19, pp. 386–397. CERN, ISBN 978-3-95450-364086-4 (1963)

[2]H. A. Willax,Status report on S.I.N., In McIlroy[47], pp. 58–72 (1969)

History of the Beam Power





1973

1974: Commissioning (25 μA)

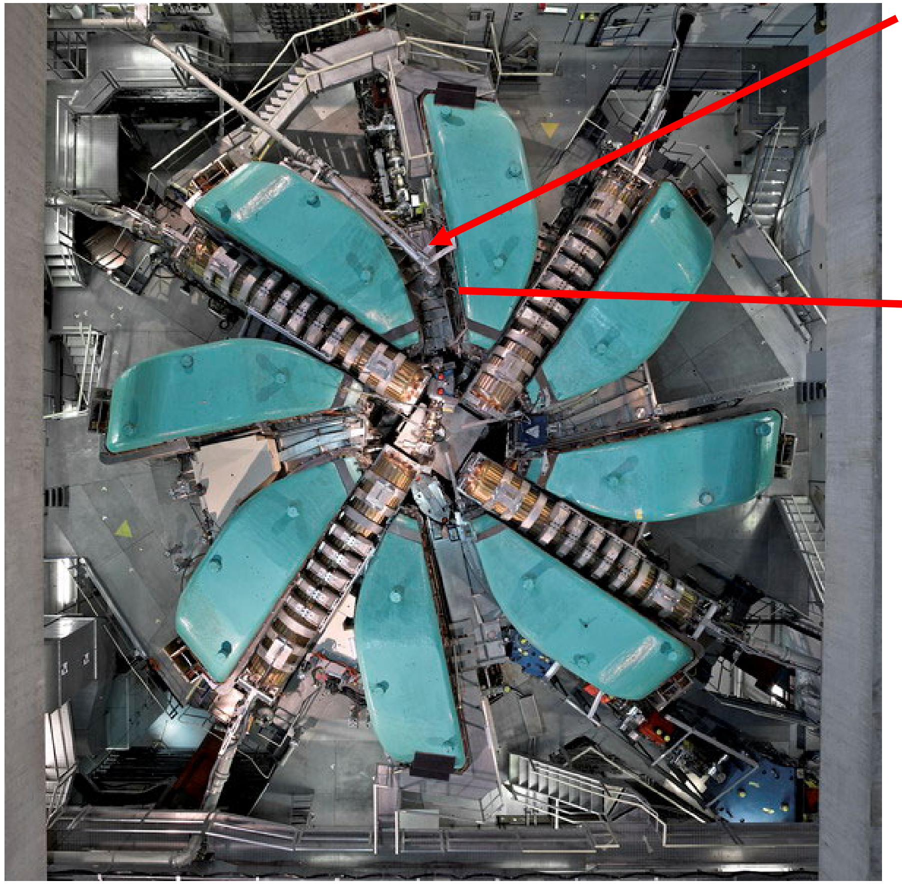
1976: 112 μA, extraction efficiency 99.9% (Ring)

Already then, beam currents of up to 2–4 mA were considered feasible

I_{max} < 180 μA (Injector I)

Proposal for new pre-accelerators Cockcroft-Walton (860 keV) and an injector cyclotron (72 MeV) approved in 1978

150 MHz Flattop Cavity (1979)



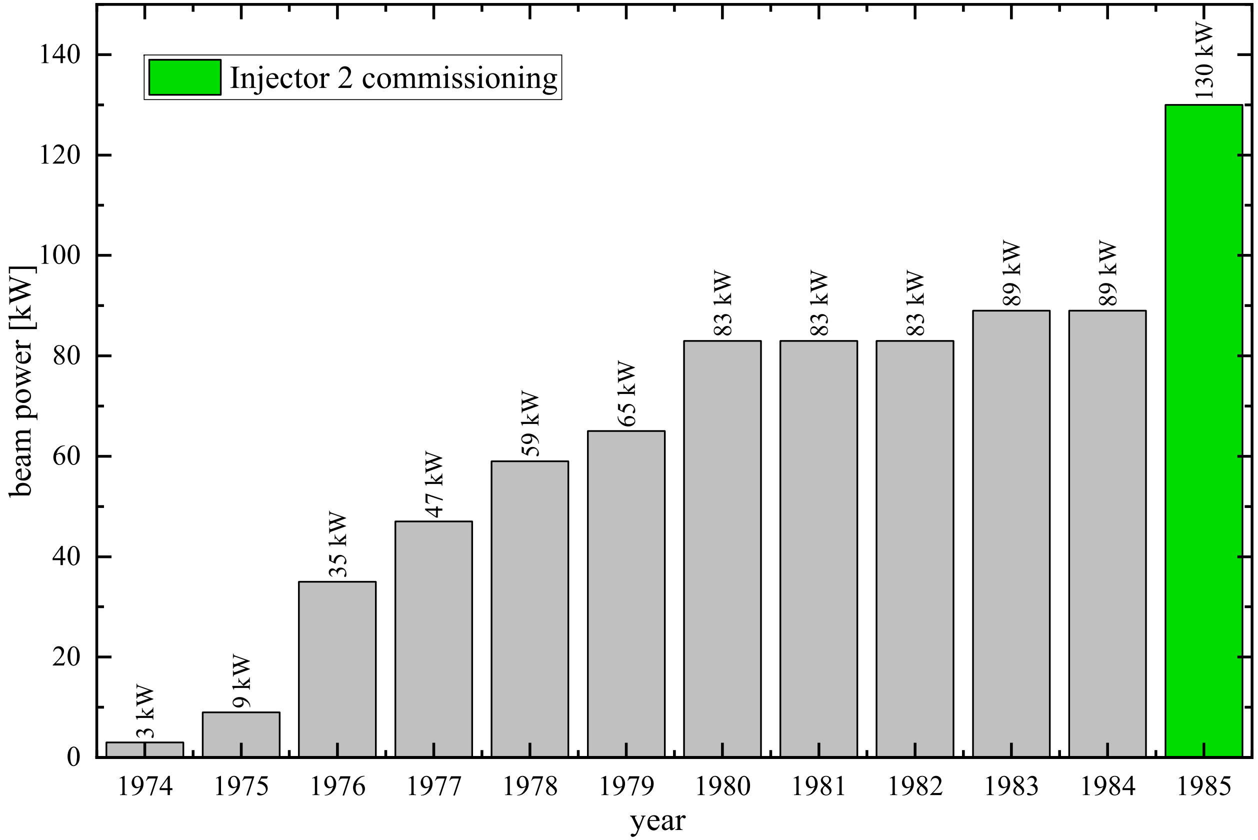
3rd harmonic «flattop» cavity

- 150 MHz
- 550 kV
- Q = 28000
- Gap g = 0.4 m

- Larger phase acceptance (40° instead of 9°)
- Factor of 10 less losses at extraction

Performance of the Facility

History of the beam power



220 μA

Cockcroft–Walton

E_{max} = 870 keV

I_{max} = 30 mA

ECR Ion Source (2009)

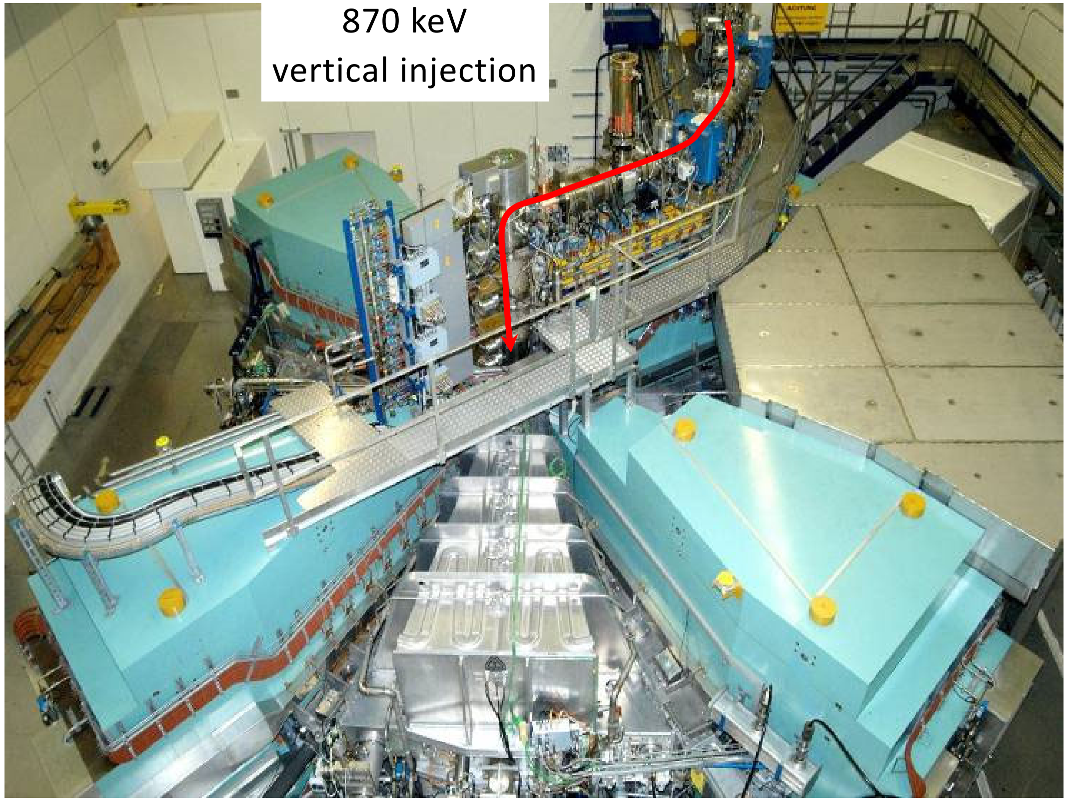
High-Voltage platform
810 kV

Acceleration tube
Acrylic glass filled with SF_6
Inside: Al_2O_2 tube

Voltage multiplier
„cascade“

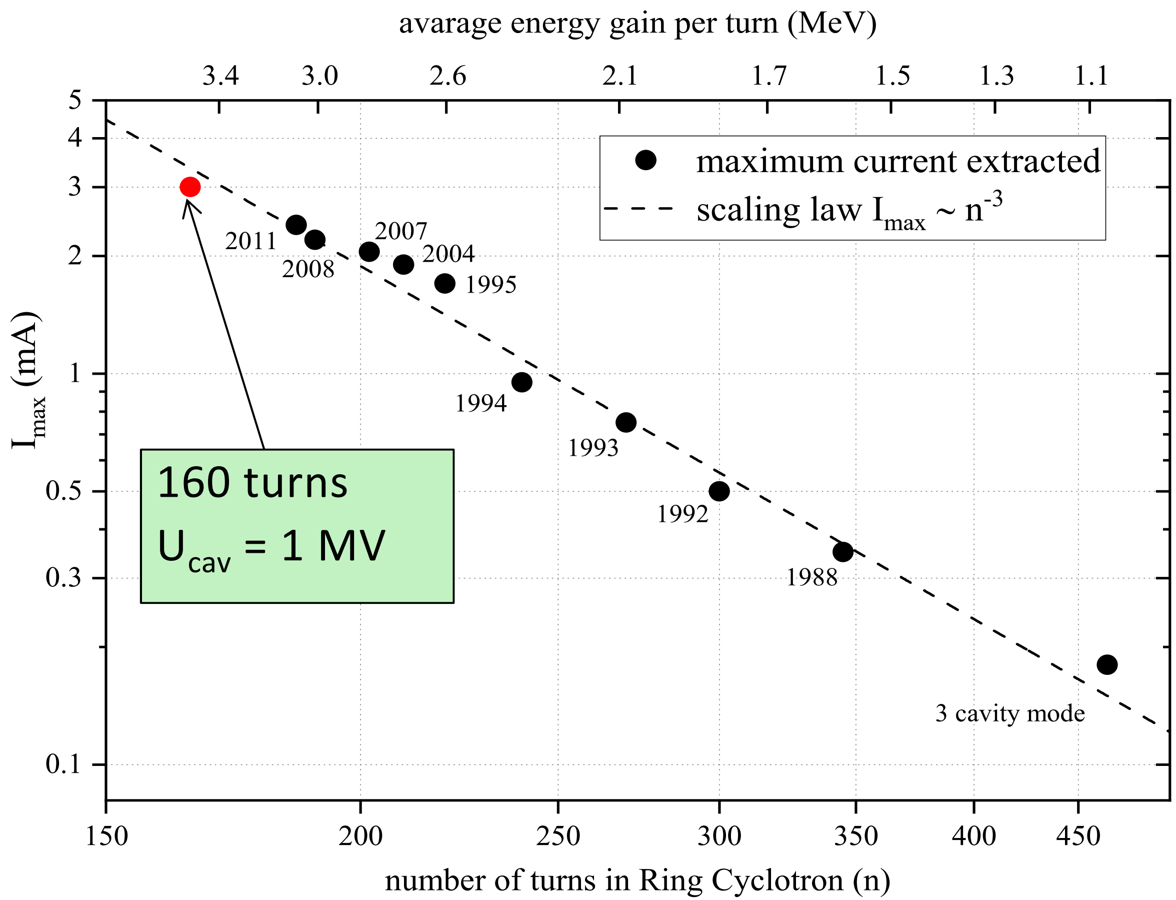
Isolation transformers

Injector 2 Cyclotron



- beam energy: 72 MeV
- max. beam current: 2.7 mA
- 4 sector Magnets: 0.33 – 0.36 T
- weight per magnet: 180 tons
- 2 resonators: 50.63 MHz
- 2 flattop resonators:150 MHz
- harmonic number:10
- injection radius: 0.4 m
- extraction radius: 3.5 m
- 80 turns

Scaling Law by W. Joho[1]



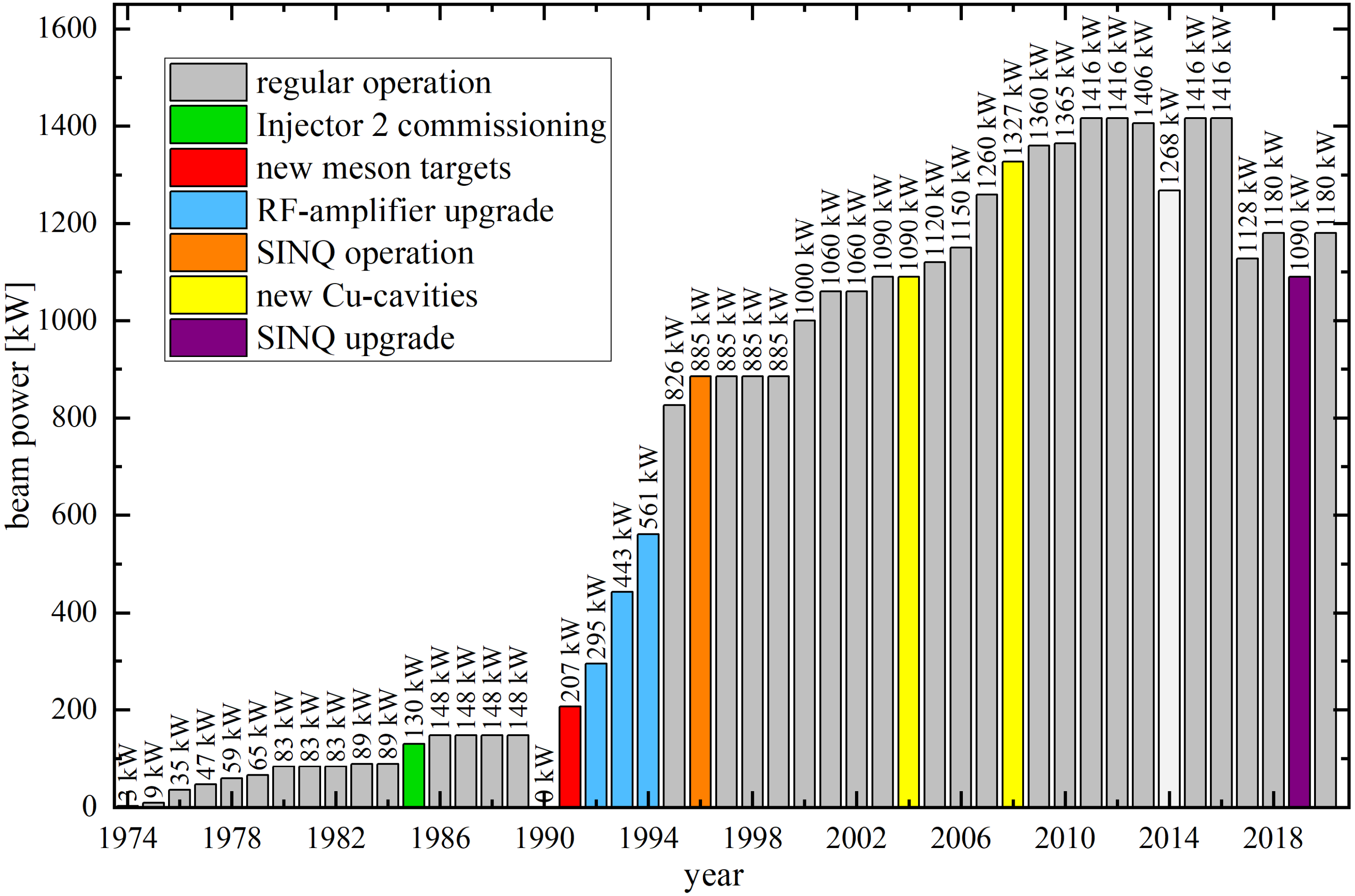
Losses scale with

- $(\text{turn separation at the extraction})^{-1}$ $\propto$ **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).

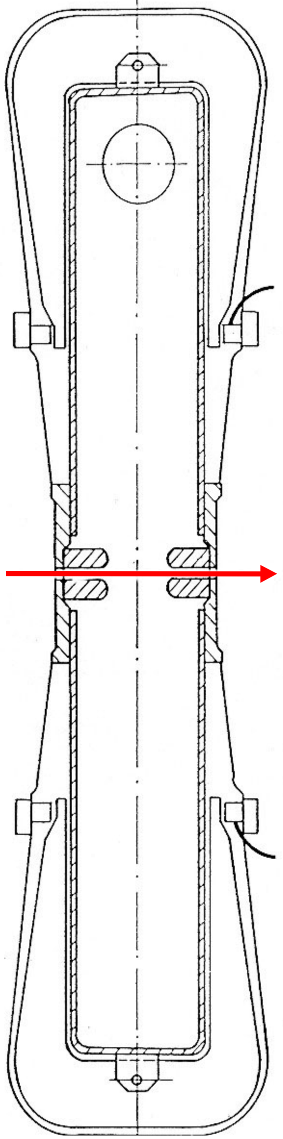
Performance of the Facility

History of the beam power

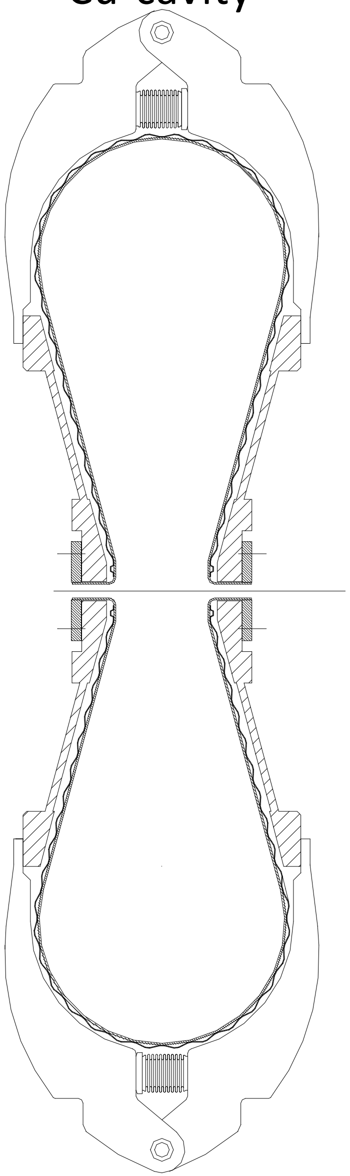


Cyclotron Cavities

Al-cavity



Cu-cavity



	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	45‘000
Bandwidth	1.8 kHz	1 kHz
Tuning Range	240 kHz	560 kHz

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

Wall plug to beam efficiency:

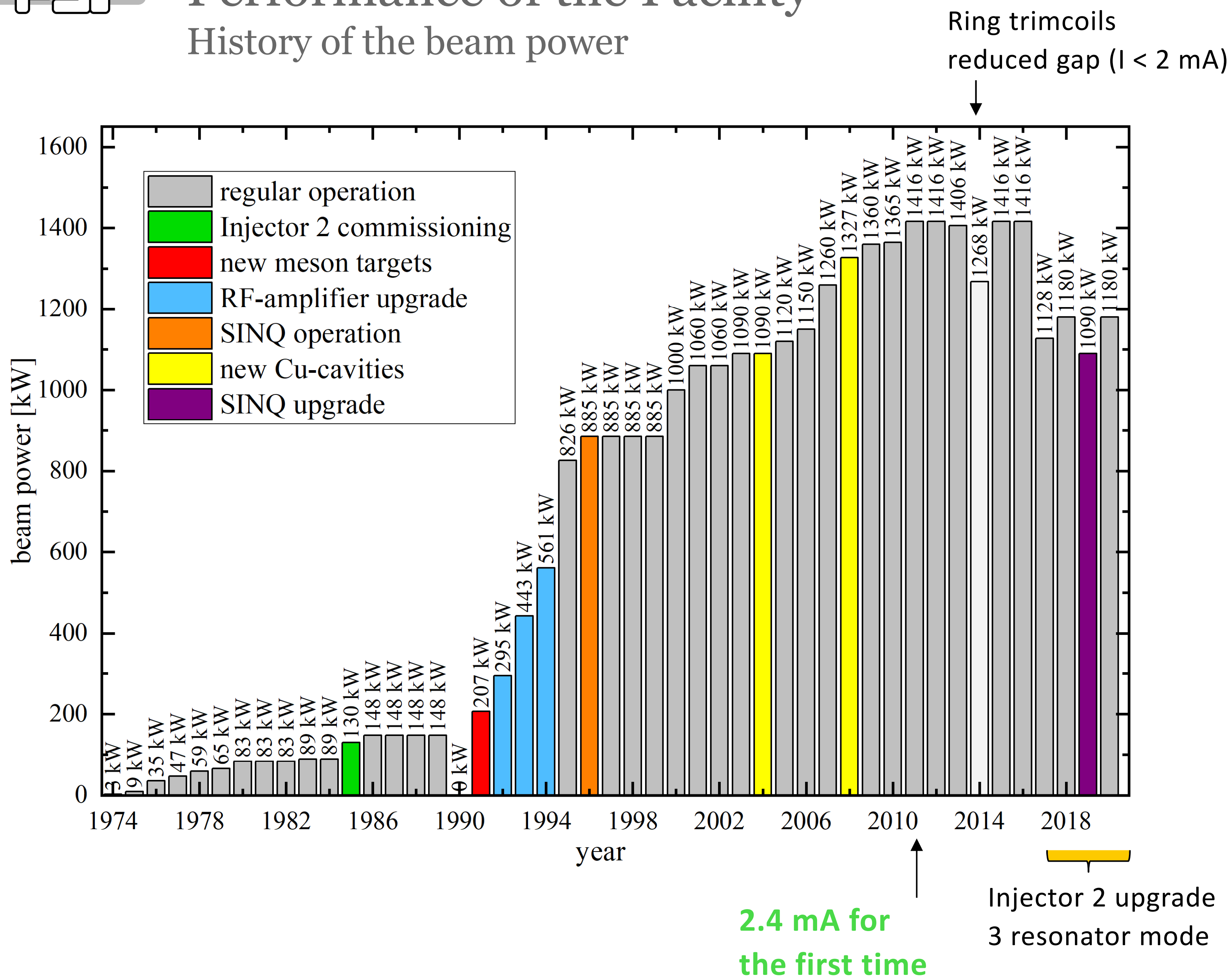
- AC/DC: 90%
- DC/RF: 64%
- RF/beam: 55%
- **All over: 32%**

Inside the resonator

hydraulic tuning devices (5x)

Performance of the Facility

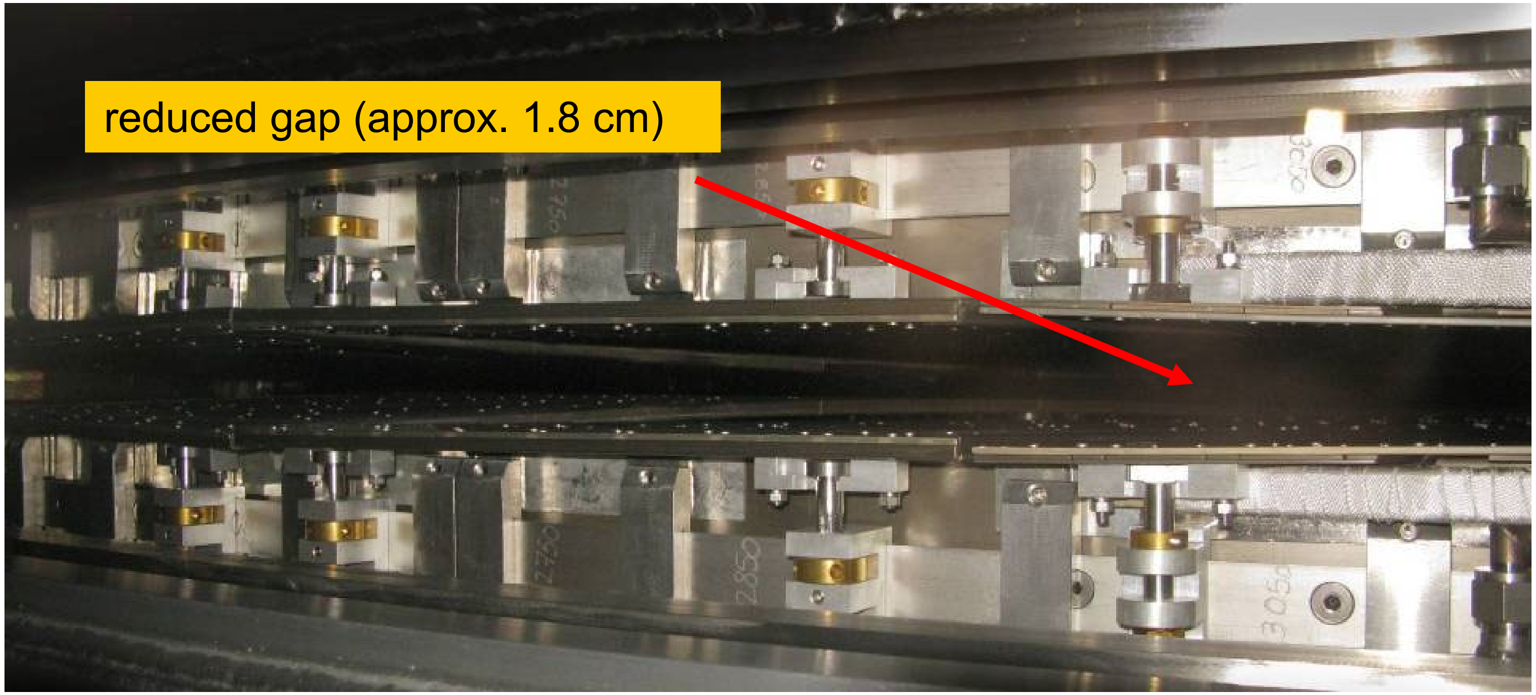
History of the beam power



Deformed Trim Coils in Sector Magnet

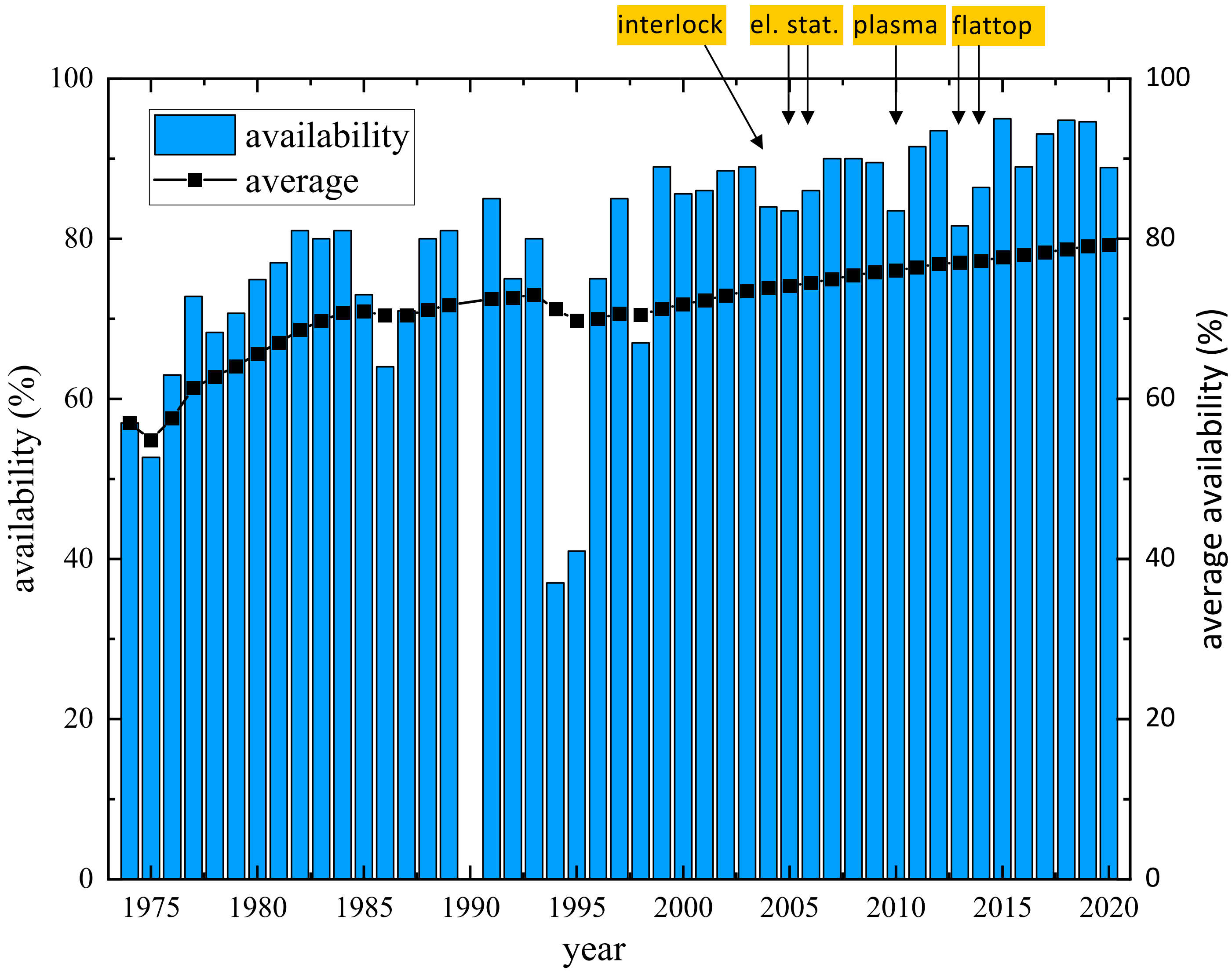
Cooling circuit failure
No interlock on RF-system

Several weeks for repair
→ continue operation **(with 2.0 mA!)**

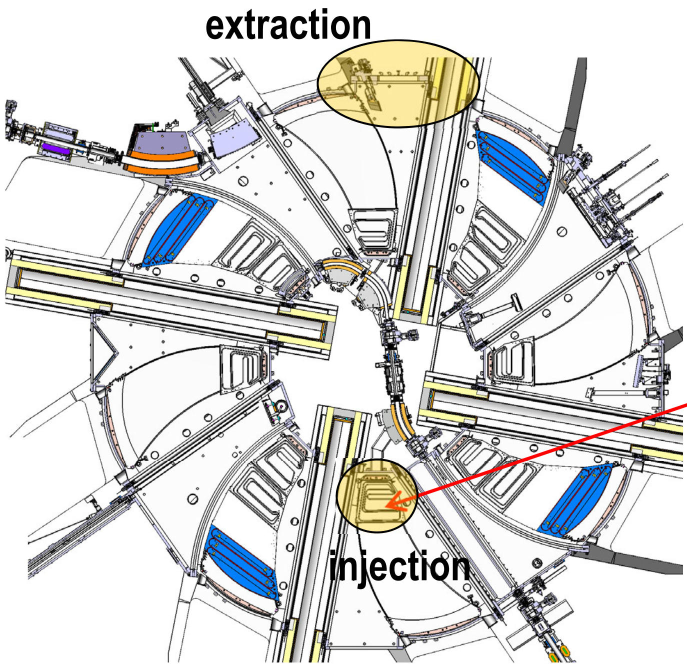


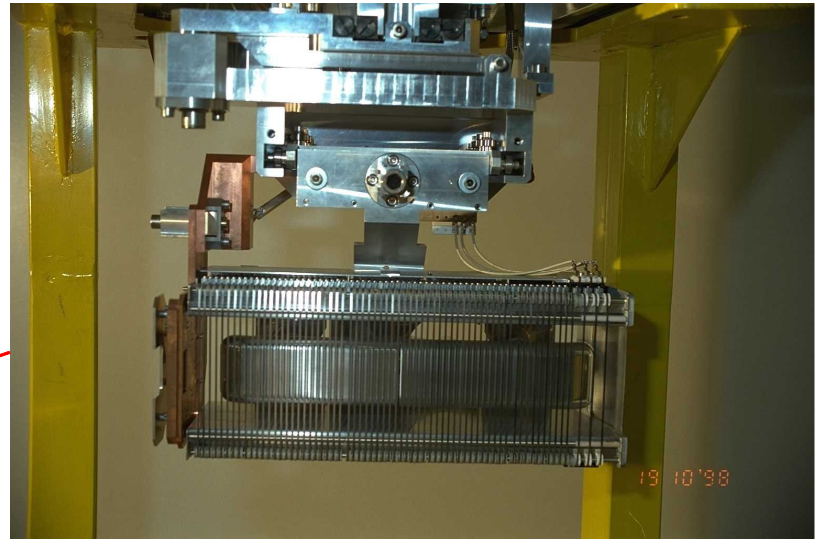
Availability of the Facility

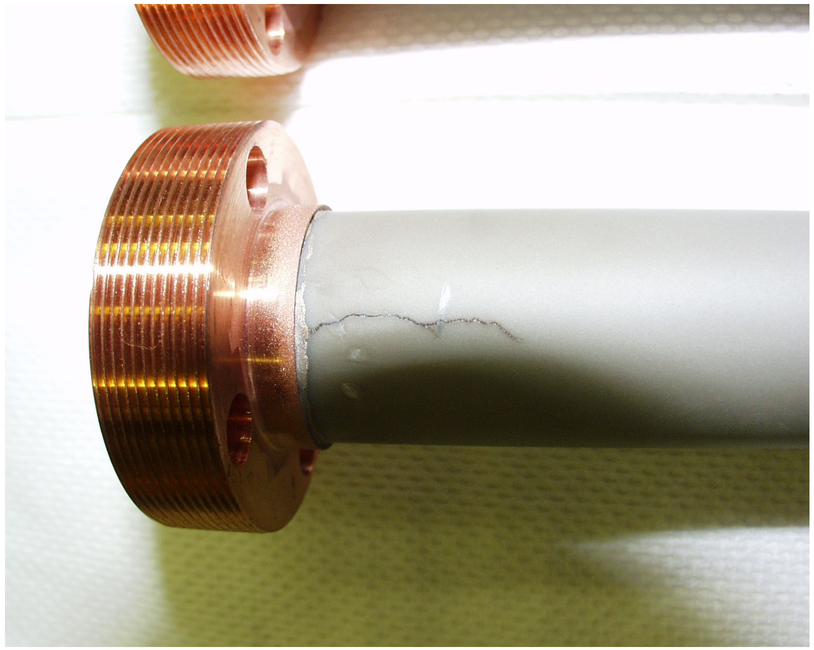
- Of uttermost importance for users
- Bobs up and down between 90 and 95%



The Spirits[1] I have cited[2]







- high dark currents at electrostatic deflector
- exchange required due to damaged insulators
- insulator coated with thin metallic layer
- discharges only with RF switched on
- RF ignites plasma in the vicinity of the elements

[1]Radio Frequency
[2]Goethe: The Sorcerer's Apprentice

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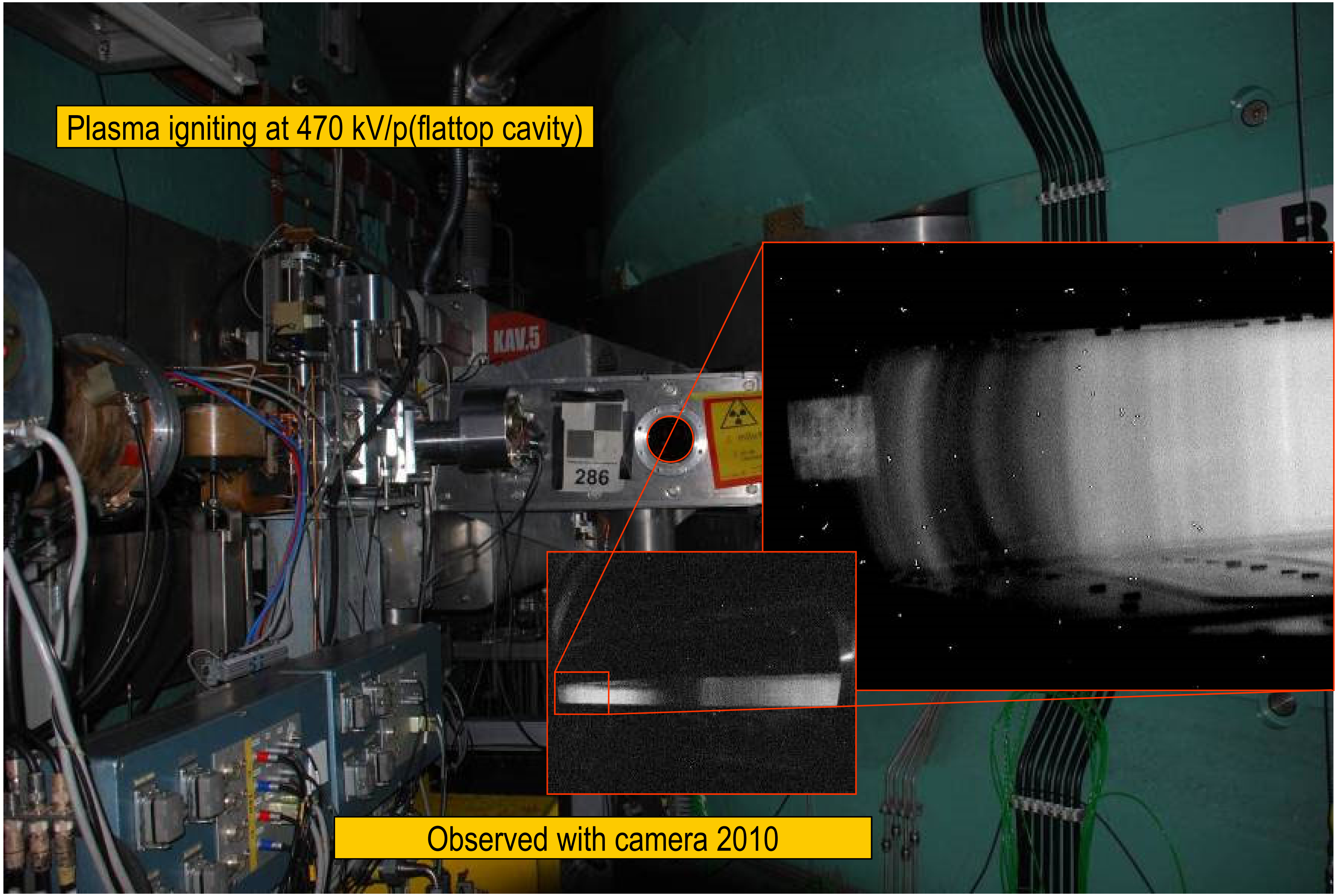
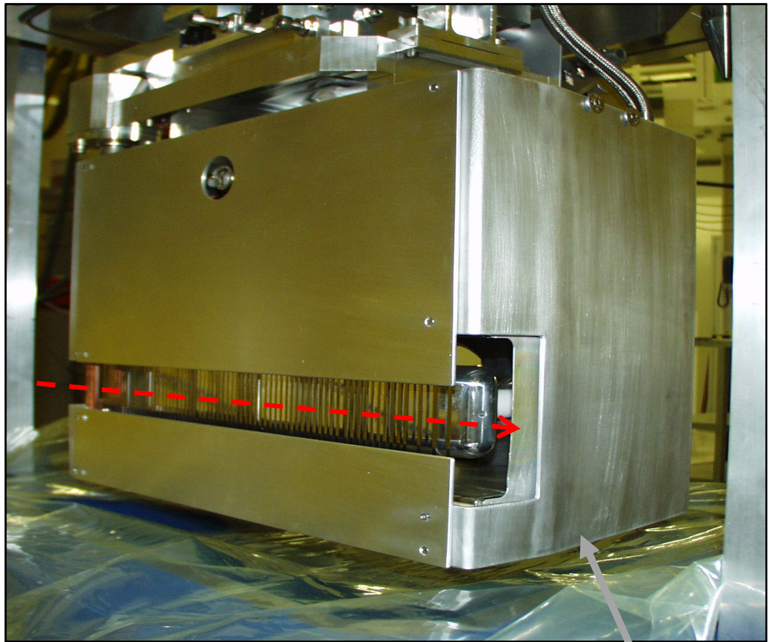
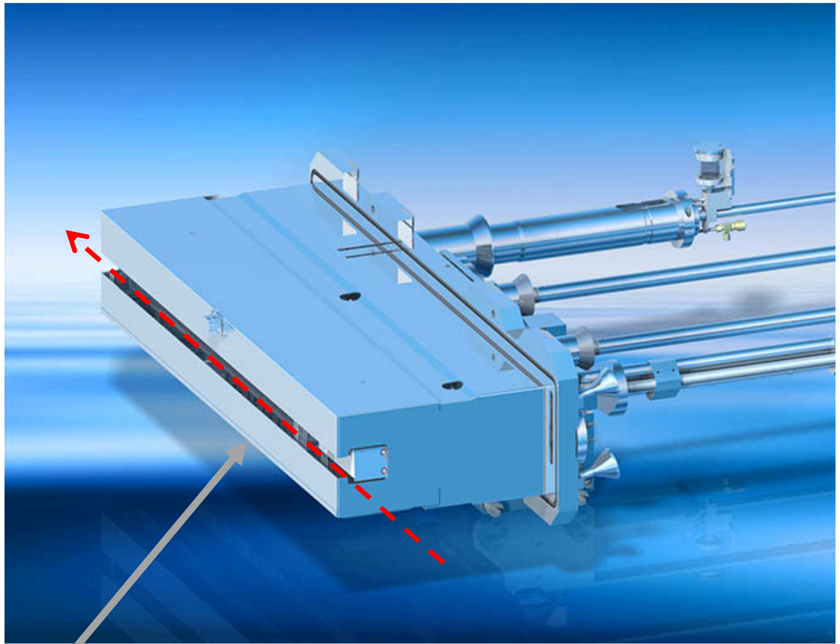
The Spirits I have cited[1]



Electrostatic Elements



Inflection channel

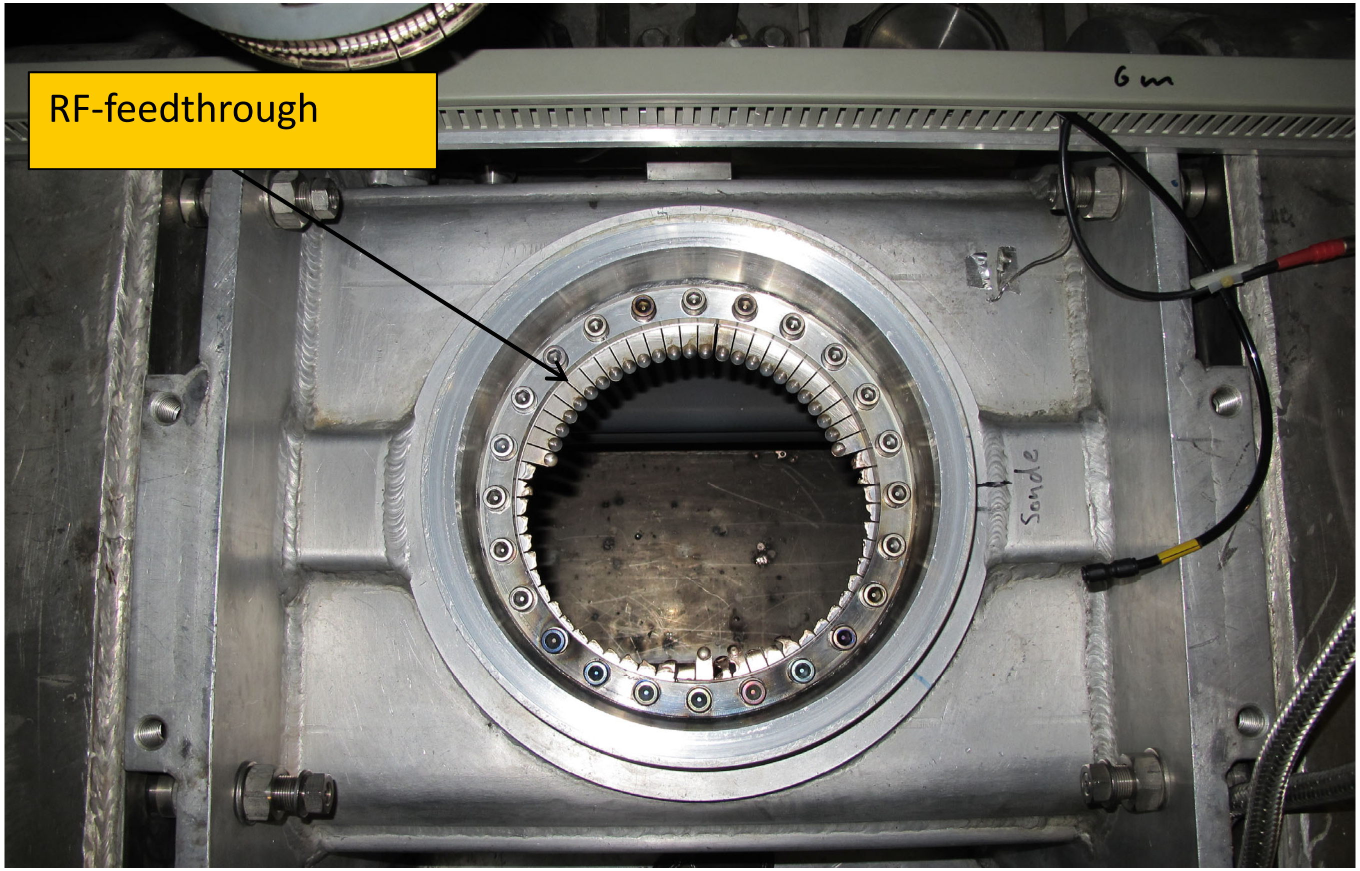


Extraction channel

Protective shield against

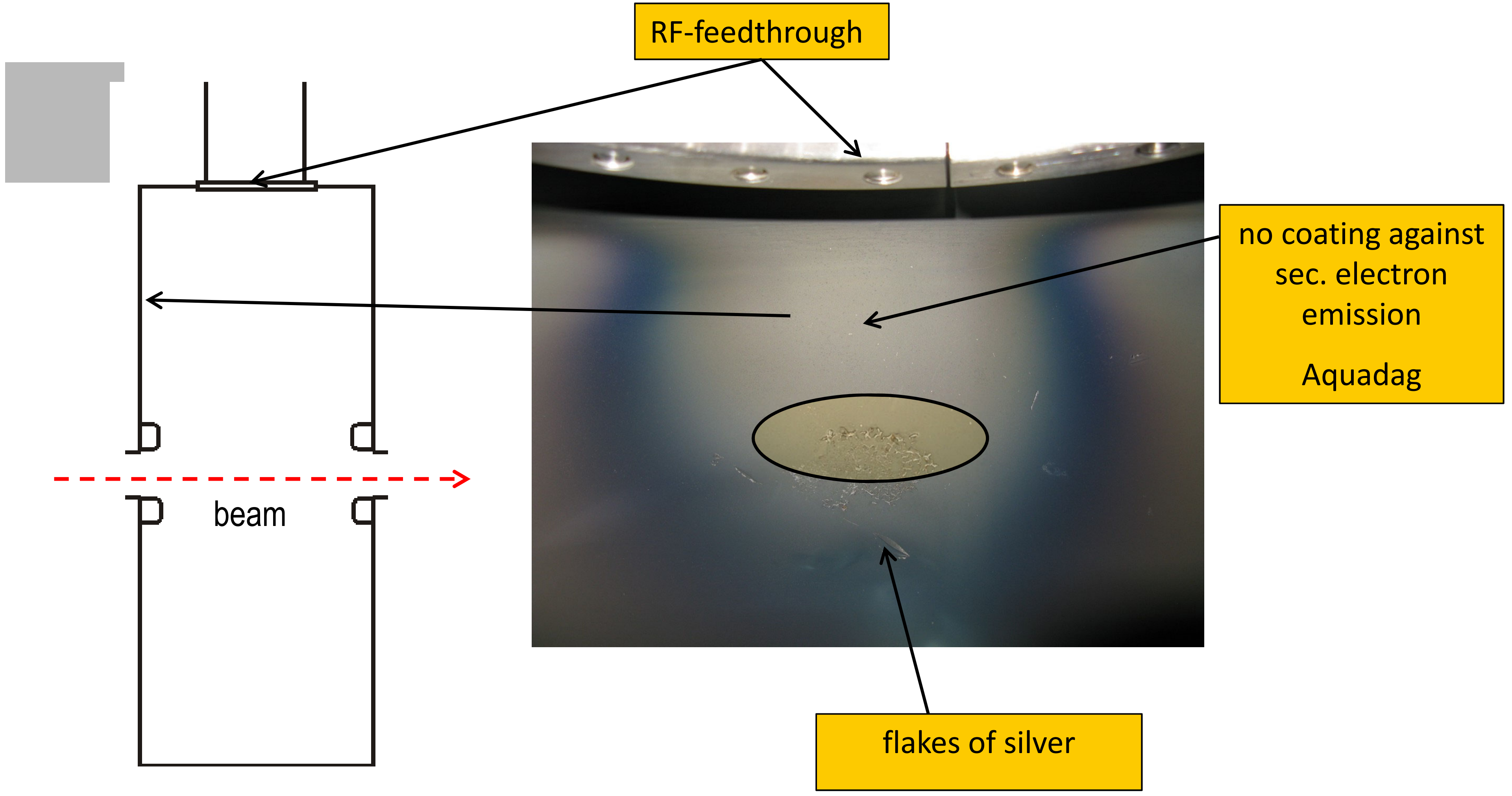
- RF
- Straying ions

Problems with flattop cavity (2013)



molten contact springs (3 times!)

Multipactoring inside Cavity



Multipactoring inside Cavity

Emission of secondary electrons in resonance with RF

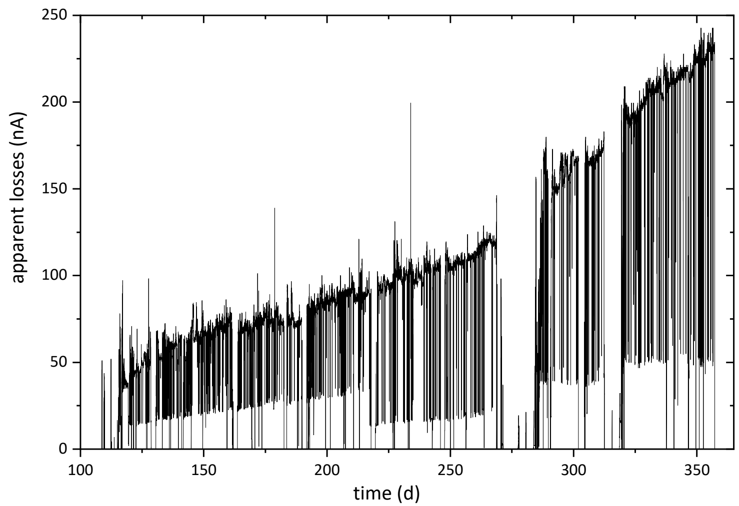
- High electric fields
- Small work function for electrons
- Fringe field (main magnets)

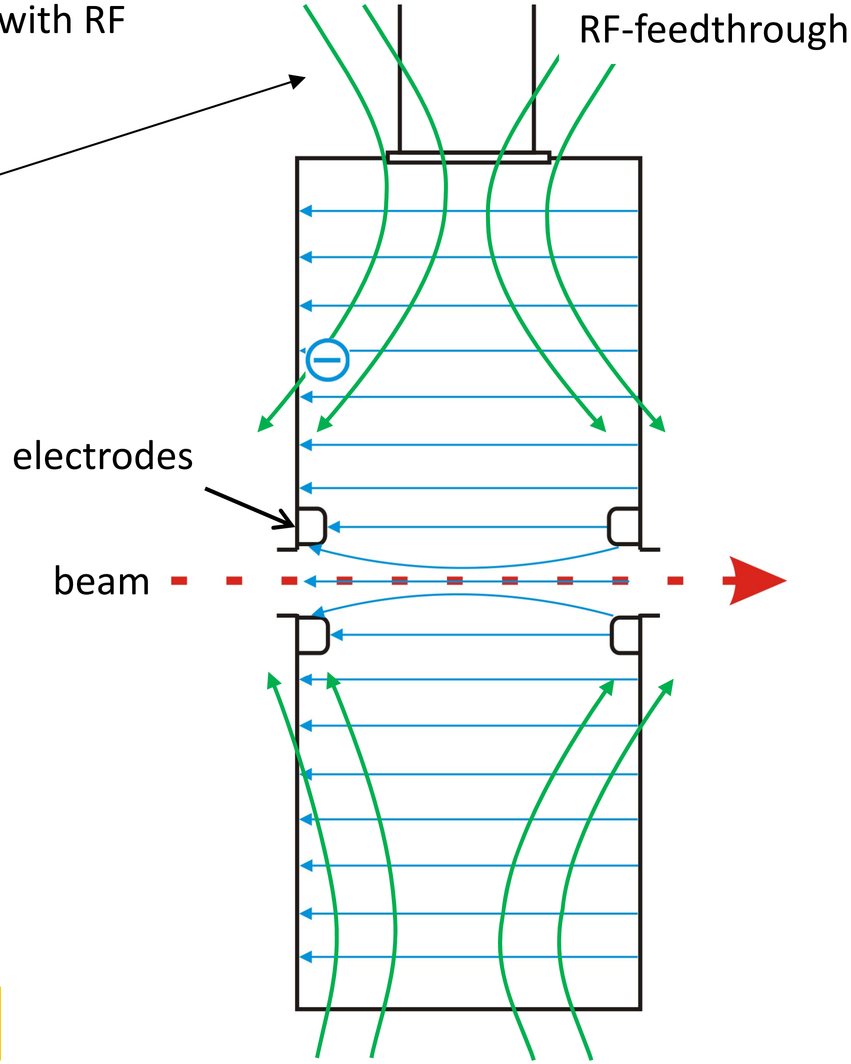
Work functions:

Al: 4.0 eV

Cu: 4.3 eV

C: 4.8 eV (Aquadag)

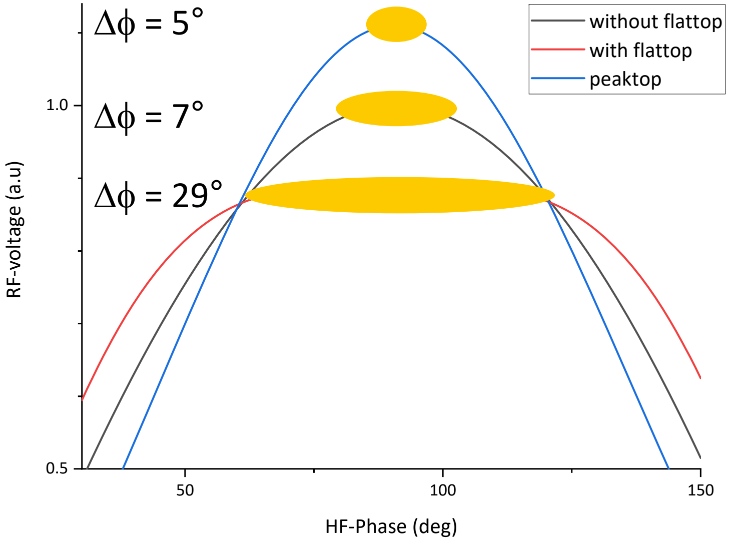




repaint cavity with Aquadag if necessary

1995 the operation discovered

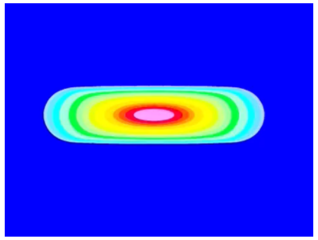
- Same extraction rate without Flattops (accidently switched off)
- Extraction rate higher with reversed phase (accelerating mode, less turns)



Explained by the «vortex effect»

M. M. Gordon,The longitudinal space charge effect and energy resolution, In McIlroy[47],425pp. 305–317 (1969)

S. Adam, Space charge effect in cyclotrons - from simulations to insights, In Comell[48],439pp. 446–448 (1995)

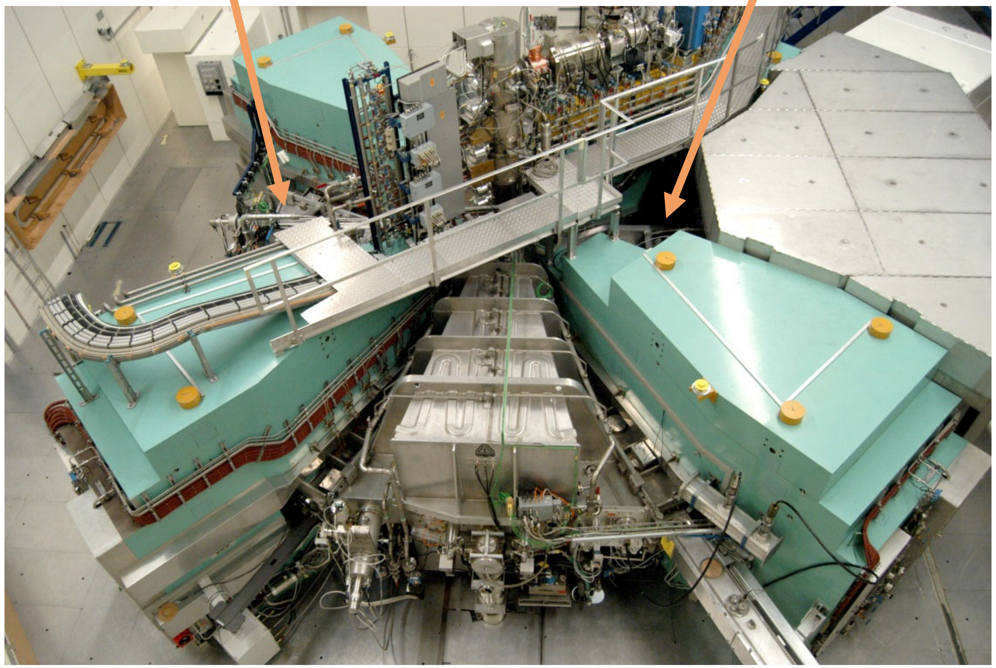


- Vortex motion stabilizes the bunch
- Space charge couples longitudinal and horizontal motion
- Longitudinal focusing (weak though)

Injektor 2 – Upgrade

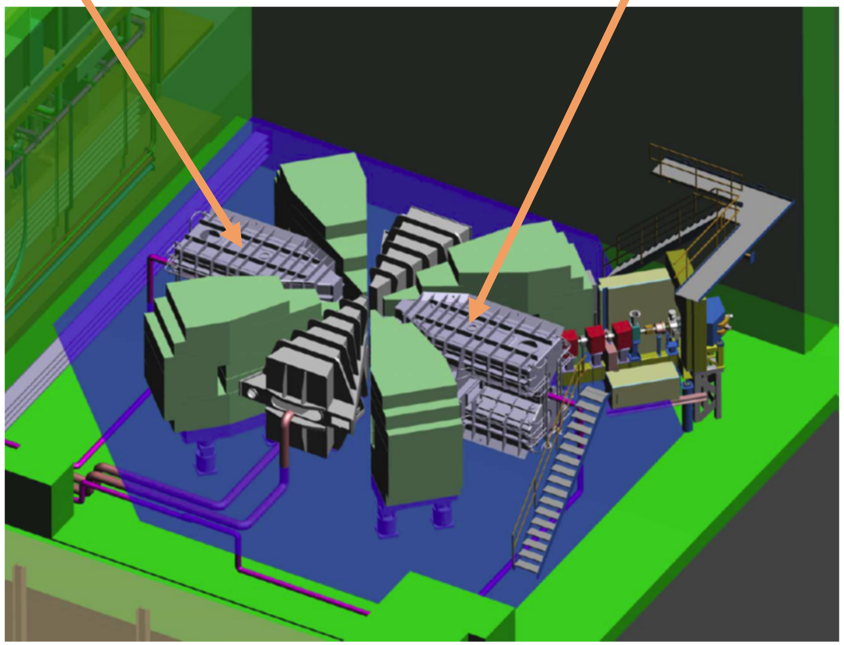
Resonator 2
150 MHz, 40 kV/p

Resonator 4
150 MHz, 40 kV/p

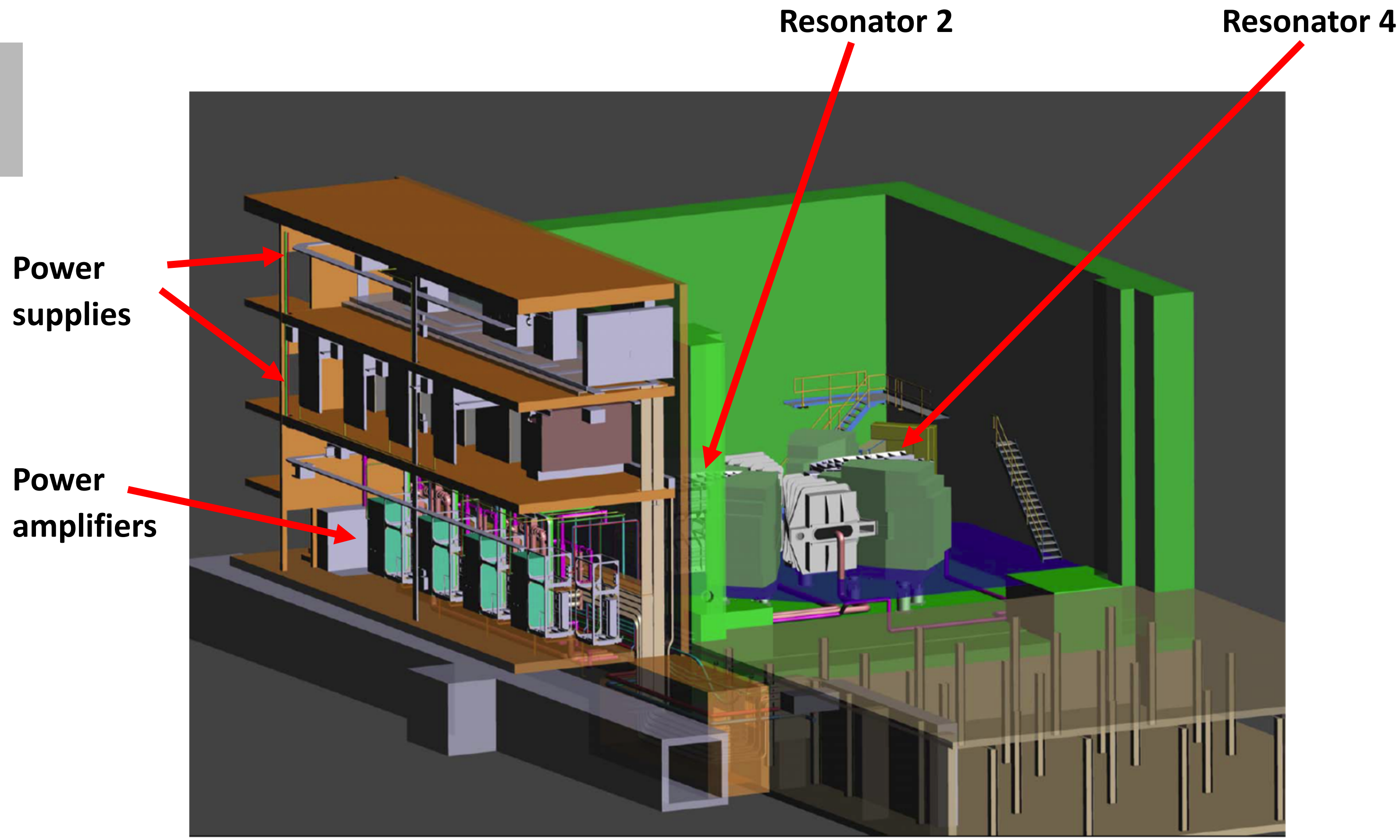


Resonator 2
50 MHz, 400 kV/p

Resonator 4
50 MHz, 400 kV/p



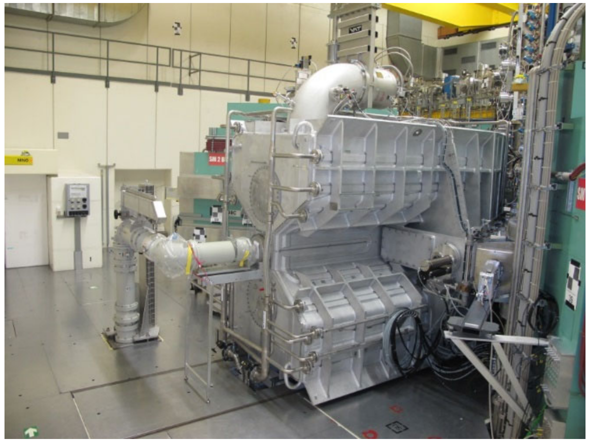
Injector 2 – Upgrade



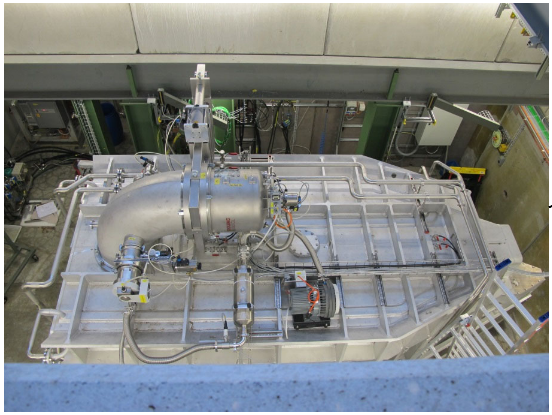
[M.Schneider]

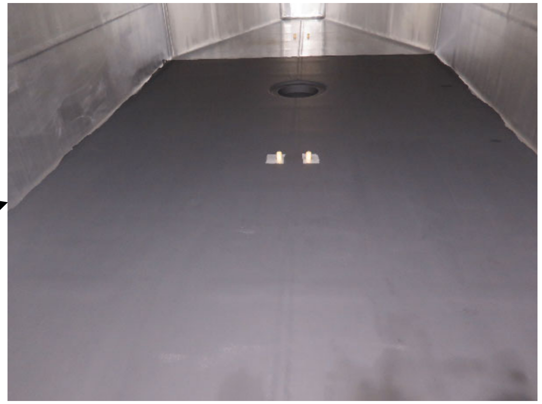
Status Injector 2 – Upgrade

Resonator 2:
- Installed in Injector 2 Cyclotron
- No tuner
- Now power
- **Limited to 2 mA**

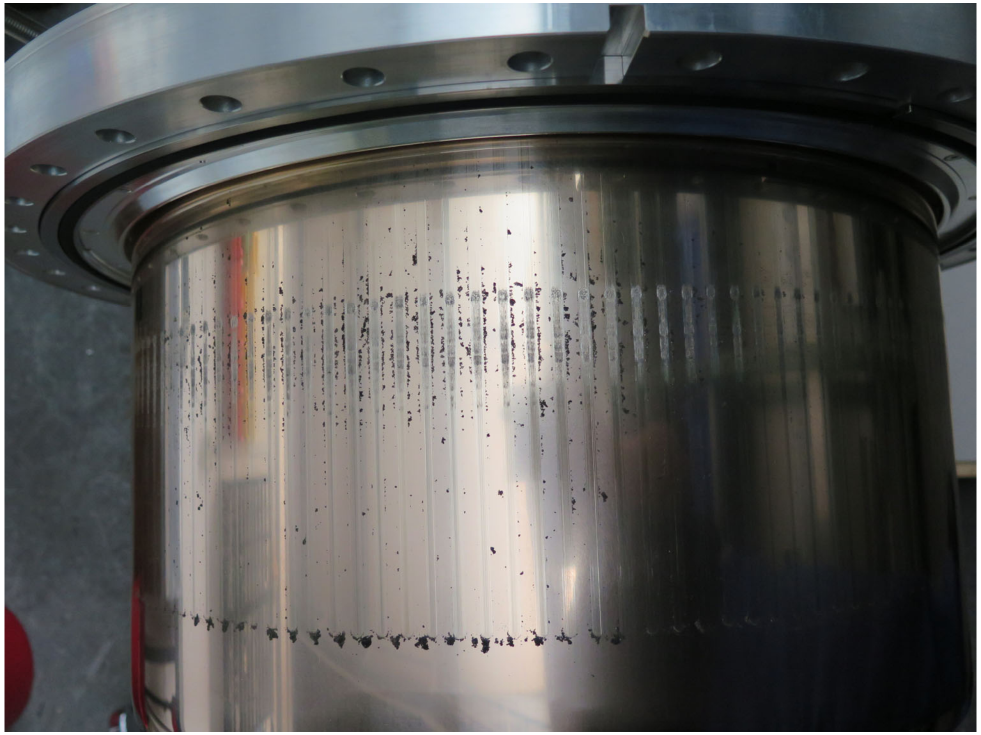

Resonator 2 installed in Injector 2

Resonator 4:
- In test stand for tuner and power tests
- Treated with Aquadag



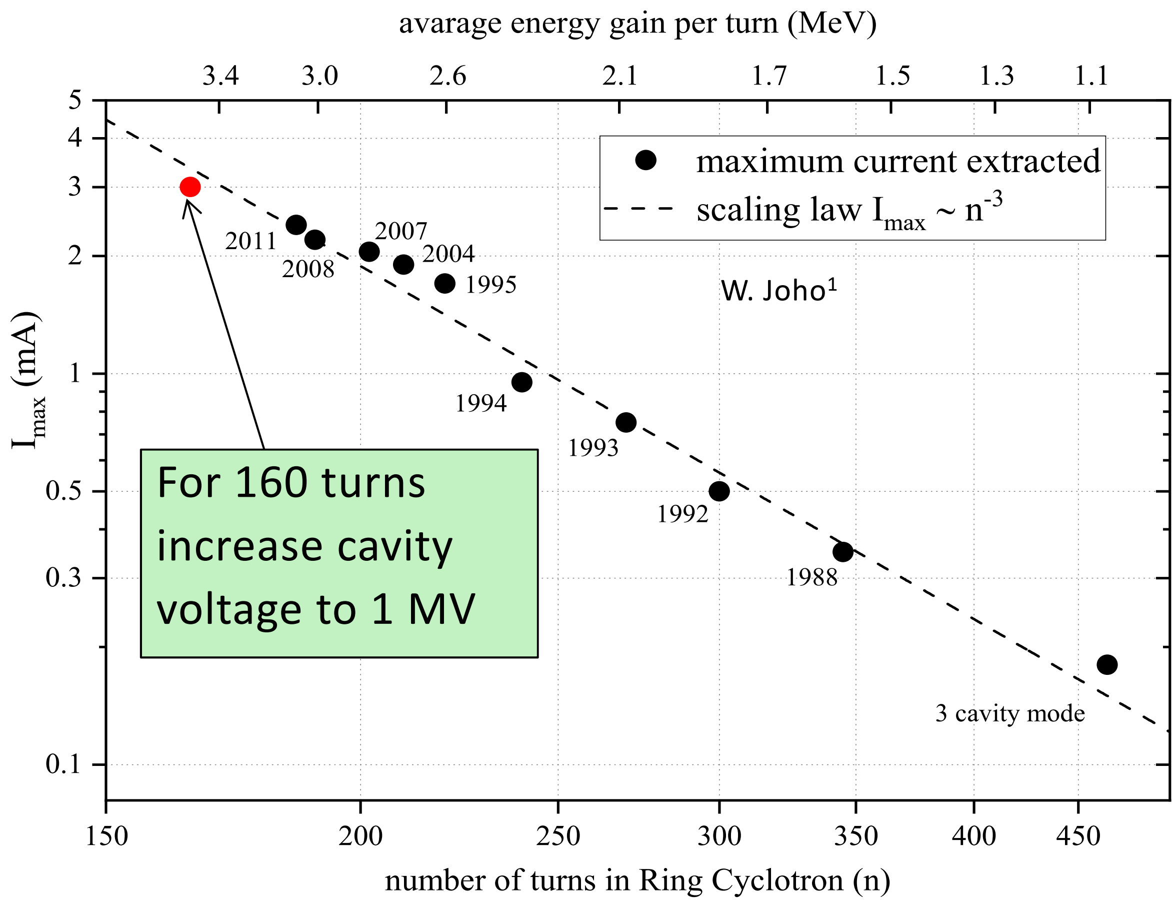

Resonator 4: treated with Aquadag

Tuner Resonator 4



- Tuners show abrasion caused by contact springs
- New concept necessary

Steps to 3 mA



Losses scale with

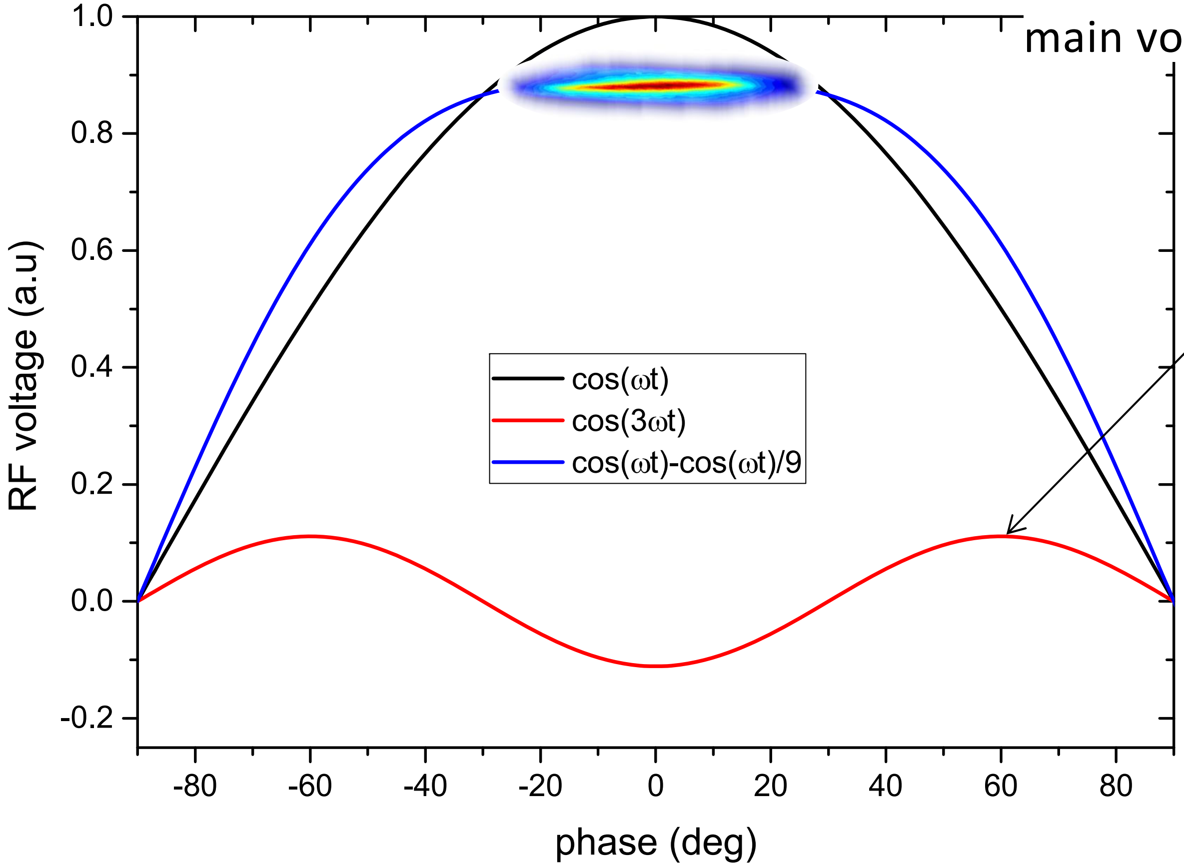
- (turn separation at the extraction)$^{-1}$ $\propto$ **N**
- Charge density in the cyclotron $\propto$ **N**
- Acceleration time $\propto$ **N**

[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).

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: $U_{\text{tot}} = U_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$

11% of the main voltage



PSI:

f = 150 MHZ

U_p = 550 kV

U_p = 660 kV

150 MHz Flattop Cavity

- New cavity (design and material)
- 660 kVp for 160 turns and 3 mA
- New RF-amplifiers

- Flattop upgrade is «kicked off»
- Choice of material is being discussed
  - low Q -> Al (above 600 μA powered by beam)
  - high work function -> Cu and RF dump
  - different coating (TiN?)

Steps Towards a Higher Performance

Beam Power

- Increase gap voltage
  - RF-amplifiers (solid state where possible)
  - new flattop system
- Finish Injector 2 Upgrade (by 2023)
- Re-bunch the beam between Injector 2 and Ring cyclotron (new buncher setup)
- More diagnostics and simulations
- Well trained operators and more beam development

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Steps Towards a Higher Performance

Availability

- Targets (48h to replace, Ønce the year)
  - ball bearings
  - new geometry (slanted target for a higher yield)

- Electrostatic Elements (50 trips/day ≅ loss of 2% of availability, now 10 trips/d)
  - shielding
  - **rapid recharging[1] (< 500 ms)**
  - improve vacuum ($p < 10^{-6}$ mbar, metallic sealings)

- Documentation (has been improved)
  - Careful planning of repair and service work
  - Stock keeping of critical elements
  - Continuous replacement of outdated components
  - Avoid knowledge drain

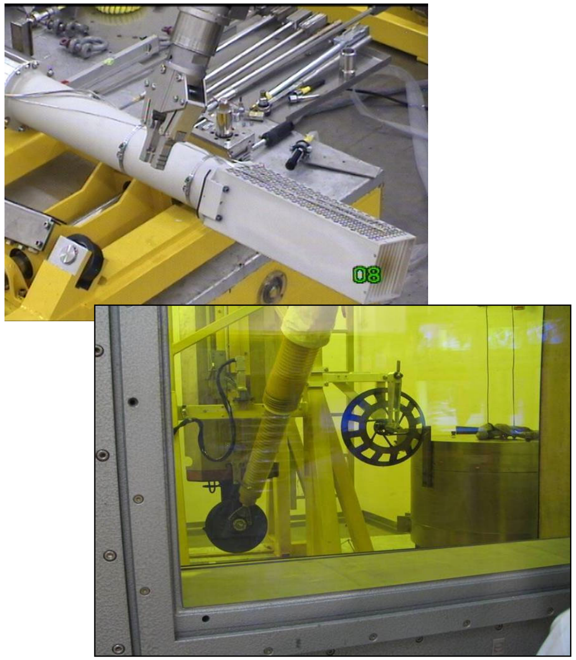
[1]R. Dölling and J. Brutscher, “Fast Recharging of Electrostatic Injection and Extraction Septa After Breakdown”, in Proc. 22nd Int. Conf. on Cyclotrons and their Applications (Cyclotrons'19), Cape Town, South Africa, Sep. 2019, pp. 90-93.

Steps Towards a Higher Performance

Infrastructure

- radiation safety, shielding, waste disposal
- hot-cell and radio-analytic laboratories
- licensing and the ability to perform required studies
- formal aspects connected to safety and radiation issues which are often underestimated

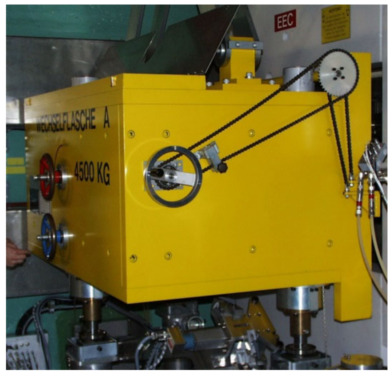
SINQ-Target in hot-cell



Exchange flasks

Target E

Electrostatic elements



Future: Robots, VR
Accept higher losses?

Summary

- The PSI accelerator delivers a 1.4 MW beam in CW mode
- Major performance steps achieved by RF-upgrades
- The average availability now is 90%
- Number of short trips (<5 min) is 10 per day
- Modular design allows for fast and save repair (< 2days, 4h average)
- Energy efficiency is 0.18 (bare accelerator)

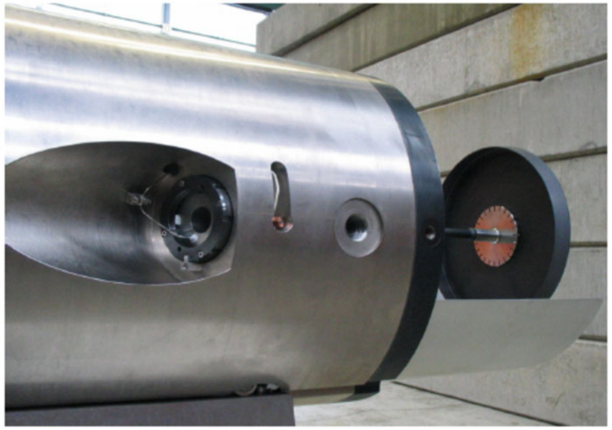
- Since 2020 new neutron guides/monochromators (factor of 2–100 more neutrons)
- New project IMPACT is on its way
- Operation until 2030+

We have to/want to prepare for another 10-30 years of operation

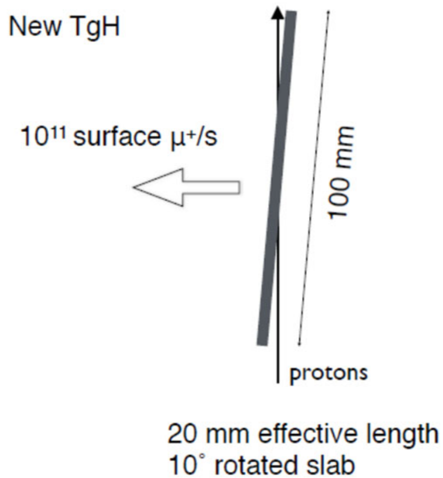
New Projects

Isotope and Muon Production using Advanced Cyclotron and Target technology

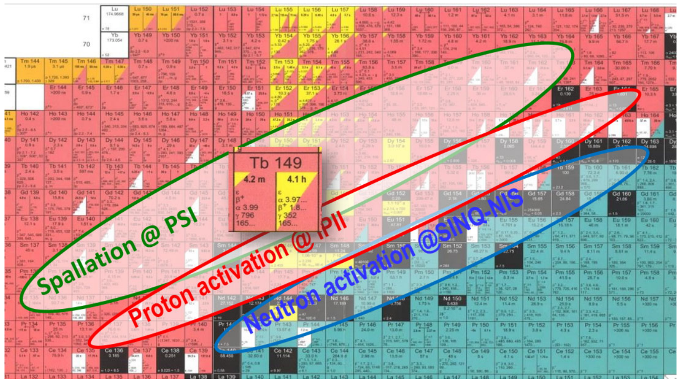
- HIMB (High Intensity Muon Beams)

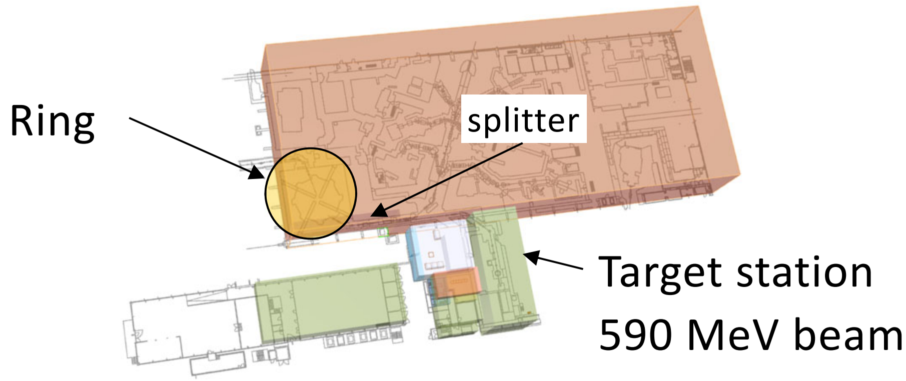


40 – 50% gain in surface muon rate



- TATTOOS (Targeted Alpha Therapy using Terbium and Other Onchological Solutions)





It's all about people...
Thank you for you attention