PAUL SCHERRER INSTITUT

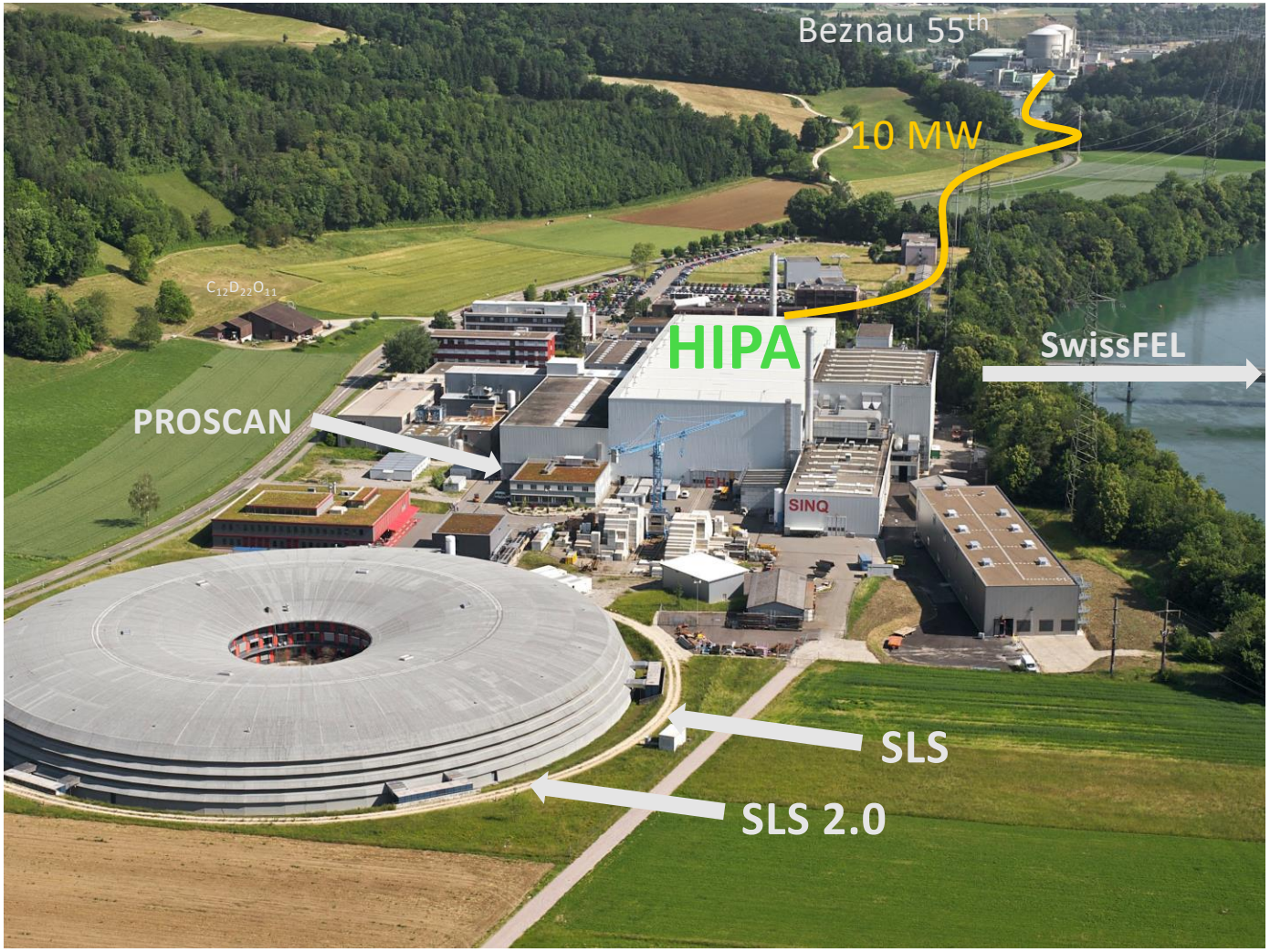
PSI

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

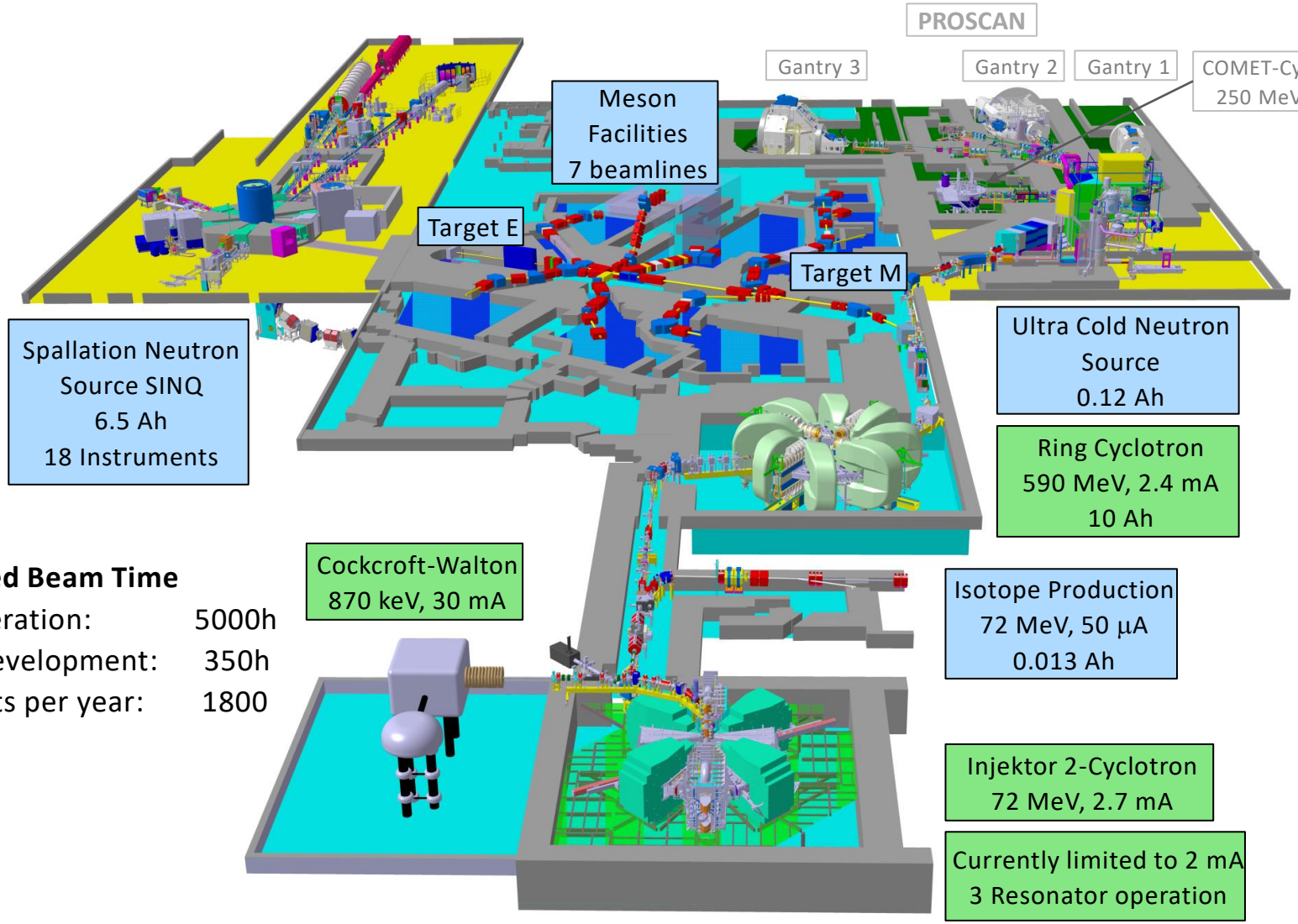
The High Intensity Proton Accelerator Facility Status and Perspectives

HB 2023

High Intensity Proton Accelerator
50th Anniversary in 2024



High Intensity Proton Accelerator Facility

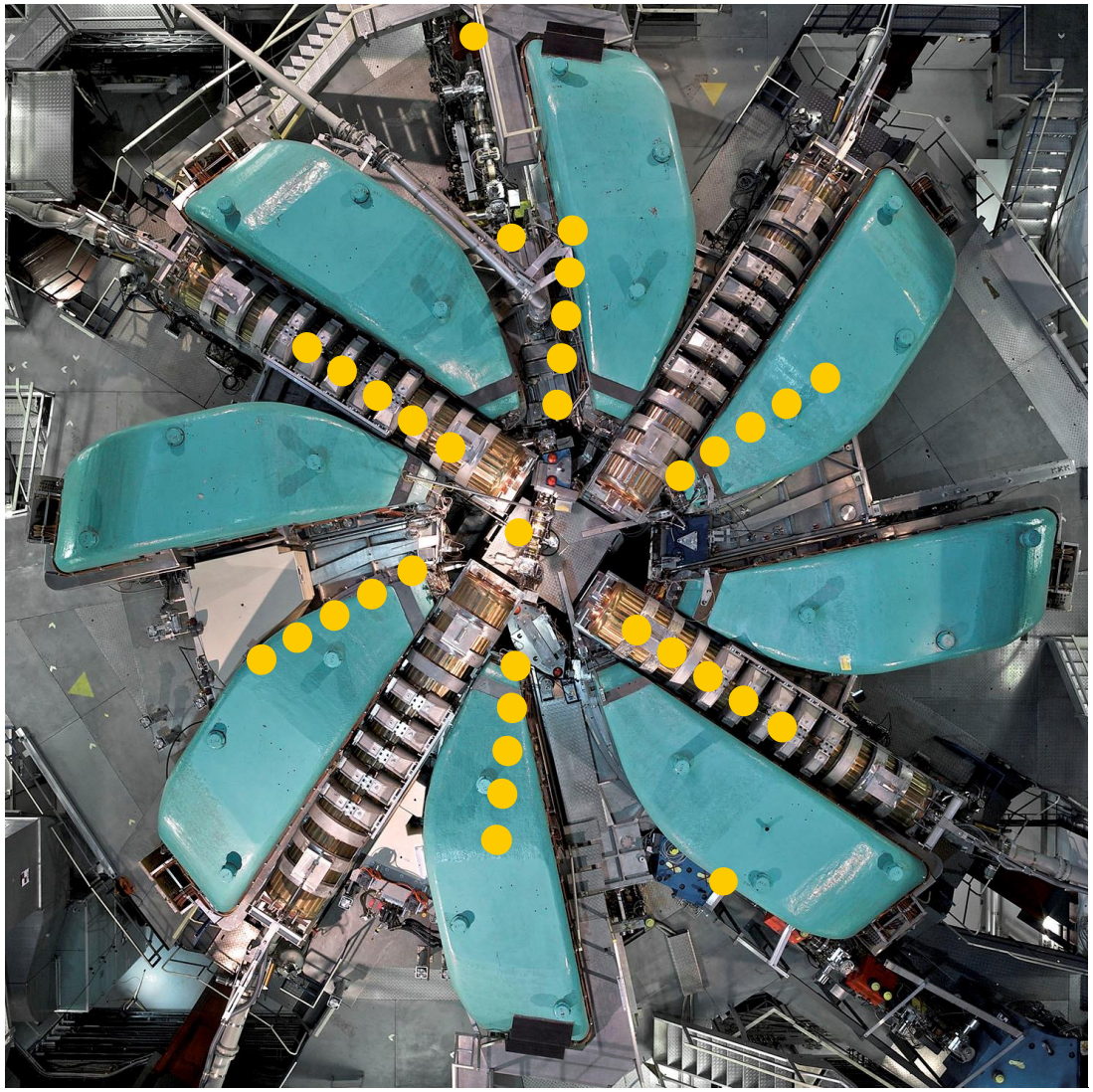


Scheduled Beam Time

User operation:	5000h
Beam development:	350h
User visits per year:	1800

590 MeV Ring Cyclotron at PSI

in operation since 49 years (19.2.1974 first muons)



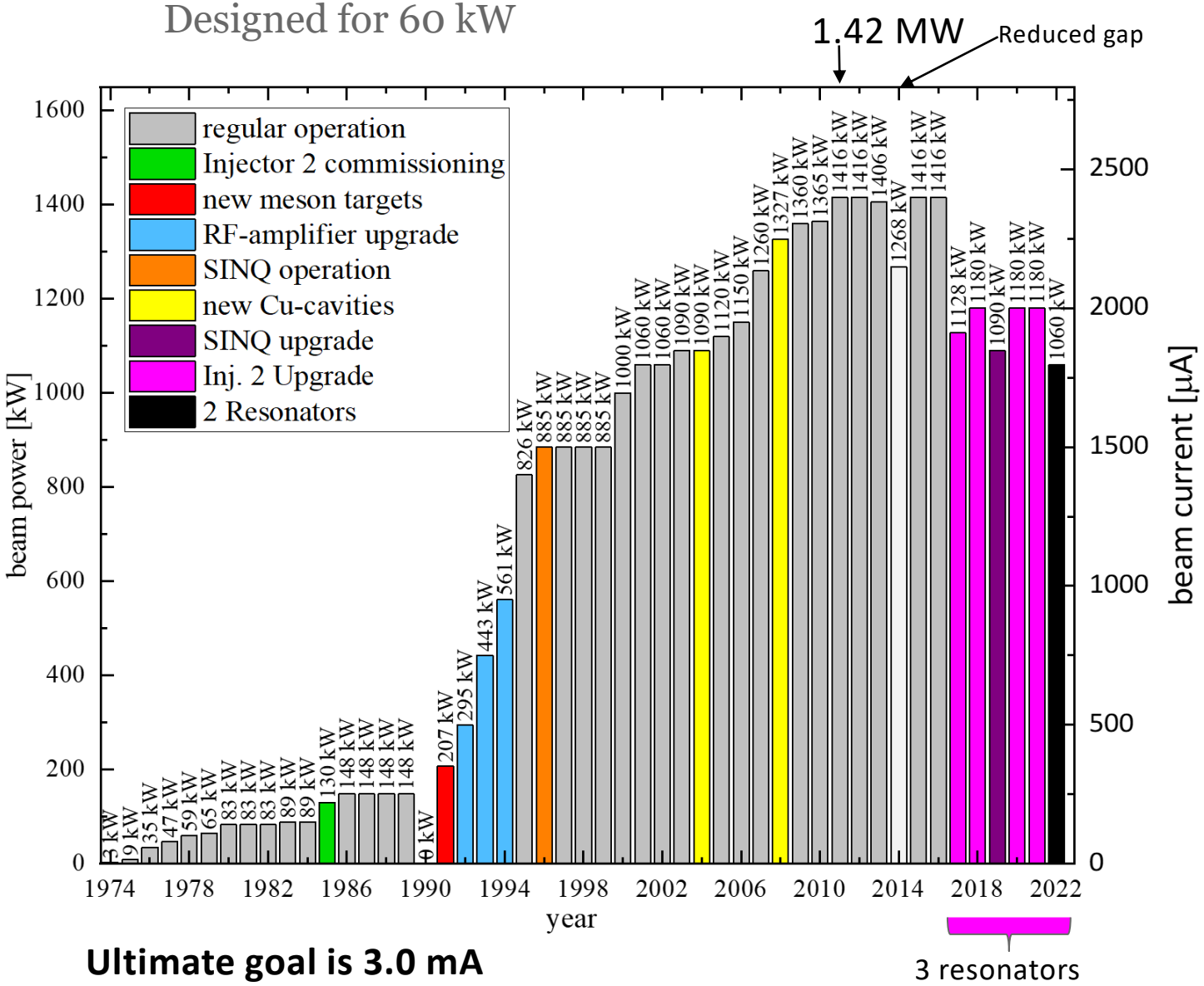
Beam energy:	**590 MeV**
Beam current:	**2.4 mA**
Beam power:	**1.4 MW**
Relative losses:	**1..2·10^{-4}**
Single turn extraction	
4 cavities (50.63 MHz):	850 kVp
1 Flattop (151 MHz):	550 kVp
Harmonic number:	6
Number of turns:	186
8 sector magnets:	0.6 – 0.9 T
R_{in}:	2.1 m
R_{out}:	4.5 m

Energy efficiency:

$$\eta_{acc} = \frac{P_{beam}}{P_{Grid}} = \frac{1.42\ MW}{8\ MW} = 0.18$$

History of the Beam Power

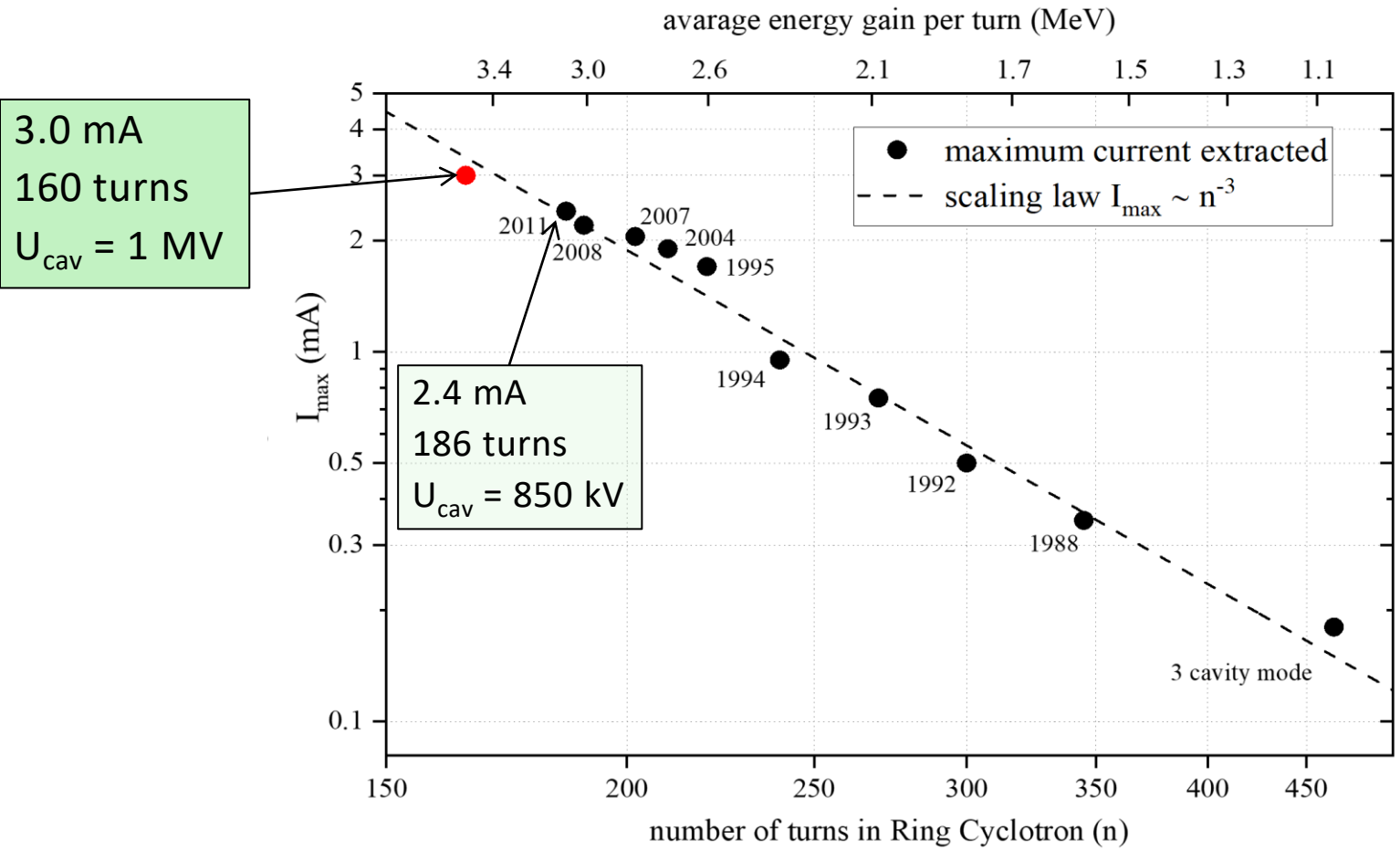
Designed for 60 kW



Ultimate goal is 3.0 mA

Corresponds to 1.8 MW

Empirical Power Scaling Law



Losses scale with

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

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).

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

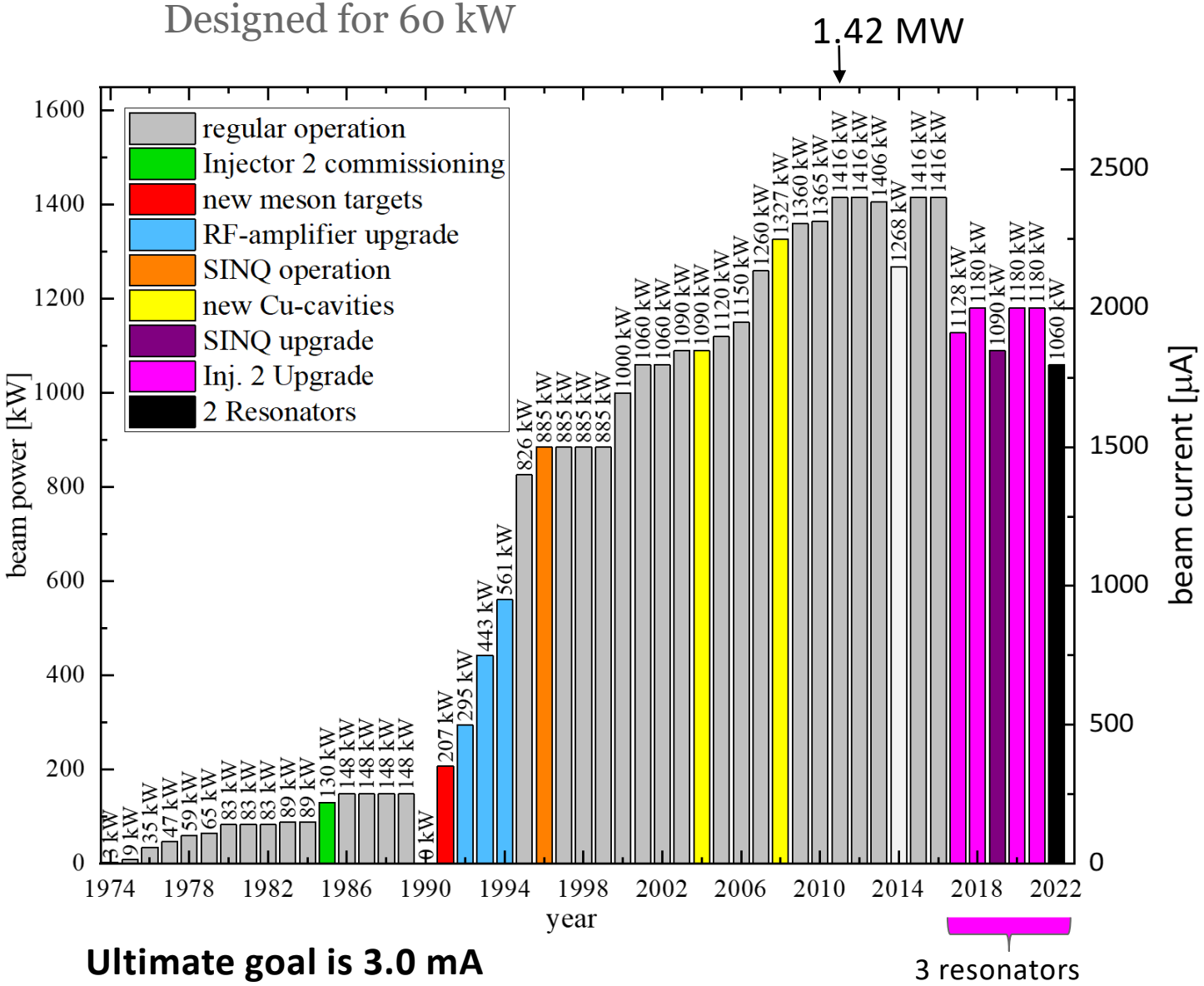
Wall plug to beam efficiency:

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

Last Cu–cavity commissioned in 2008

History of the Beam Power

Designed for 60 kW

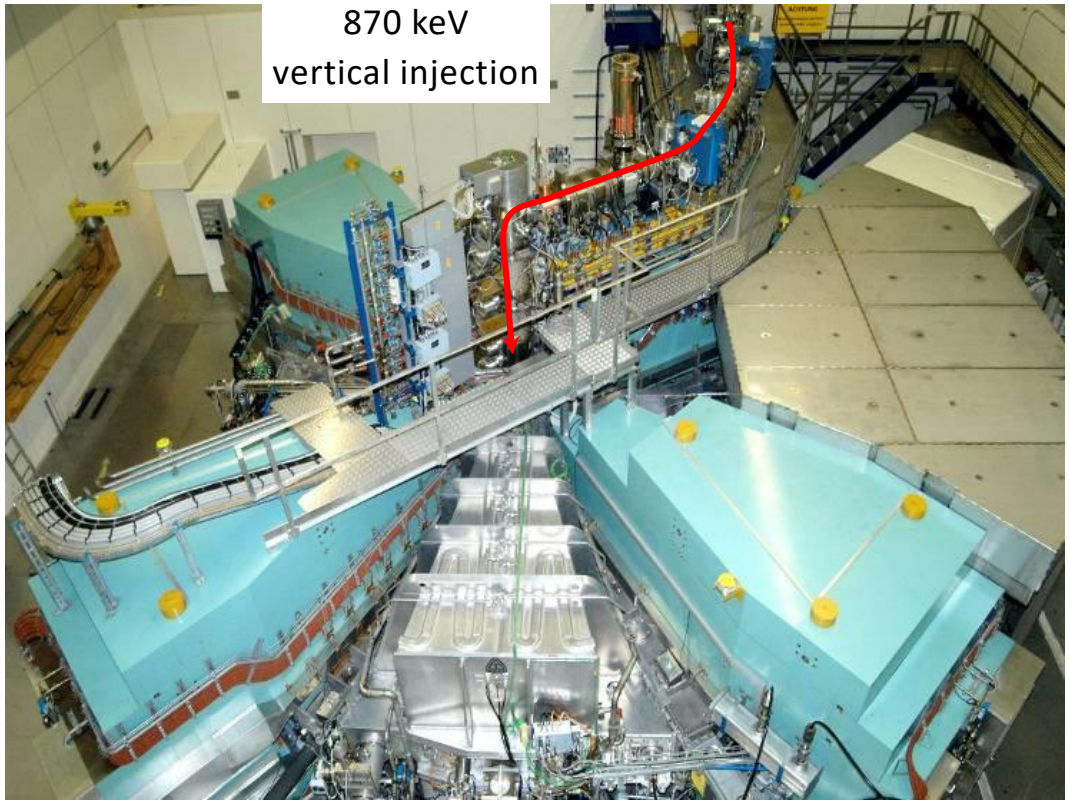


Ultimate goal is 3.0 mA

Corresponds to 1.8 MW

Injector 2 Cyclotron

Commissioned in 1985



- 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**

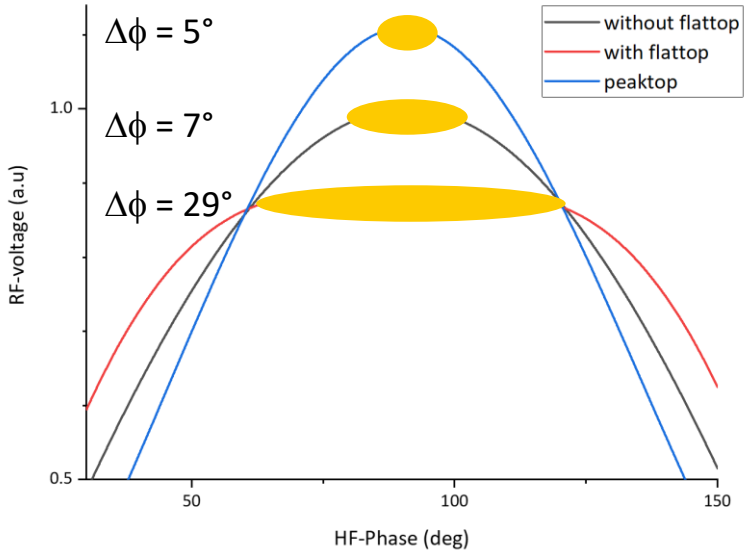
Beam power: 72 MV • 2.7 mA = **194 kW**

Ongoing upgrade project for 3.0 mA and reliability

Injector 2 – Upgrade

1995 the operation observed in Injector 2

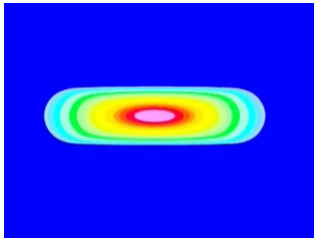
- the same extraction rate without Flattops (accidently switched off)
- a higher extraction rate with reversed phase (accelerating mode, less turns)



Explained by the «vortex effect»

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

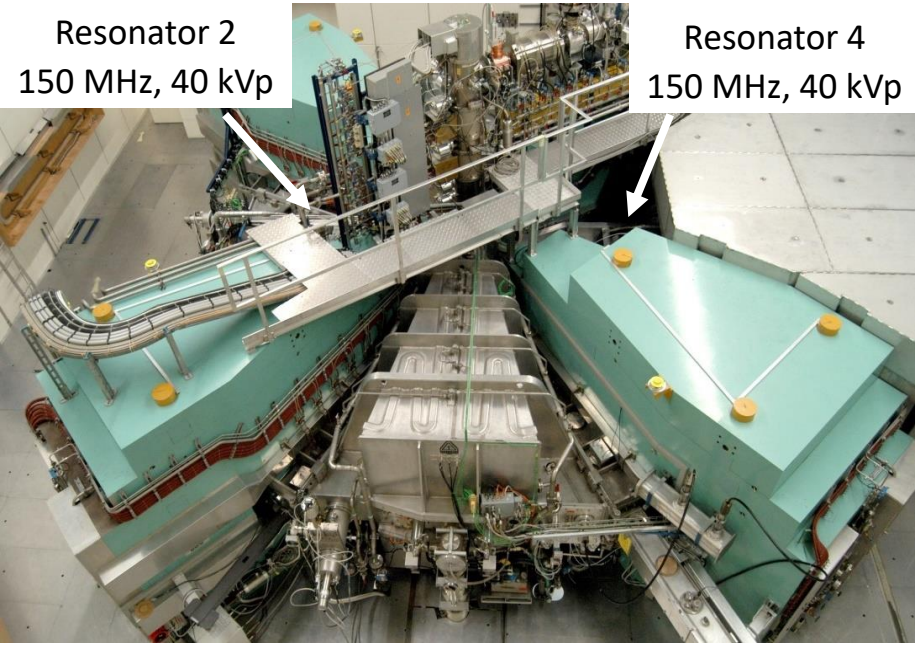
S. Adam, Space charge effect in cyclotrons - from simulations to insights, In Comell[48],439pp. 446–448 (1995)

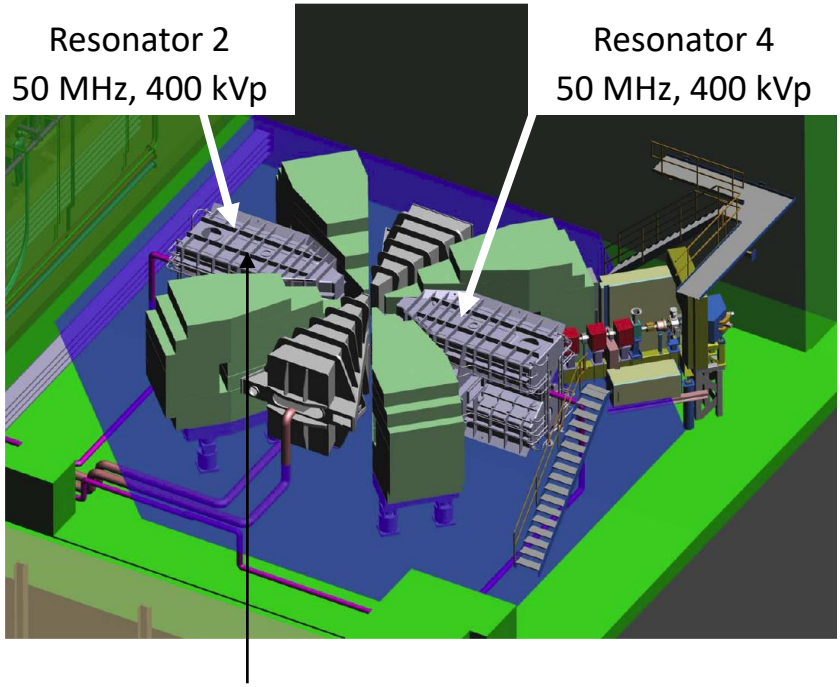


- Vortex motion stabilizes the bunch
- Space charge couples longitudinal and horizontal motion
- Longitudinal focusing (weak though)

Injector 2 – Upgrade

1. **Goal:** reduce the number of turns from **83 to 60 for 3 mA (n^{-3} – law)**
   ⇒ Increase energy gain per turn ⇒ Increase acceleration voltage





150 MHz Flattops not needed (Vortex Effect)
double energy gain per turn

Already installed 2018

60 instead of 83 turns -> 3.0 mA according to $I \simeq \frac{1}{n^3}$ where n = number of turns

Injector 2 – Upgrade

New Resonator 2
Installed 20.02.2018

resonance frequency	50.6328 MHz
accelerating voltage	400 keV @ R_{out}
dissipated power	50kW @ 400kVp
Q	24’500
Tuning range	200 kHz
material cavity RF-wall	EN AW 1050
material structure	EN AW 5083
cooling water flow	15 m^3/h
dimension	5.6 x 3.3 x 3 m
weight	7000 kg

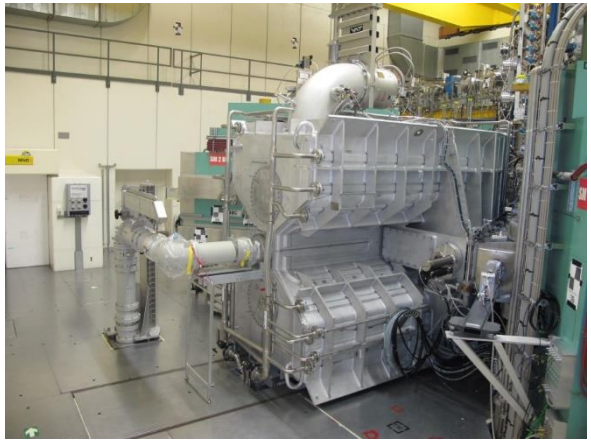
Resonator	type	material	frequency	gap voltage	Wall losses in cavity	incident power @ 2.4 mA Beam
1 & 3	Double gap cavity	aluminum	50 MHz	~ 420 kVp	~ 150 kW	~ 225 kW
2 & 4	Flattop cavity	aluminum	150 MHz	~ 31 kVp	~ 5 kW	~ 14 kW
2 & 4 new	Single gap cavity	aluminum	50 MHz	~ 400 kVp @ extraction	~ 50 kW	~ 100 kW

Status Injector 2 – Upgrade
The new 50 MHz Resonators

Resonator 2:

- Installed in Injector 2 Cyclotron in 2018
- **No tuner up to 2023**

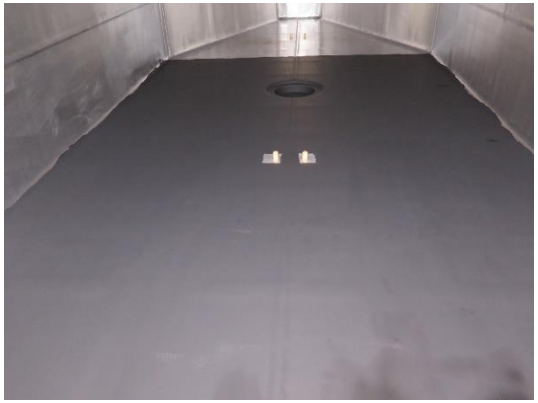
served very well as a vacuum chamber…..



Resonator 2 installed in Injector 2

Resonator 4:

- In test stand for tuner and power tests
- Treated with Aquadag (multipactoring)

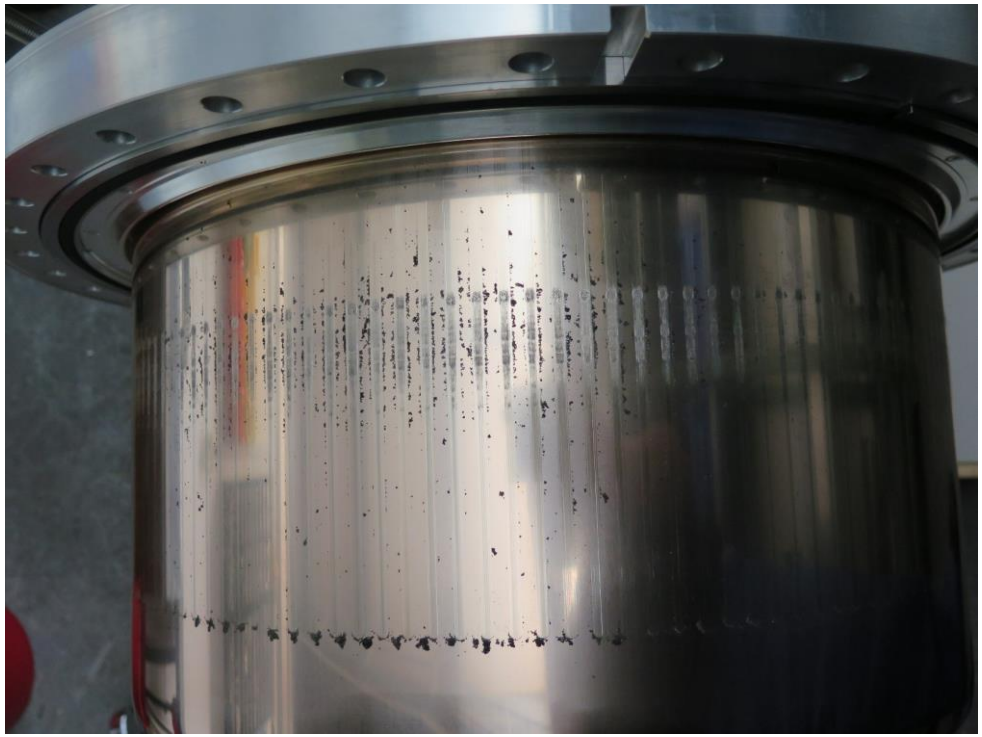


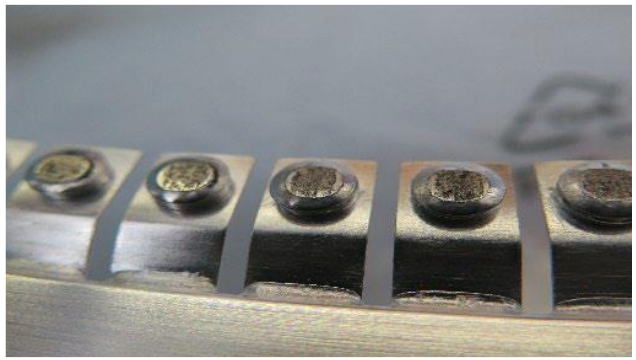
Resonator 4: treated with Aquadag

Resonator 4 in test bunker

Installation in 2024

Tuner for new Resonators
tested in Resonator 4

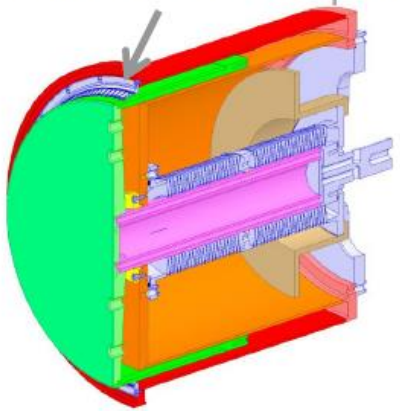




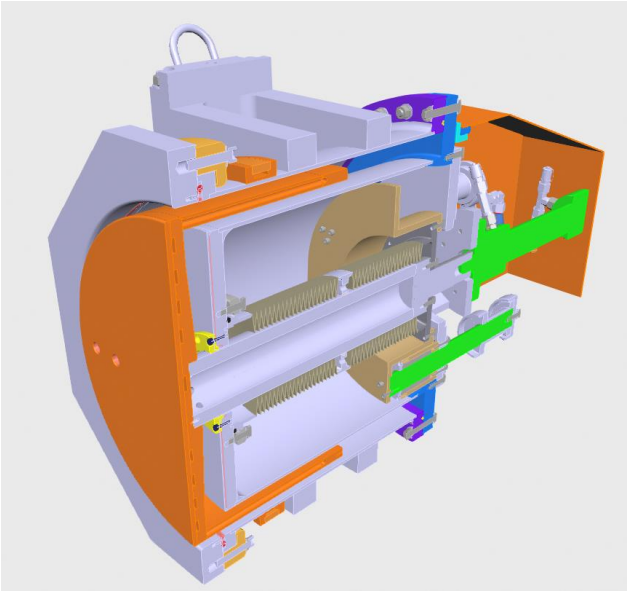
Strong abrasion of contacts

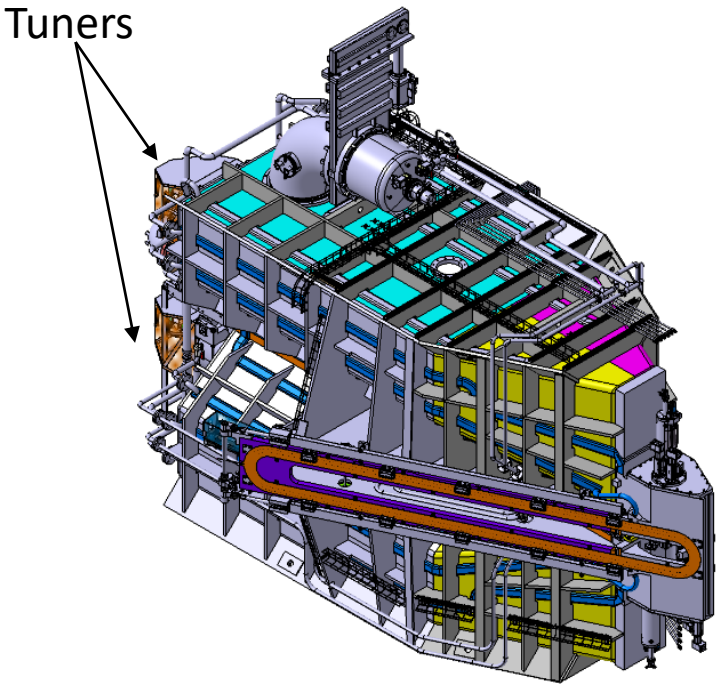
- Tuners show abrasion caused by contact springs
- Tests with different materials, different spring preload, … failed
- New concept was necessary

Finger contacts between vaccum vessel and plunger



New Tuner Concept





- No spring contacts
- New vacuum vessel Al instead of steel
- Additional cooling channel on vacuum vessel
- Optimized geometry to reduce RF leaking into vessel
- New plunger with improved cooling channels

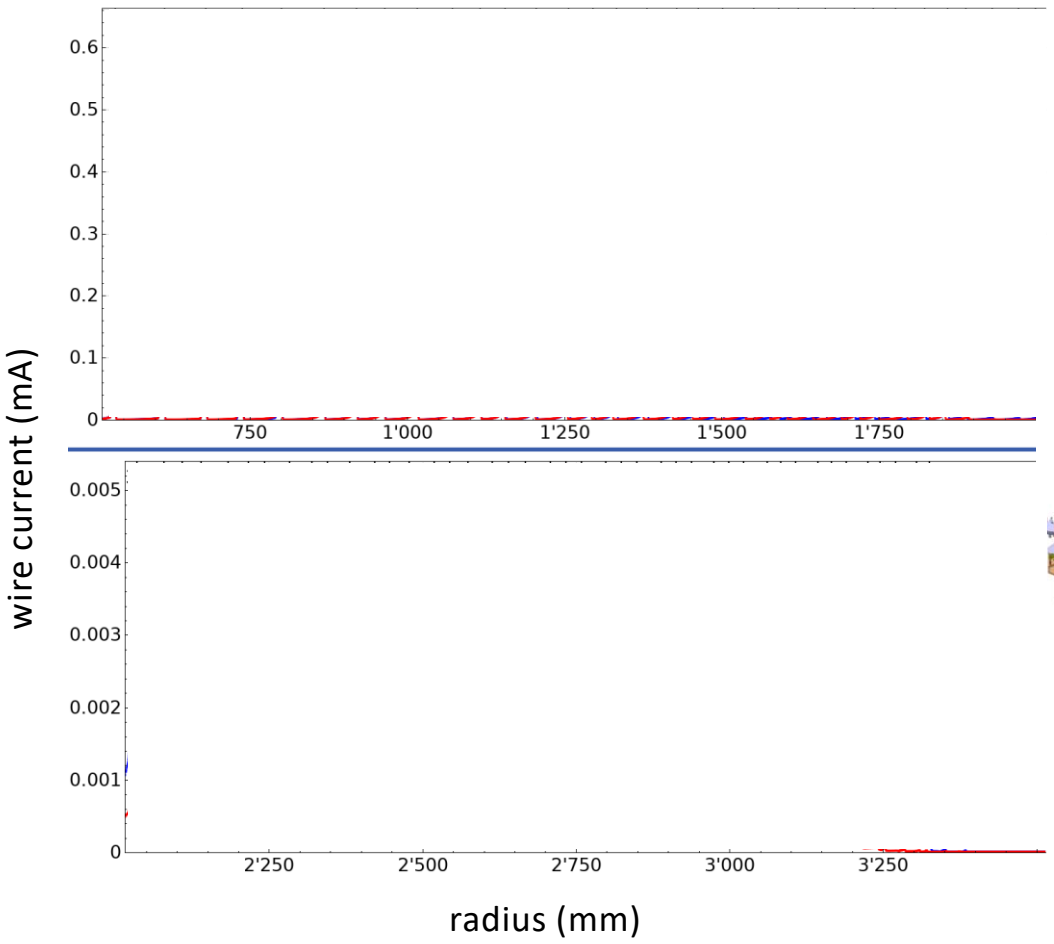
Installation of tuners during Shutdown 2023

Installation team

Coaxial transmission line (RL100-230, Spinner)
New tuners installed

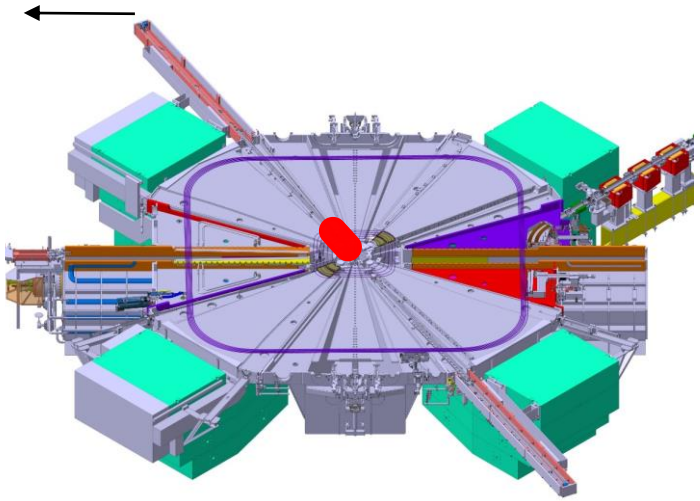
6. September 2023 first beam through Ring with 1 mA

Resonator 2 Commissioning



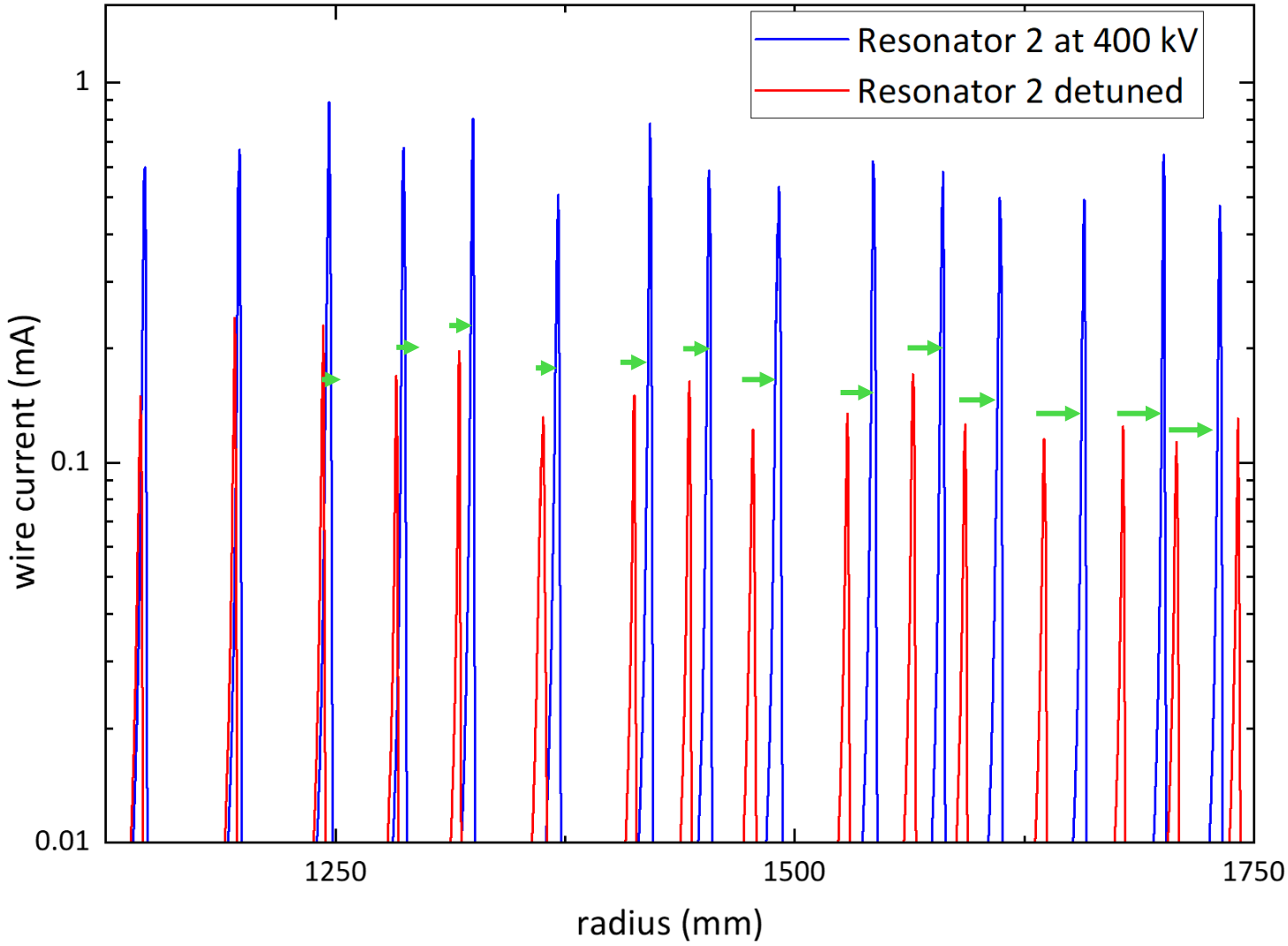
Resonator 2 at 400 kV

Resonator 2 detuned

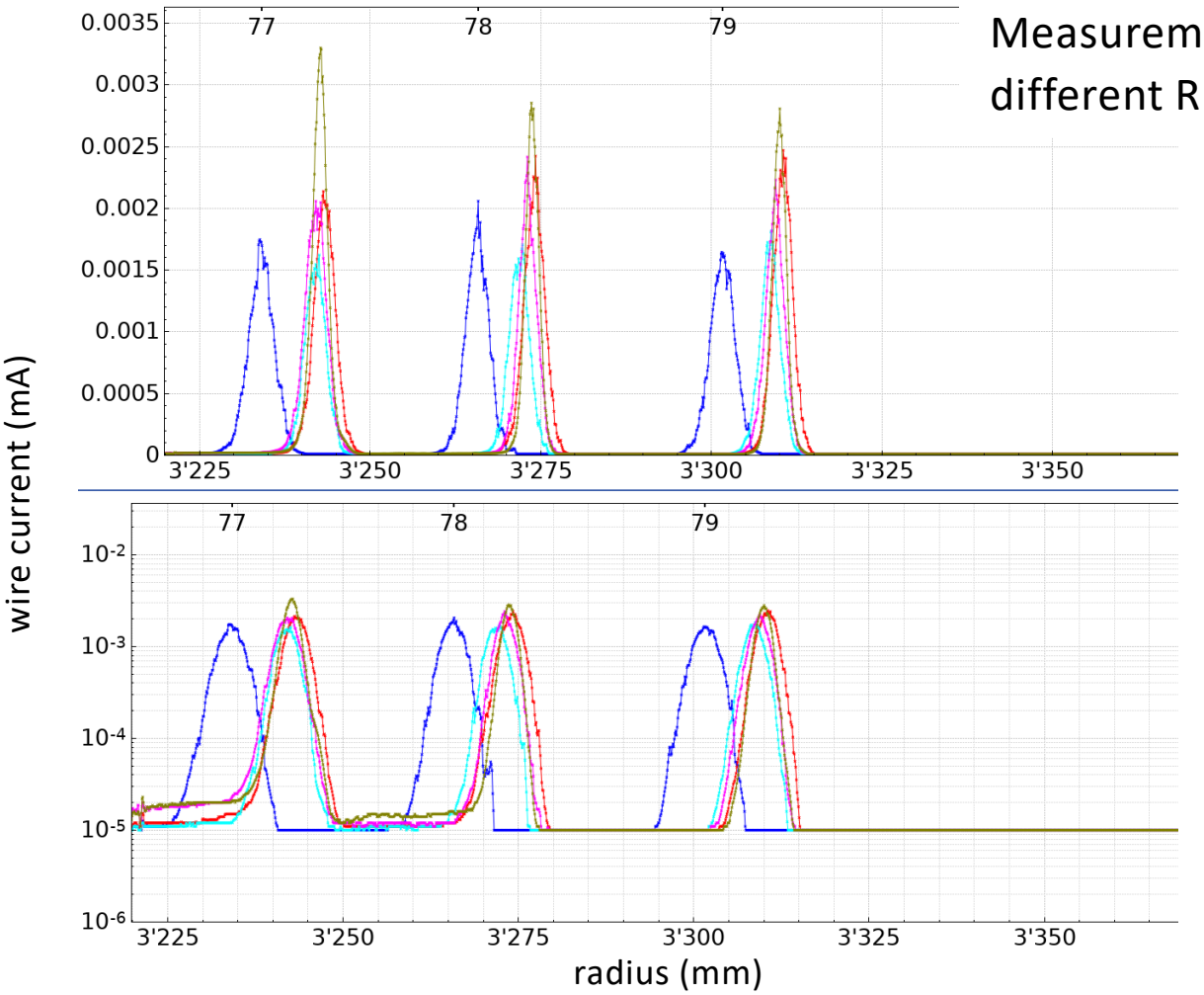


Resonator 2 Commissioning

Peaks shift as desired → higher energy gain per turn



Resonator 2 Commissioning

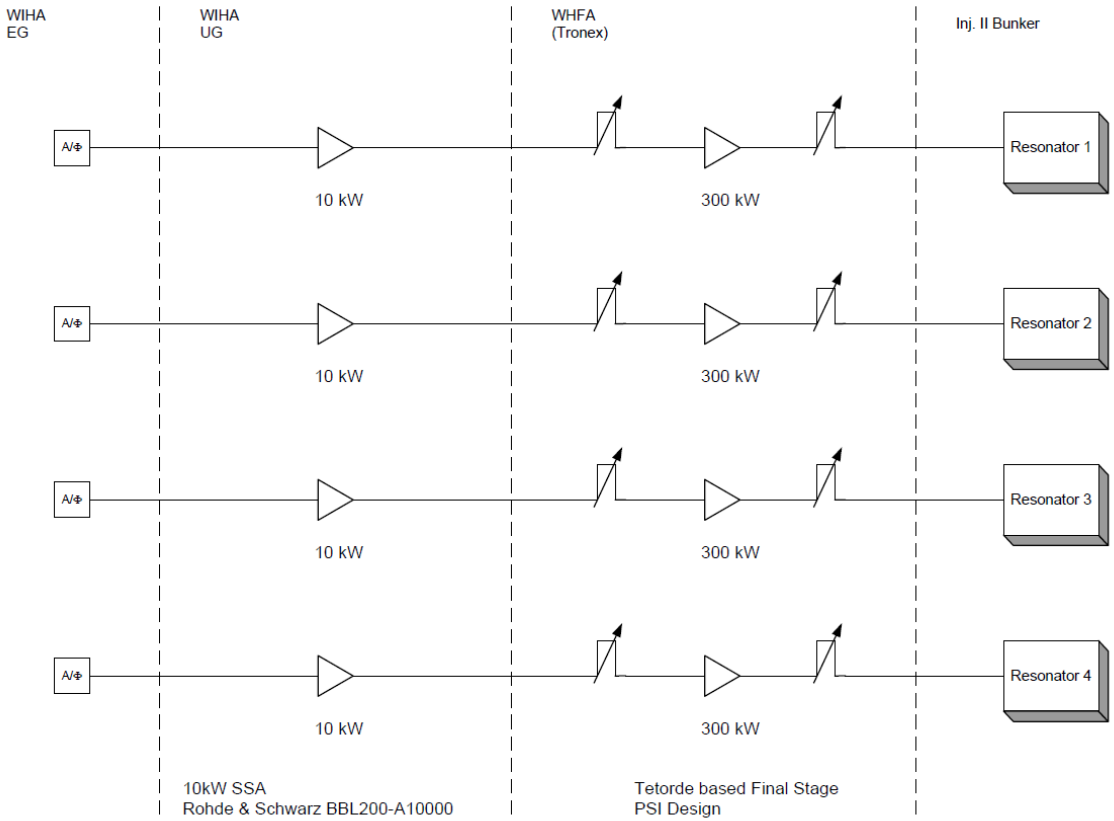


Measurements with different RF-phases

Injector 2 – Upgrade Amplifiers

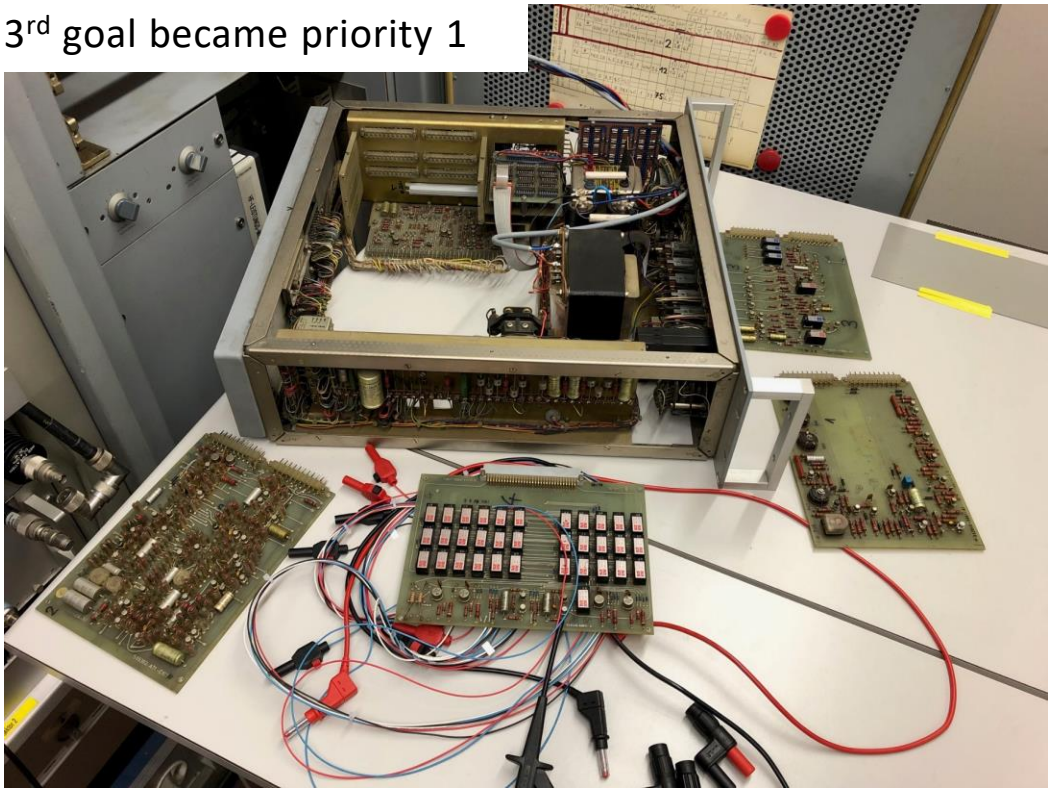
2. Goal: Higher RF-voltage for new Resonators 2 + 4

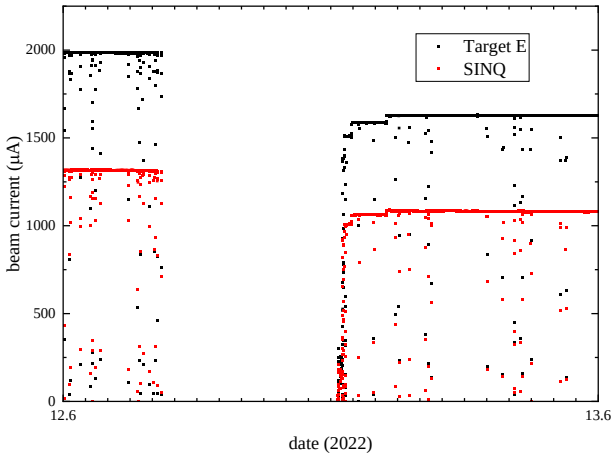
3. Goal: replace outdated amplifier chains for resonators 1 + 3



Resonator 4
Amplifier control unit

3rd goal became priority 1





Reduced beam current for 6 months
1.8 mA instead of 2 mA

- Unit failed in June 2022
- 40 years old / no documentation
- No spare parts
- Amplifier replaced with two SSAs BBL200-A10000
- Will be used as drivers for Res. 1-4

2 X BBL200-A10000 @152 MHz

Injector 2 – Upgrade Amplifiers

2. Goal: Higher RF-voltage for new Resonators 2 + 4

3. Goal: replace outdated amplifier chains for resonators 1 + 3

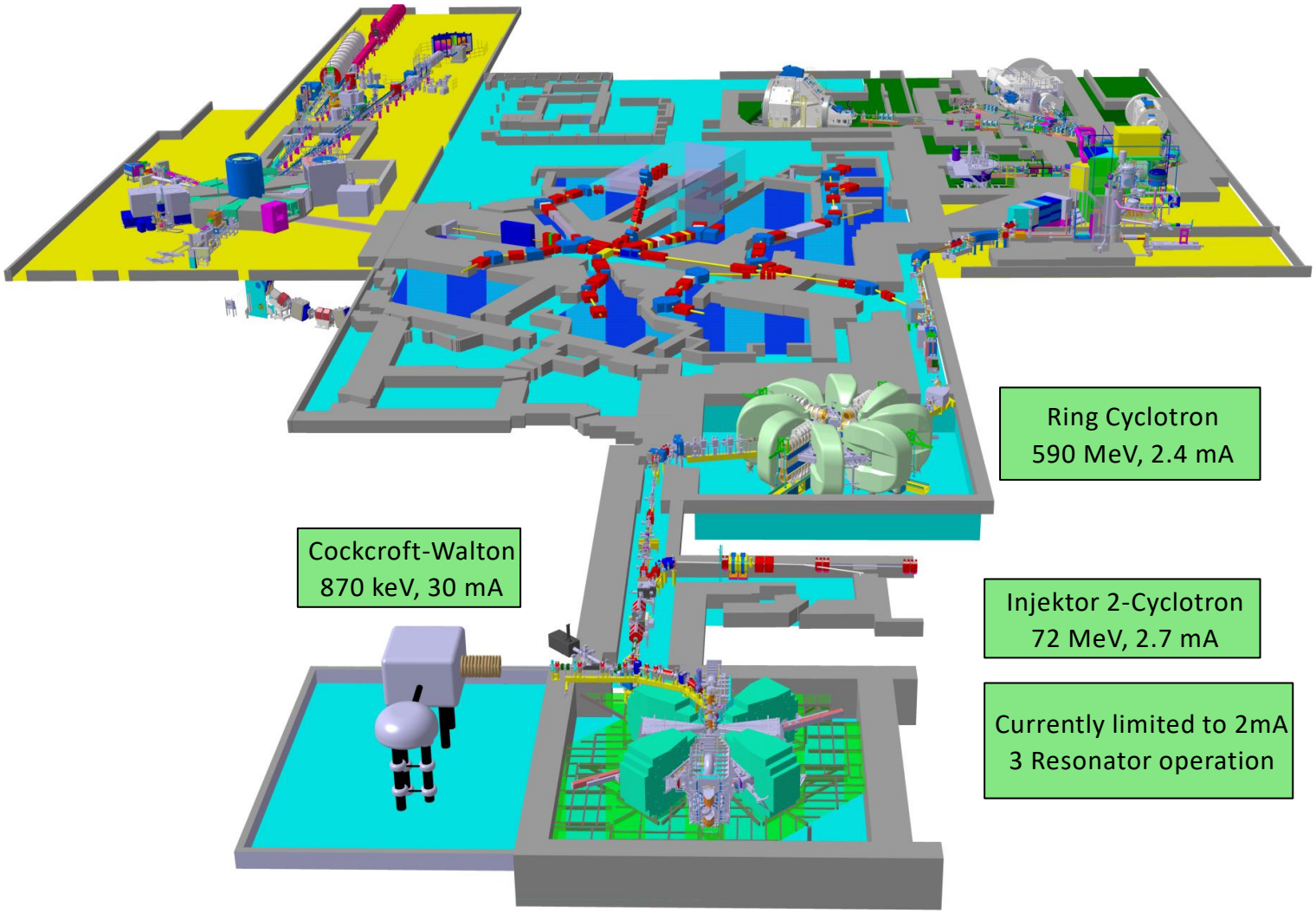
RF annex

Anode PS
15 kV / 40A
Ampegon

400 kW stages
Thales RS2074

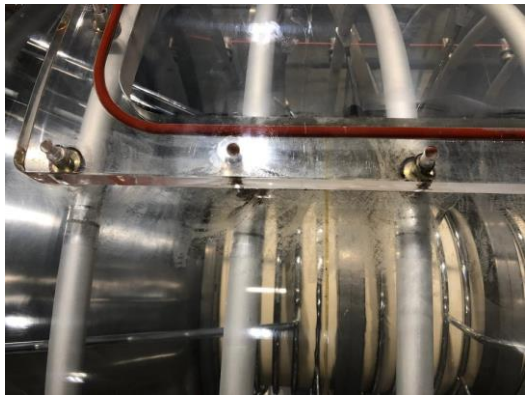
Commissioning: Res 2 in 2023, Res 4 in 2024, Res 1 & 3 in 2025

High Intensity Proton Accelerator Facility
Cockcroft – Walton

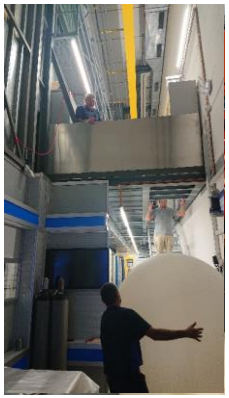


Cockcroft – Walton
870 keV, 30 mA

Cockcroft-Walton with 810 kV platform and acceleration tube
ECR-source very reliable (>99%)



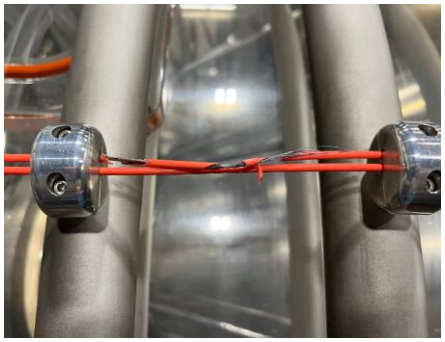
2020: HV breakdown due to scorched acrylic glas



SF_6 disposal

polishing

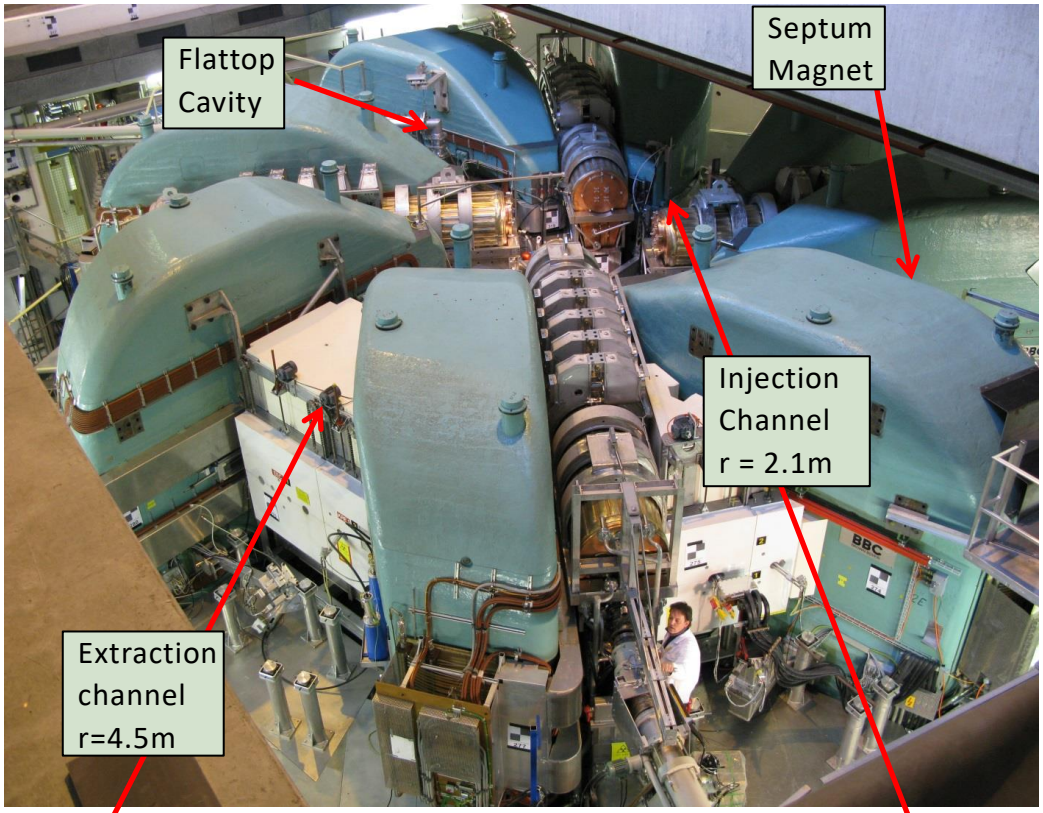
Recurring: burnt fibre optics

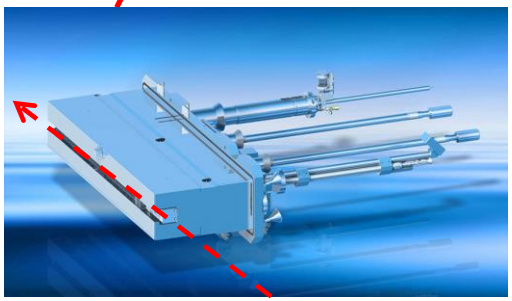


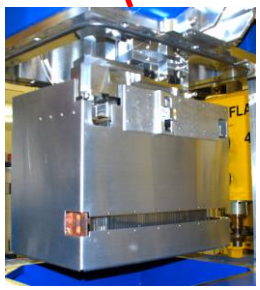
different supplier or laser transmission

Defect transformer in microwave amplifier
No more support
New solid state version

Status of the Ring Cyclotron



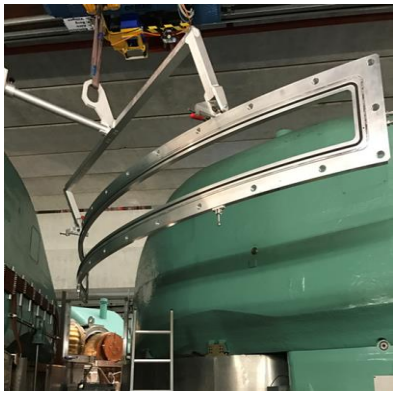


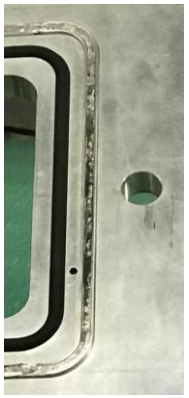


Current routine operation at 2 mA

Reason: Injector 2 – Upgrade

- Vacuum improved (rad. hard In sealings)





- Electrostatic Elements shielded (RF)

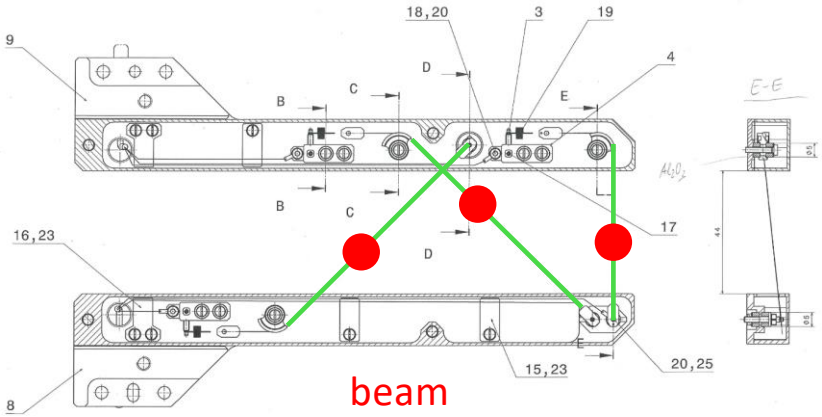
- **Cu–Cavities ready for 3.0 mA**
- **RF-Amplifiers need upgrade for 1.8 MW**

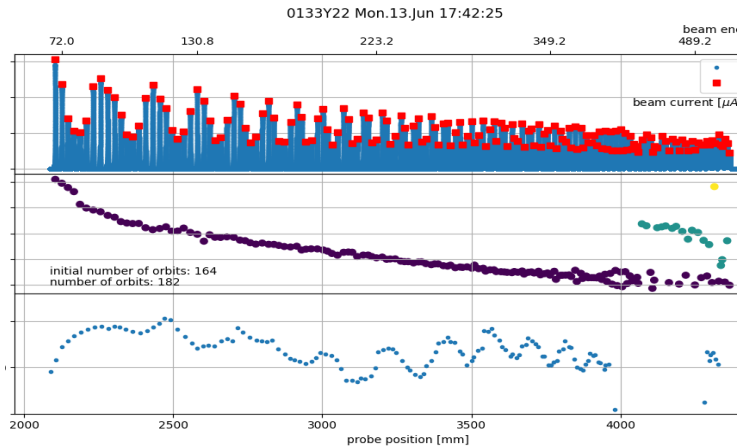
- **New long radial probe**

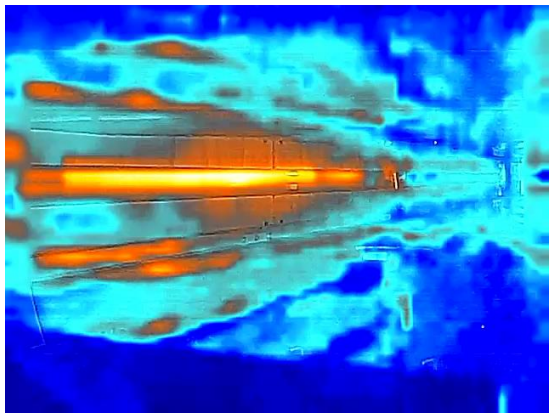
Long Radial Probe Ring cyclotron
Renewal Project

Not available since 2012 but important for beam dynamics

- New mechanical drive
- New wire fork





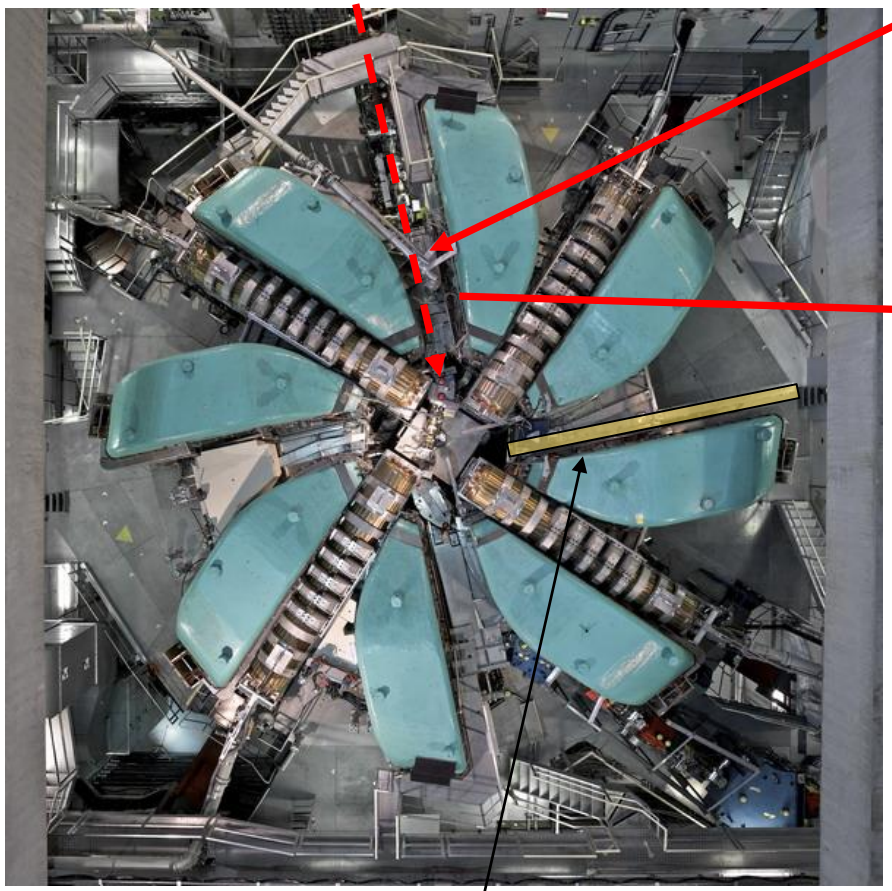


Wires still burn out even with RF only
Studies with C-nano tubes ongoing

accelconf.web.cern.ch/ibic2020/papers/wepp33.pdf

150 MHz Flattop Cavity (1979)

72 MeV beam



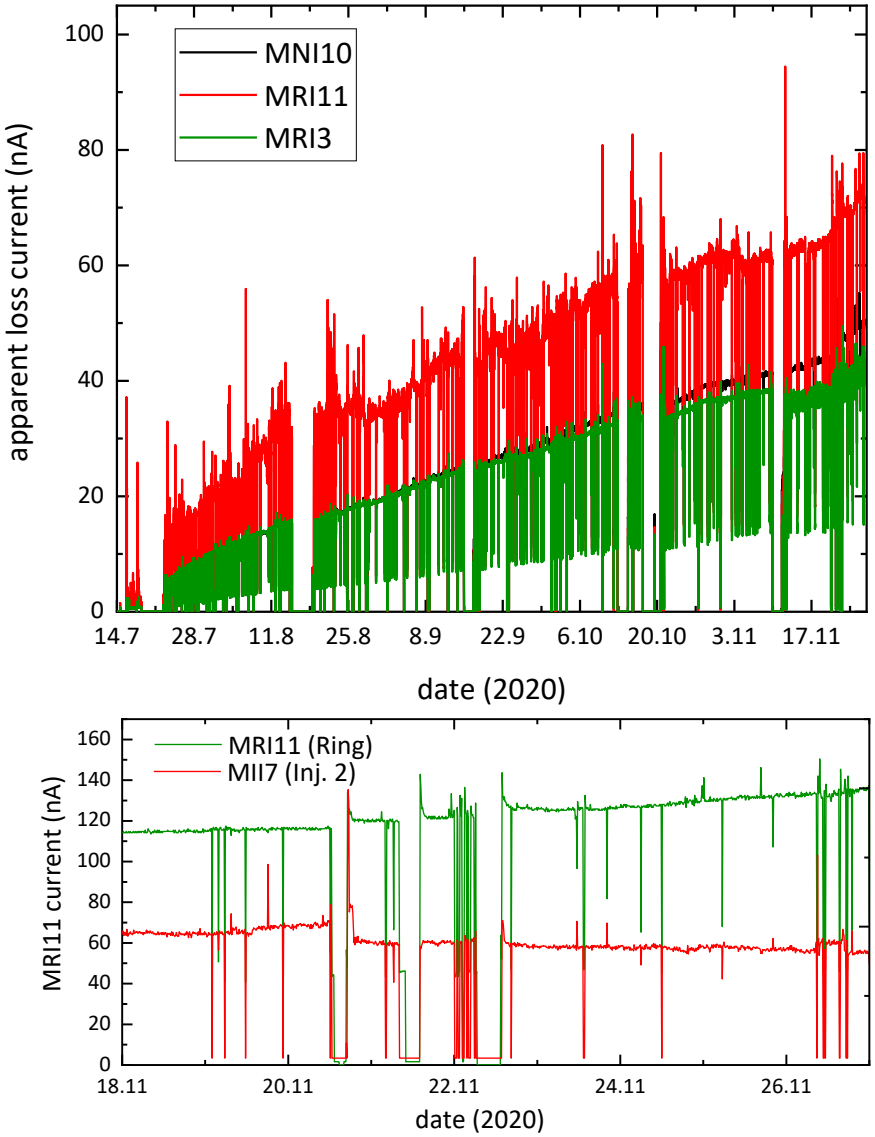
Probe RRL I just showed

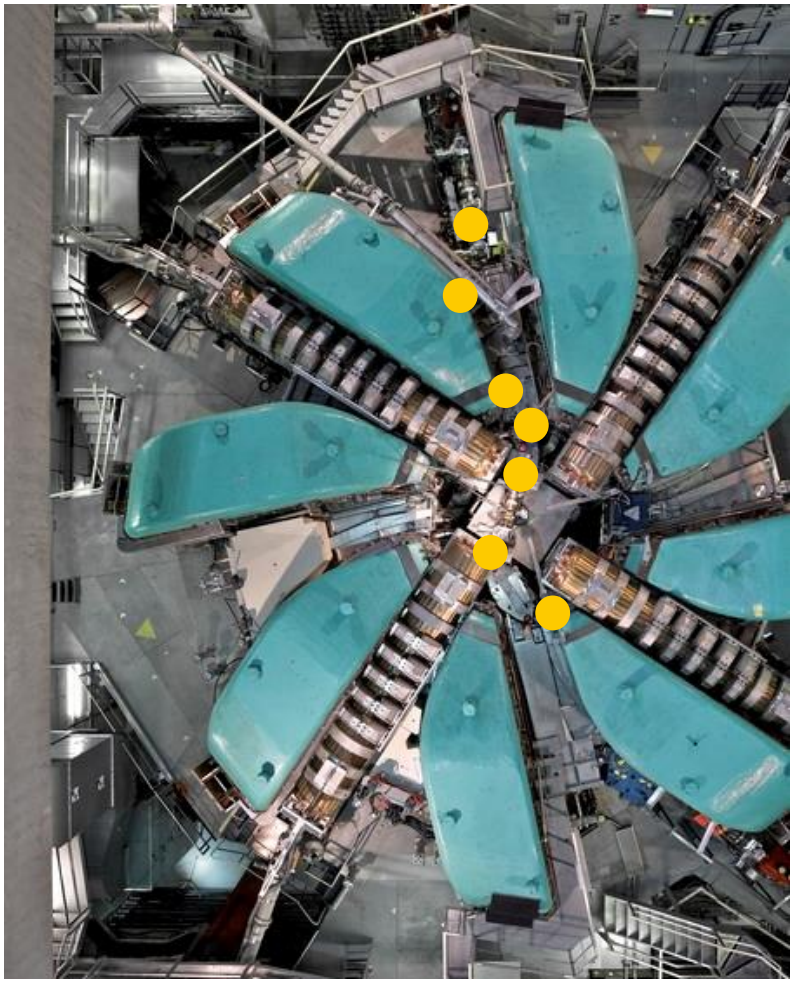
3rd harmonic «flattop» cavity

- 151 MHz
- 550 kV (11% of main voltage)
- Q = 28000
- Gap = 0.25 m

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

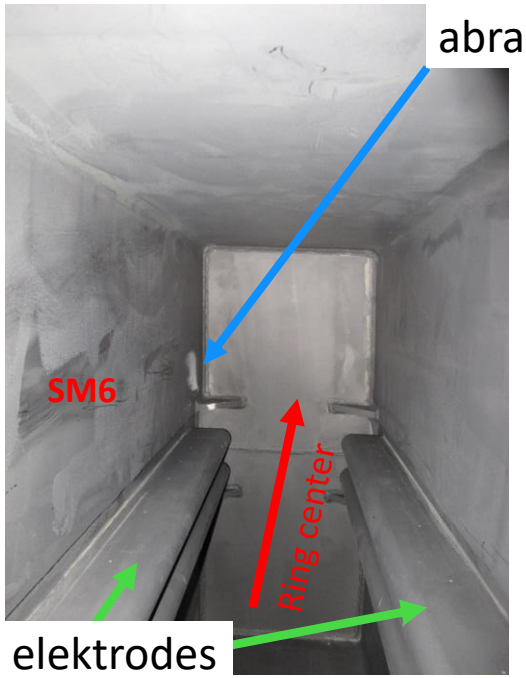
Röntgen Emission Cavity 5

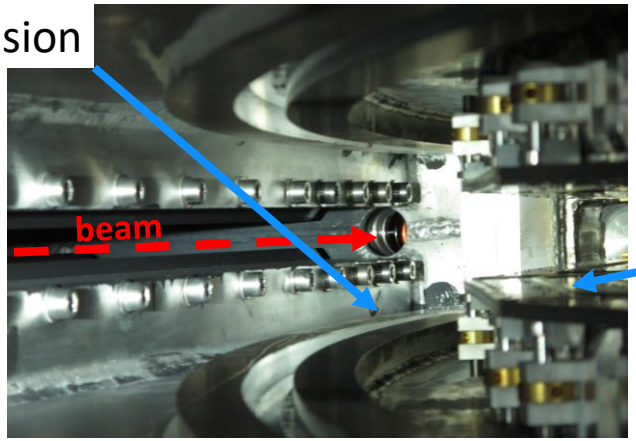


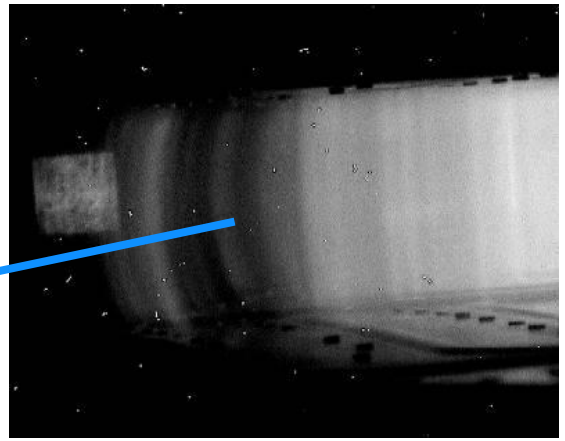


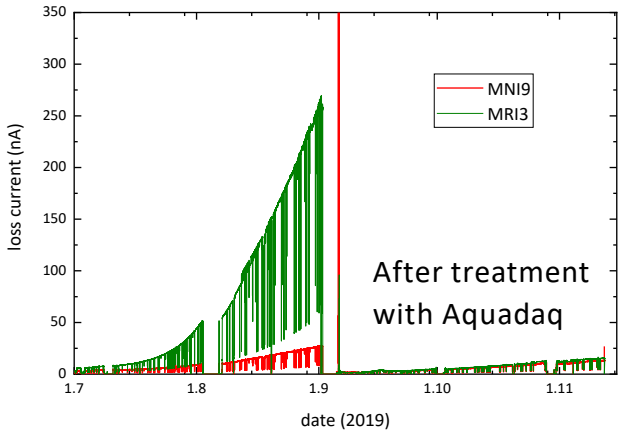
Ionisation chambers

Multipactoring Flattop
Aquadag Coating





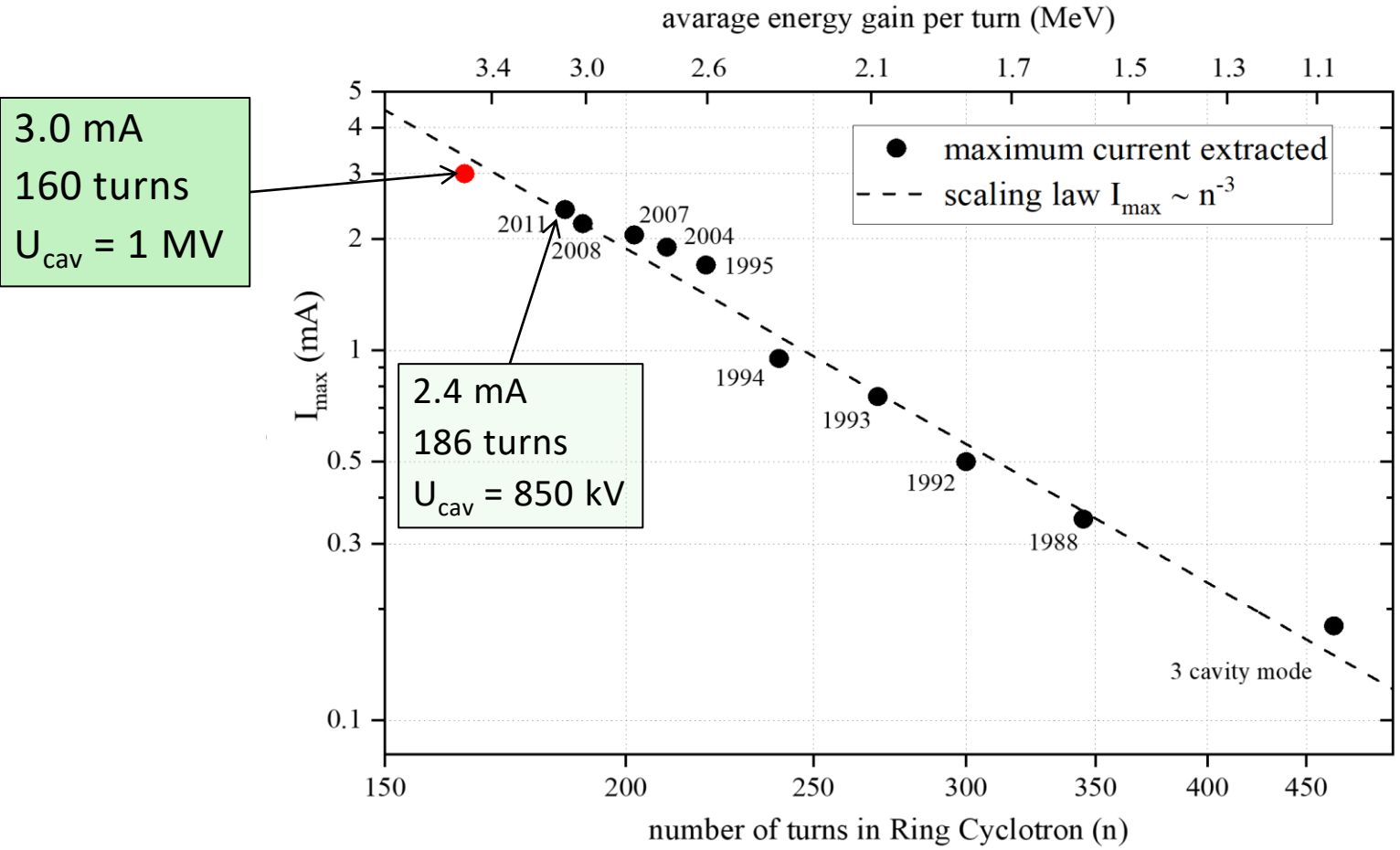




- Plasma ignition in sector magnet above 450 kV flattop voltage
- 20 kW of RF-power “leak” into vacuum chamber
- **Cooling insufficient for $I > 2.4$ mA / $U_{cav} > 550$ kV/p**

Aquadag to suppress secondary electron emission

Empirical Scaling Law by W. Joho[1]



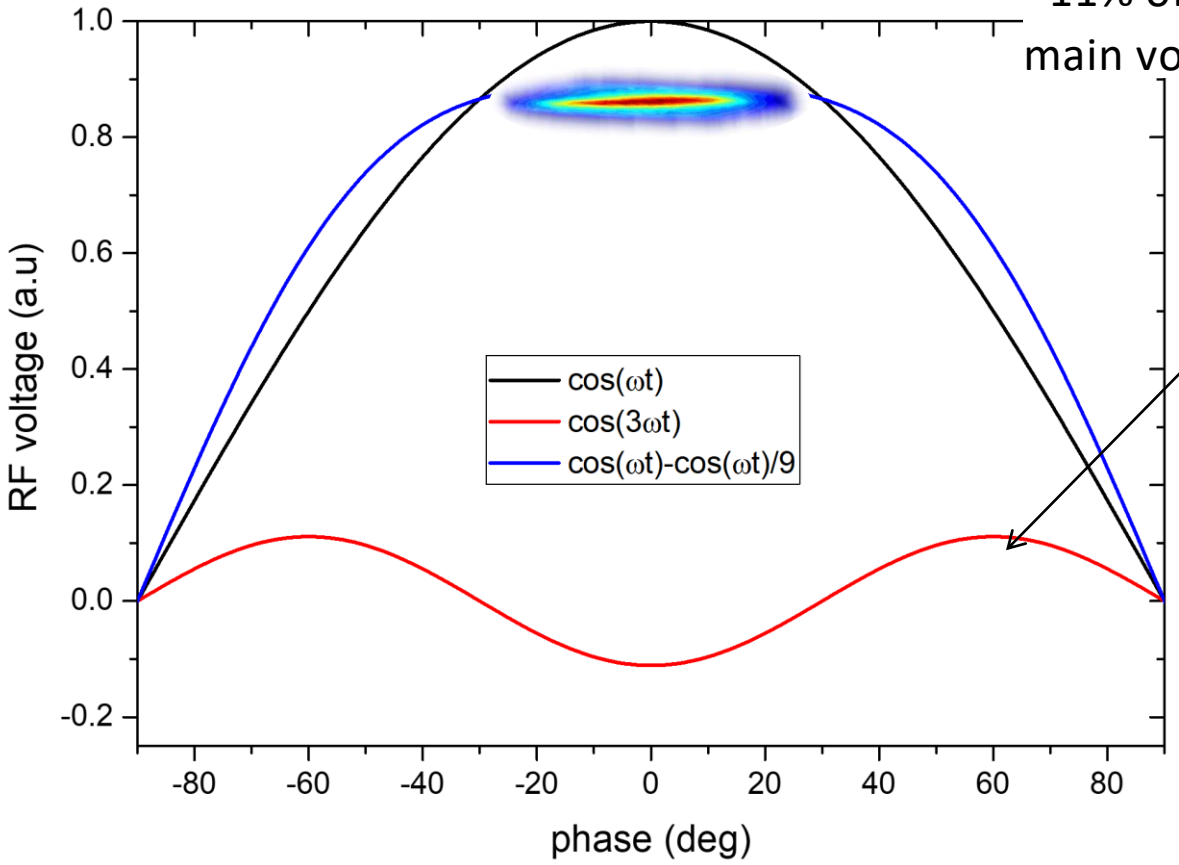
Losses scale with

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

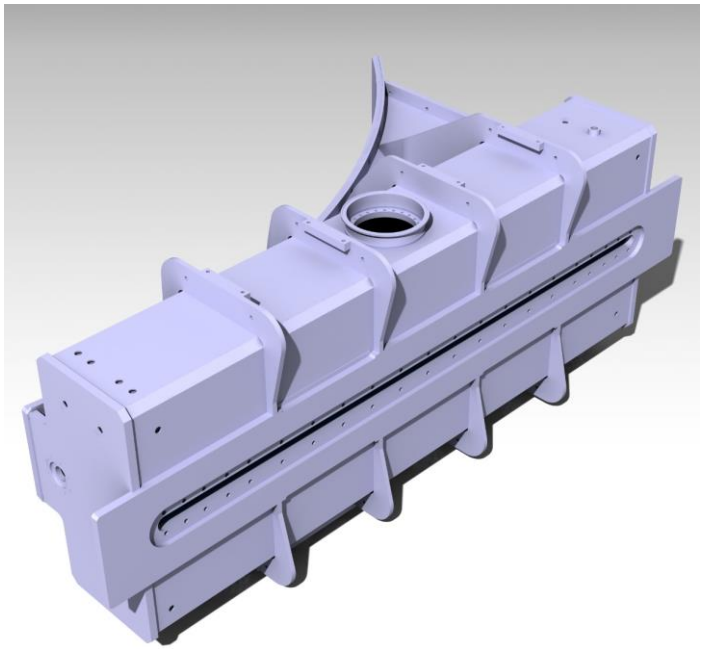
- variation of accelerating voltage over the bunch length **increases energy spread**
- thus a third harmonic flattop resonator is used to **compensate the curvature** of the cavity voltage w.r.t. time (apparently no vortex effect in Ring cyclotron)
- optimum condition: $U_{\mathrm{tot}} = U_0(\cos\omega t - \frac{1}{9}\cos 3\omega t)$



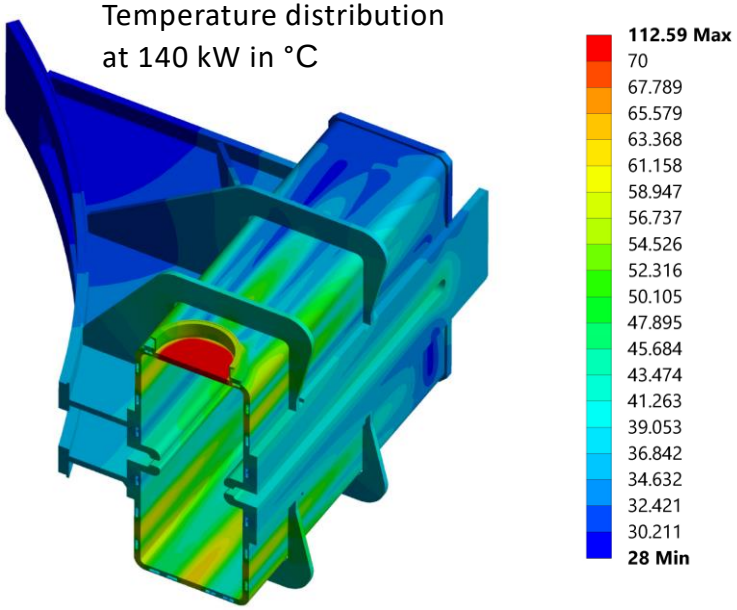
PSI:
f = 150 MHZ
U_p = 550 kV

U_p = 660 kV
for U_{acc} = 1 MV

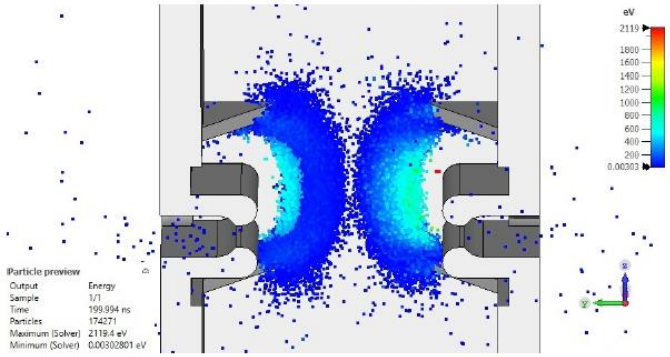
New 150 MHz Flattop Cavity for 3.0 mA



Temperature distribution
at 140 kW in °C



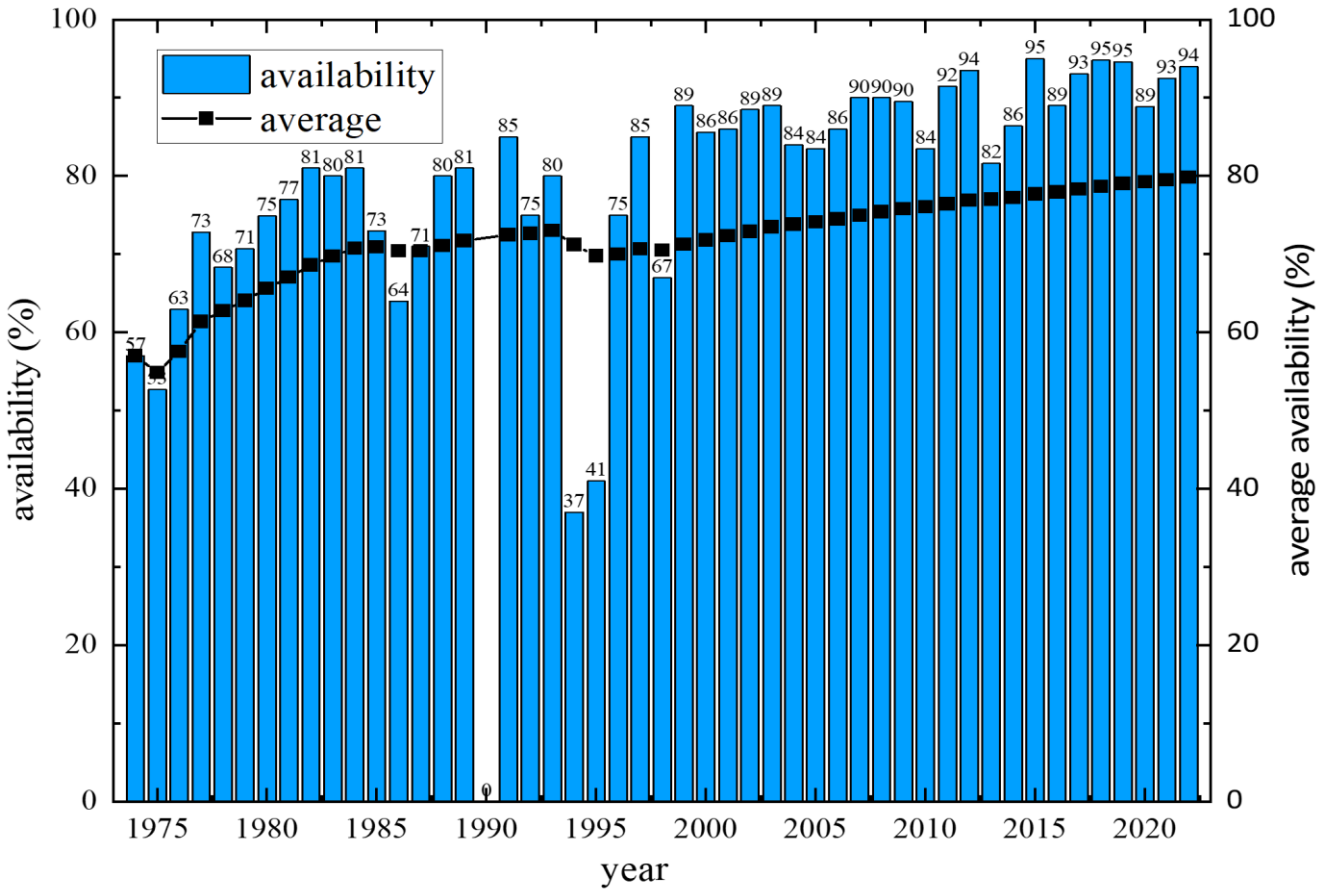
- Material choice: pure Aluminum
- New shape of the electrodes (increase peak shunt impedance)
- Improved cooling for 140 kW dissipated power
- New coupler design (ongoing)



Multipactoring studies

J.-Y. Raguin, M. Bopp, R. Fortunati, J. Grillenberger, T. G. Lucas, M. Pedrozzi, M. Schneider, M. Stoll, PSI
E. Solodko, Transmutex

Availability of the Accelerator Facility



2004: interlock system

2005: Electrostatic Extraction Channel

2010: reduced gap

2013: Flattop Target E

2014: infrastructure magnet gap Target E

2016: Target E SINQ Septum magnet

2020: Cov19

2023: Control System

High availability is of uttermost importance for the users

Secondary particle yield comes second

Target E – Upgrades

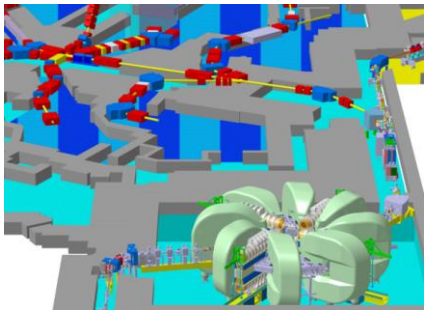
- Life-time of ball bearings 6 months (1 failure per year)
- Life-time of motor 3 years

Exchange flask

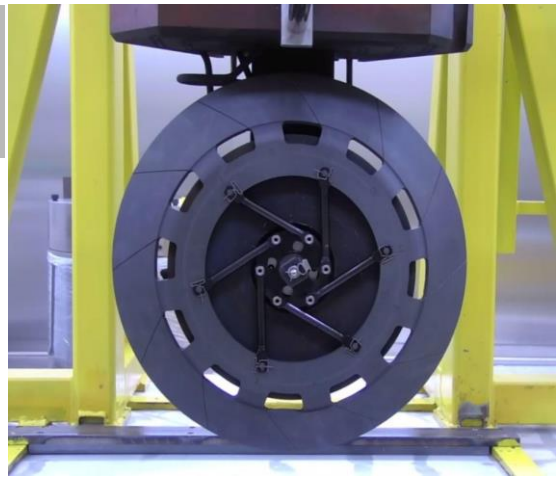
Hotcell

~48h

1-2% availability



Target E – Upgrades



Standard 40 mm Target E

Challenges

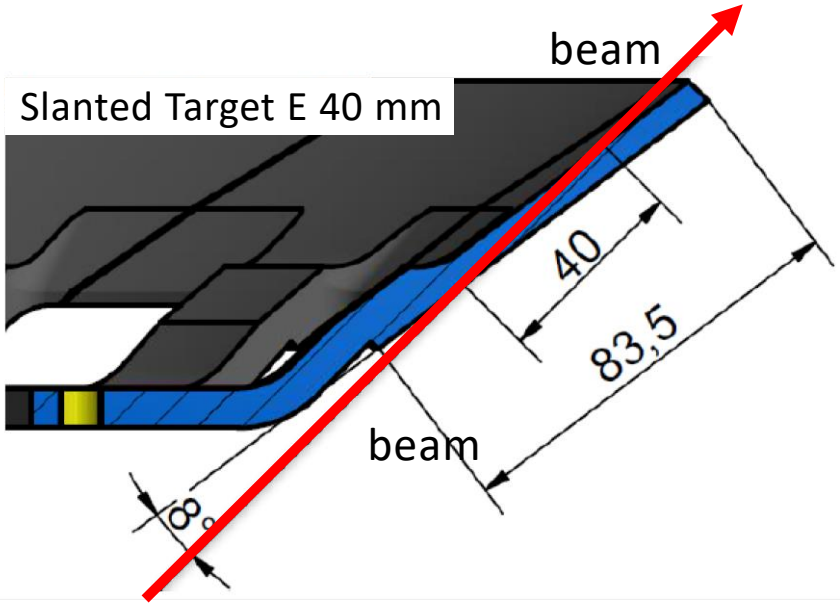
- 50 kW on Target E ⇒ Rotation 1 Hz (**bearings**)
- Cooling (1700 K) ⇒ Radiation, Cu-shielding cooled
- Temperature resistant material ⇒ Polycrystalline graphite
- Thermal stress (deformation) ⇒ Spokes (thermal expansion)
  Slits in wheel

Bearings were the neuralgic spot

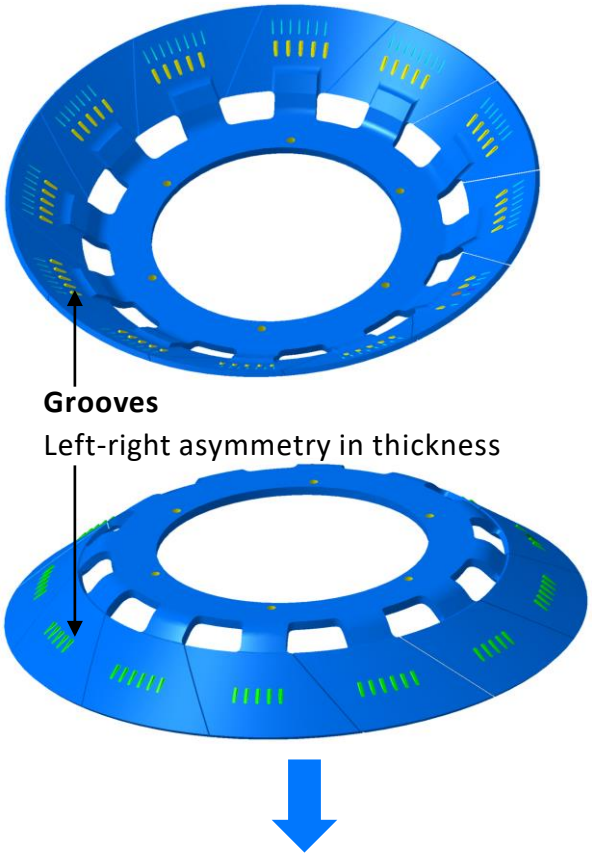
New ball bearings with solid state WS_2 lubricant
by S. Makimura (J-Parc) & KOYO®
Installed in 2019

No target failure during user operation since December 2019

Target E – Upgrades



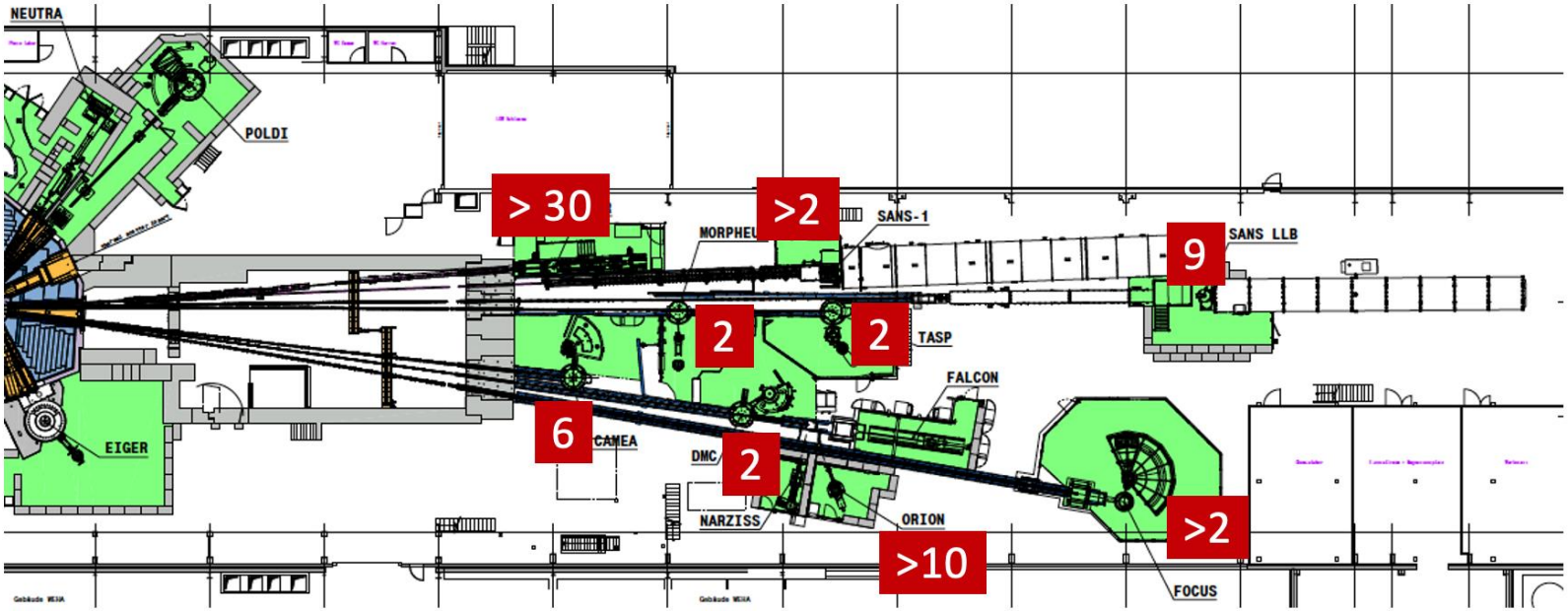
30 – 50% increase in surface muon rate
(measurement and simulation agree)



Beam position monitoring by
current transmission measurement

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
- **The Accelerator's uptime and beam intensity remain the primary driving forces!**

Steps Towards a Higher Performance
Accelerator part

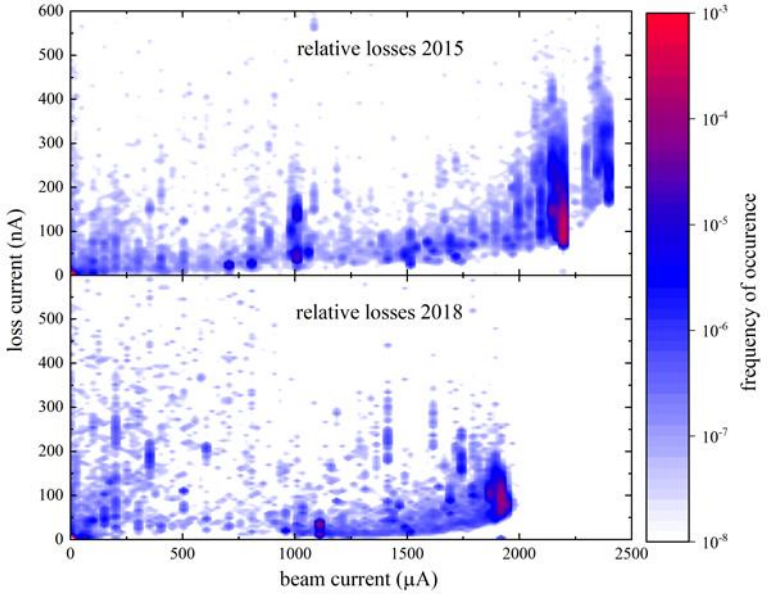
Increase Beam Power to 1.8 MW

- Understand and reduce losses
- More diagnostics and simulations

- Finish Injector 2 Upgrade (by 2025)

- Increase gap voltage in Ring (n^{-3} – law)
  - More powerful RF-amplifiers (SSA?)
  - new flattop system

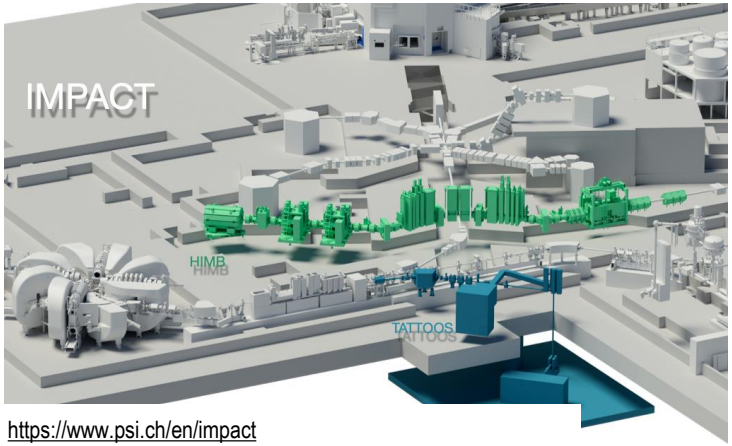
- **Well trained operators and more beam development (A.I. does not exist…)**



Summary

- The PSI accelerator has already deliverd 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)**

- High demand of Neutron Sources
- Since 2020 new neutron guides/ monochromators (2–30 more neutrons)
- **New project IMPACT is on its way**
- Operation until 2030+



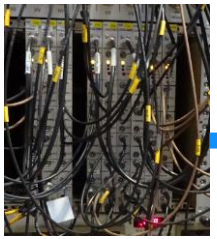
https://www.psi.ch/en/impact
CDR: https://www.dora.lib4ri.ch/psi/islandora/object/psi:41209

We have to/want to prepare for another 20-30 years of operation

Infrastructure, conventional systems, cooling, hotcells, etc are in good condition

10 Year Upgrade Plan

- **Electronics and Control System** — started -2026
  - Replacement of CAMAC-based system
  - New Firmware and Control system integration
  - interlock integration and level adaption



- **RF – Renewal and/or Upgrade** — Injector 2 -2025
  - new Flattop — prestudies -2030
  - Renewal / Upgrade of RF-amplifiers (SSD) — strategic decision

- **Magnet Renewal and Spares** — inventory
  - many coils over 50 years old — stock keeping
  - Bending magnets critical stock

- **Diagnostics** — started -2026
  - Fast Wire Scanners (beam current 3 mA) — strategic
  - BPMs in 590 MeV beamline — started -2030
  - Profile monitors in 590 MeV beamline — started -2026
  - Radial Probes (new wire material, e.g., nano tubes) — promising

- **Power Supplies**
  - On-Going and recurring project — running -2026
  - New design with Silicon Carbide

- **Vacuum System** — recurring

My thanks go to

- Markus Schneider
- My Colleagues

- Your attention!

?

!