PAUL SCHERRER INSTITUT


WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

Daniela Kiselev :: 8100 :: Paul Scherrer Institut

High-Power Targetry and the IMPACT Initiative @ PSI

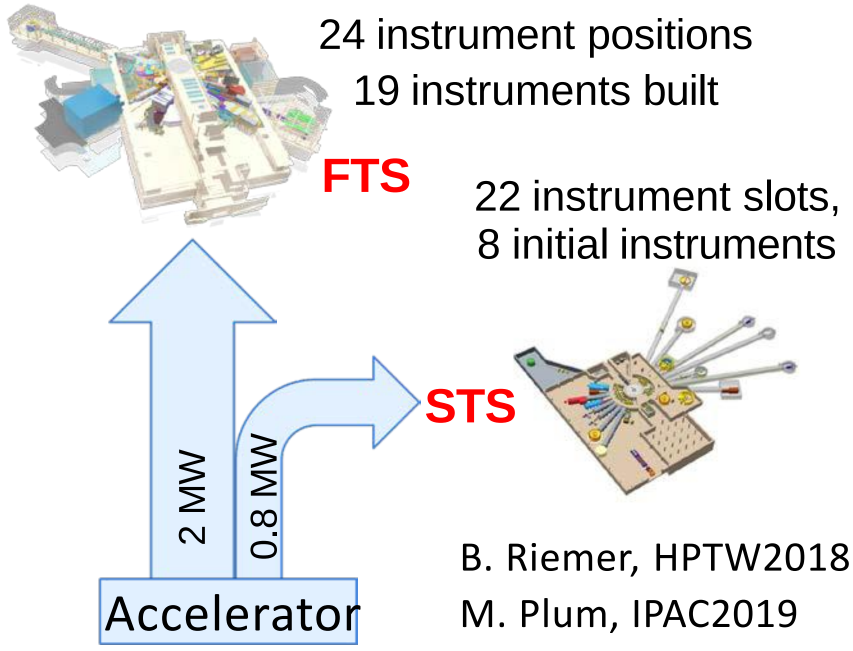
HB2023 workshop, CERN, 9-13.10.2023

The need for high power targets

- Demand for higher statistics, more exp/time
  → higher (secondary) particle fluxes

- Feasible due to faster detectors (segmented), electronics, DAQ/computers
  → processing of larger rate

- driven by: More powerful accelerators

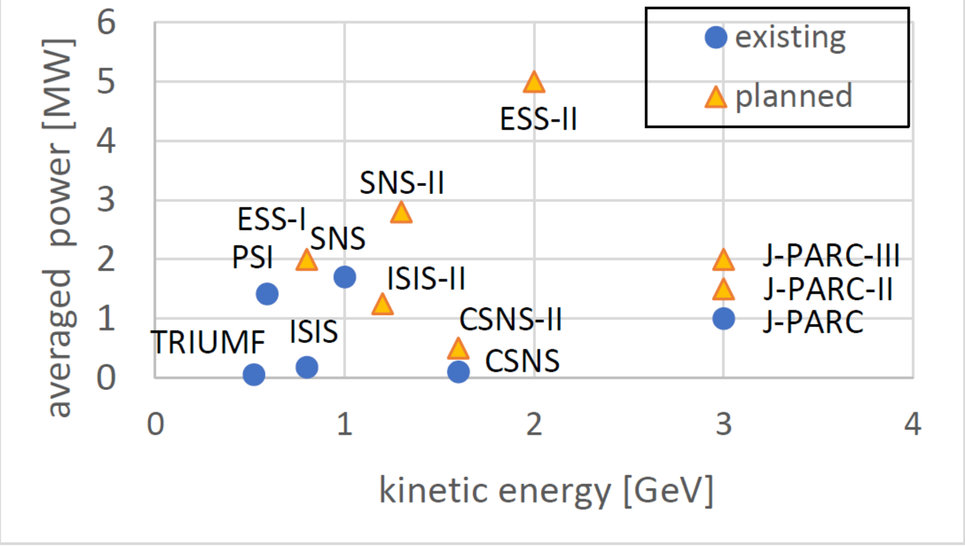


24 instrument positions
19 instruments built

22 instrument slots,
8 initial instruments

B. Riemer, HPTW2018
M. Plum, IPAC2019

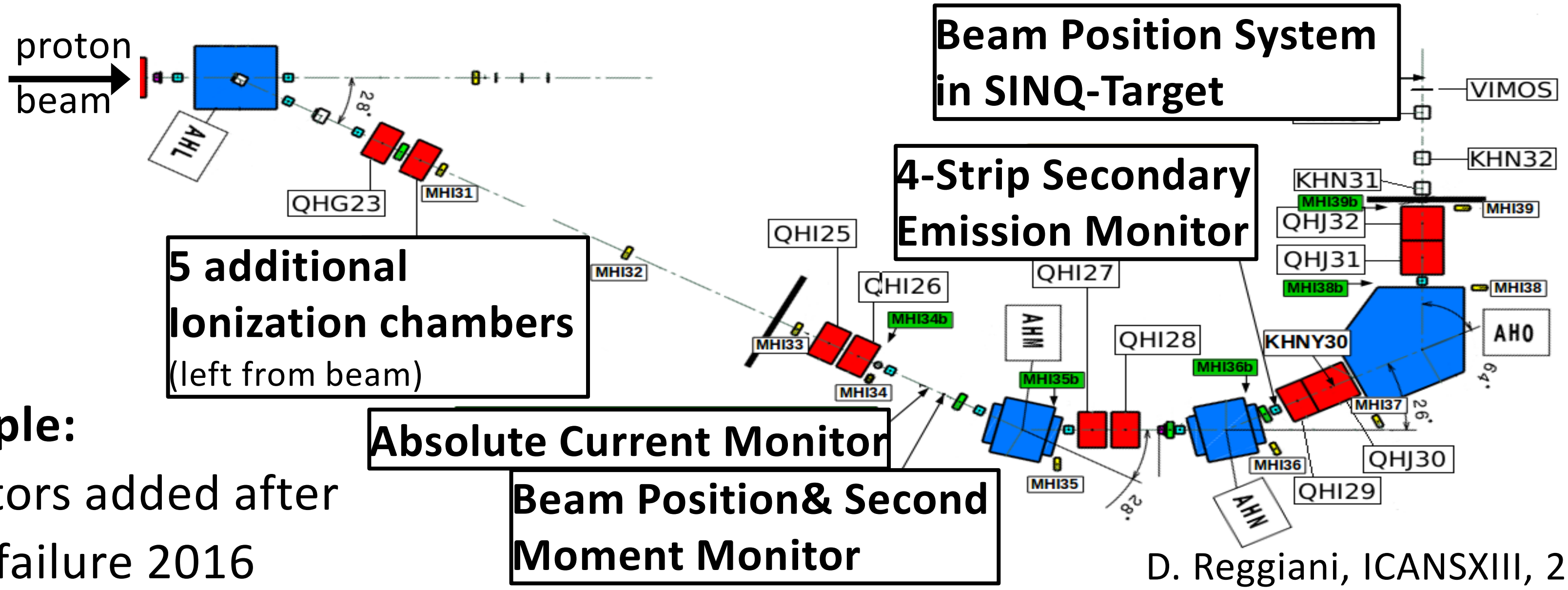
Power of proton accelerators



SNS-II → 2.8 MW
(after Proton Power Upgrade)

Challenges on the accelerator side

- **Redundant beam monitors:** detection failure can damage target



Beam Position System in SINQ-Target

4-Strip Secondary Emission Monitor

5 additional Ionization chambers (left from beam)

Absolute Current Monitor

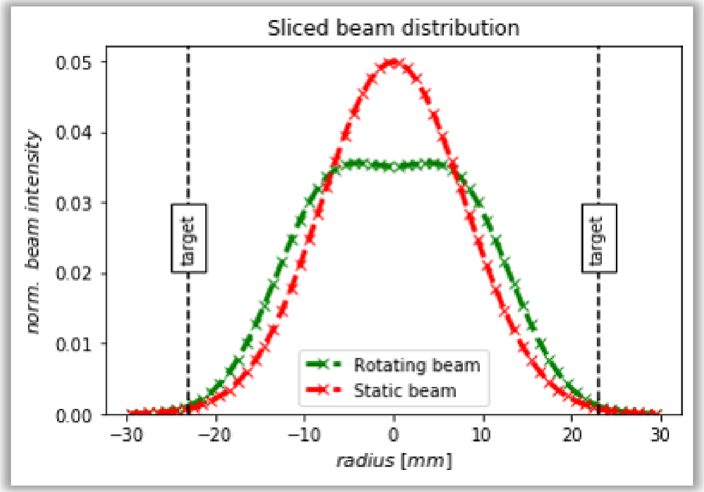
Beam Position& Second Moment Monitor

Example:
Monitors added after
SINQ failure 2016

D. Reggiani, ICANSXIII, 2019

- **Fast interlock system:** 10 ms at HIPA, PSI

- **Special beam profiles:**
  → distributing power on the target
  → enlarging beam profile
  Ideal: rectangular profile
  → wobbling/painting/rotating



M. Hartmann, PSI

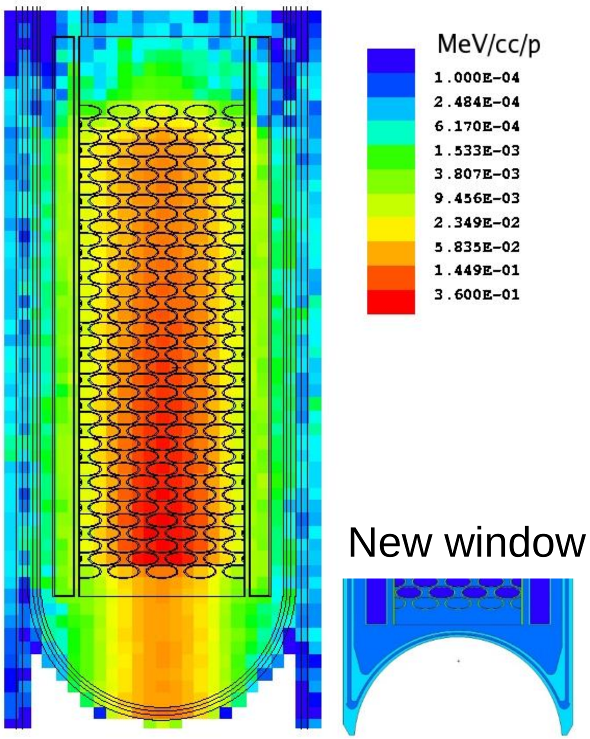
(Many) Challenges on the target side

- **Monitoring** of target operation to prevent damage:
  possible failure of sensors (temperature, flow....)
  due to harsh environment
  → redundant sensors

- **Replacement/repairing/disposal** of the target:
  very high dose (~ several Sv/h)
  → remote handling in a shielded cell,
  special tools

- **Thermal stress** (for solid targets)
  due to temperature gradients
  - heat sink/cooling agent
  - inhomogeneous energy deposition

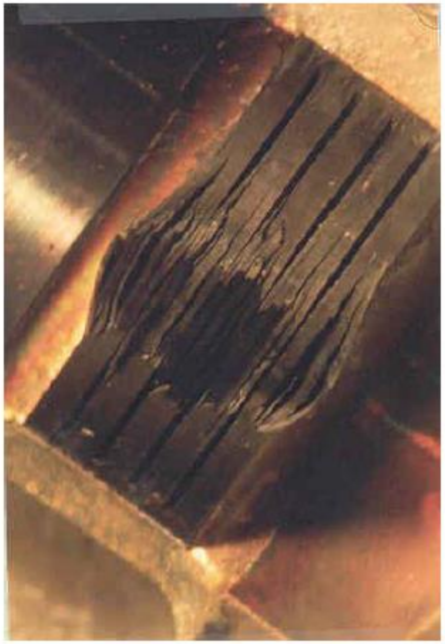
SINQ:
energy deposition



Radiation damage on material structure

- **Hardening** → embrittlement, cracks (depending on local stress)
- **Swelling** → increased stress
  → can lead to cracks
- **Degradation of thermal conductivity**
  → loss of cooling efficiency

500 MeV
Protons
at TRIUMF,
150 μA



anisotropic properties ← Water-cooled/Edge-cooled pyrolytic graphite target

E.W. Blackmore *et al.*,
in *Proc. PAC 2005*, 1919

- H, He (produced by nuclear reactions)
  → enhance swelling, embrittlement, blistering on the surface
- Diffusion coefficient: tremendous increase
  e.g. 10 order of magnitude increase in steel (M. Song J. Nuc. Mat. 518 (2019) 461)
  → increased formation of molecules, e.g. H_2O
  → cracks at high temperature

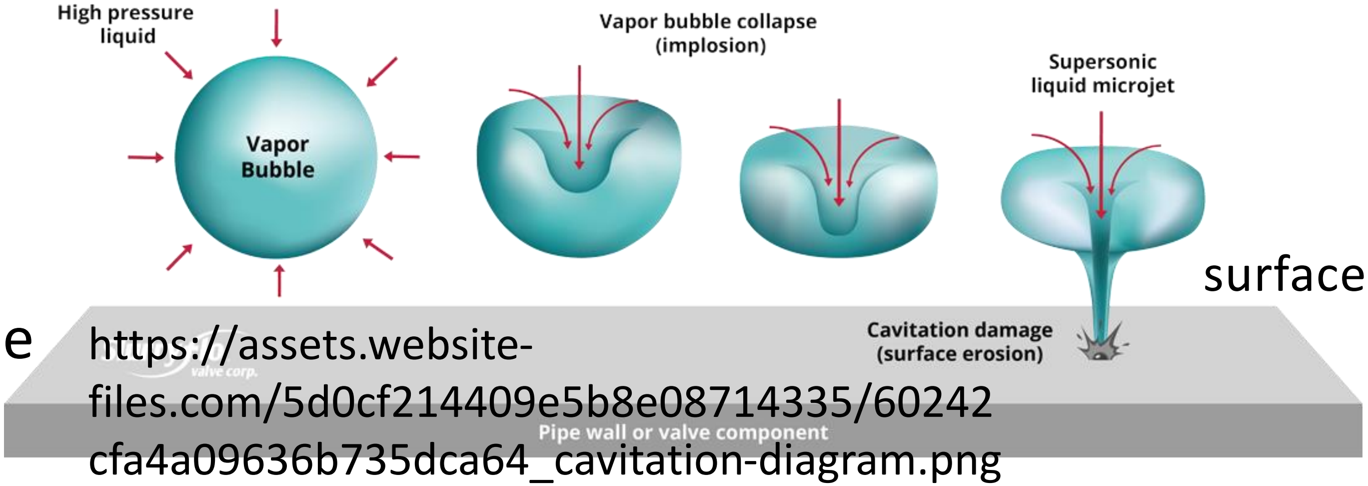
Healing: Recovery after annealing or operation at evaluated temperatures
effect enhanced by radiation due to increased diffusion coefficient

Pulsed sources

- **Fatigue** due to thermal cycles (expansion/contraction)
  → at 10 – 60 Hz pulse rate high no. cycles
  → leads to cracks above fatigue damage cycle limit (10^5-10^9)

- **Shock/pressure wave** (e.g. LHC beam dump): sharp raise of high energy pulse
  travels from the zone of highest energy deposition to the outside,
  → mechanical stress on vessel

- **Cavitation** in materials containing fluids
  Collapsing bubbles create jets which erode vessel walls → pitting
  (also known from damaged water pipes)



vessel surface

https://assets.website-files.com/5d0cf214409e5b8e08714335/60242cfa4a09636b735dca64_cavitation-diagram.png

surface erosion/ pitting

Strategies of successful High Power Targets (1)

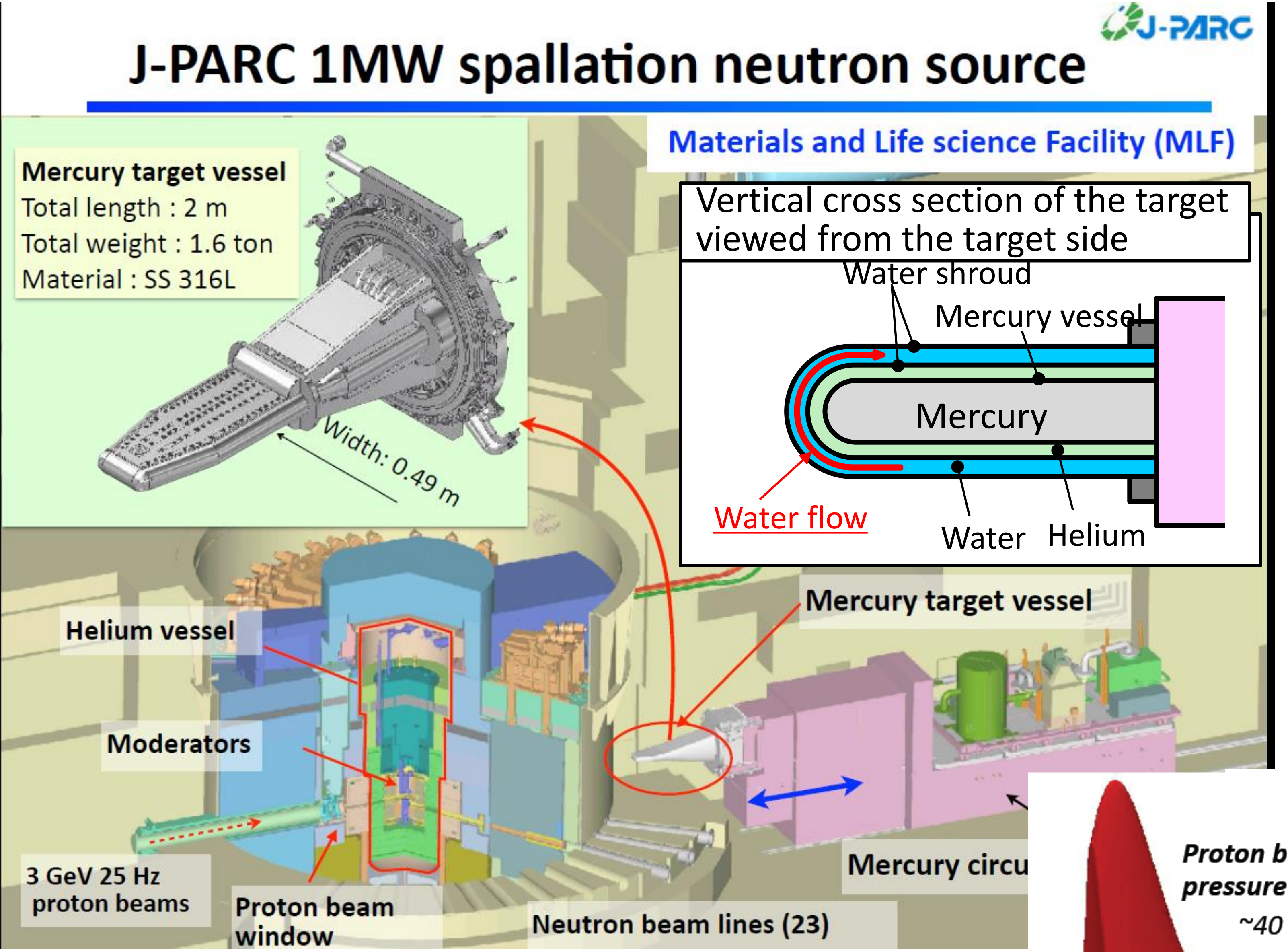
1) **Fluid material:**

- used as target material as well as for cooling
  → particular efficient:
  no dilution of effective target density

- no radiation damage ←→ no structure
  BUT: needs target container/window
  → to be exchanged regularly
  → fluid can be reused
  → reduced radioactive waste

- Difficult to handle (remotely) → usually own specialized shielded cell
  to ensure containment
  to dispose (needs solidification)
  to license (approval of the authority)

Solution: reuse!



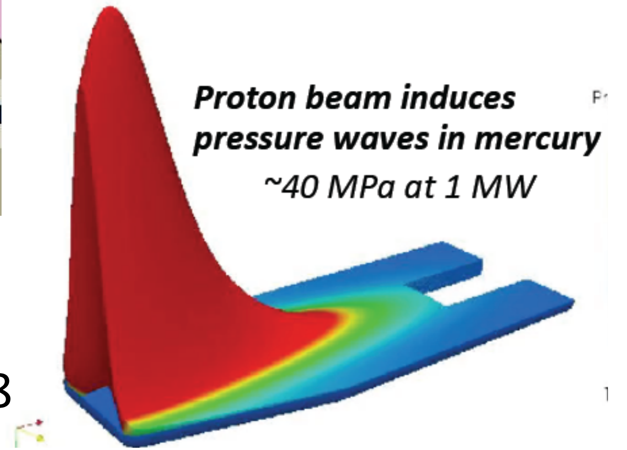
J-PARC 1MW spallation neutron source

Materials and Life science Facility (MLF)

Mercury target vessel
Total length : 2 m
Total weight : 1.6 ton
Material : SS 316L

Vertical cross section of the target viewed from the target side

Mitigation of cavitation damage



Proton beam induces pressure waves in mercury
~40 MPa at 1 MW

K. Haga HPTW2016

H. Kinoshita, HPTW2018

T. Naoe, HPTW2018

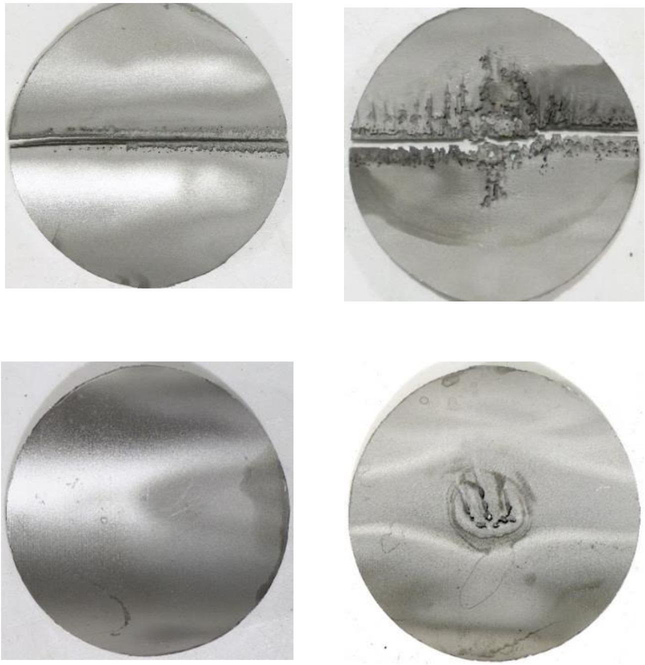
Cavitation: Mitigation by He

Post irradiation core samples indicate clear reductions in cavitation damage

SNS: TS1

Helium off:
(Target 17)

Helium on:
(Target 18)

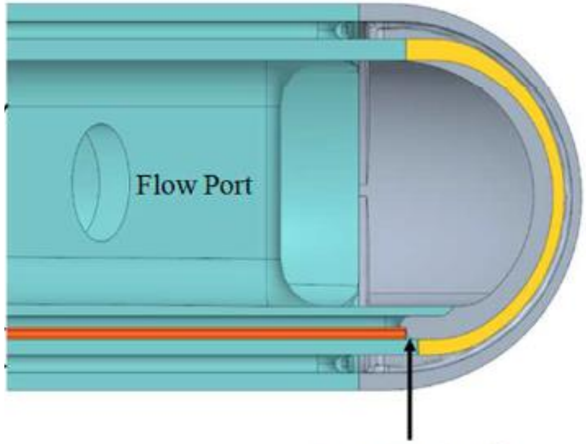


Experience from previous targets and J-PARC target operation.

Effect of gas bubbles or flow on Cavitation damage cannot be simulated yet.

B. Riemer et al, JNM 450 (2014) 183–191

B. Riemer, HPTW2018



Hg
- Jet flow →
- Window flow →

Nose Gas supply
He, up to 10 l/min

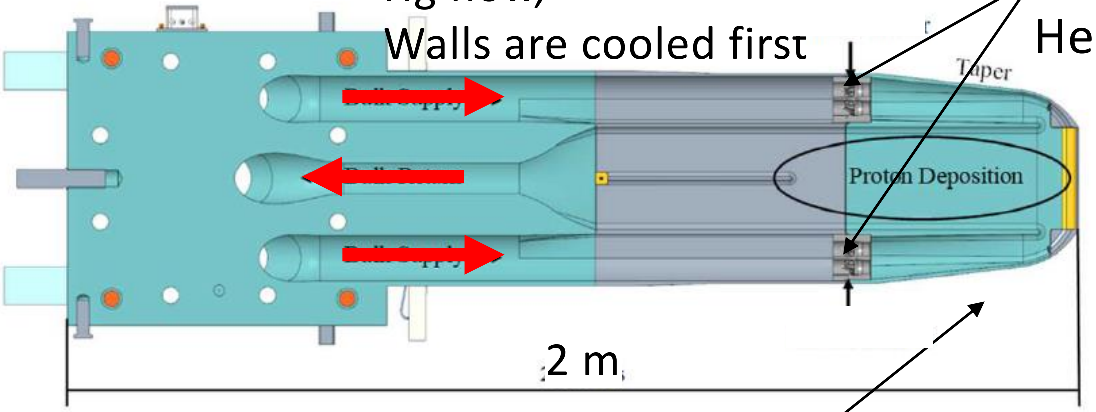
K. Johns et al., NIMA 1018, 165799 (2021)

Mercury targets in pulsed beam

SNS target (TS1):

Hg flow,
Walls are cooled first

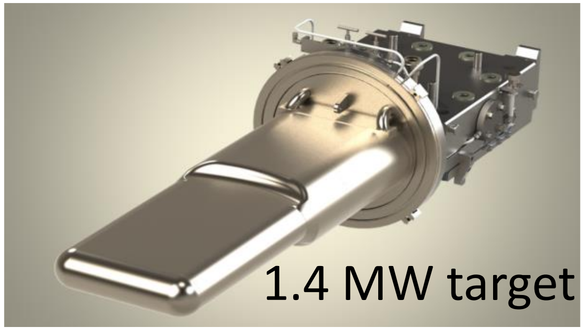
Swirl bubblers,
He, 5 l/min each

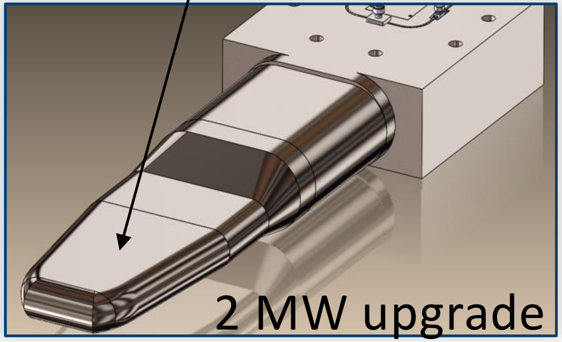


Proton beam
1.0 → 1.3 GeV
1.4 MW → 2 MW

K. Johns et al., NIMA 1018, 165799 (2021)

Tapered version: Better cooling flow


1.4 MW target


2 MW upgrade

J. Galambos, ICANS23

Strategies of successful High Power Targets (2)

2) **Segmentation** of target material

- Larger surface and surface/volume ratio
  → better, more efficient cooling
  → higher power depostion possible

<u>Disadvantage:</u>

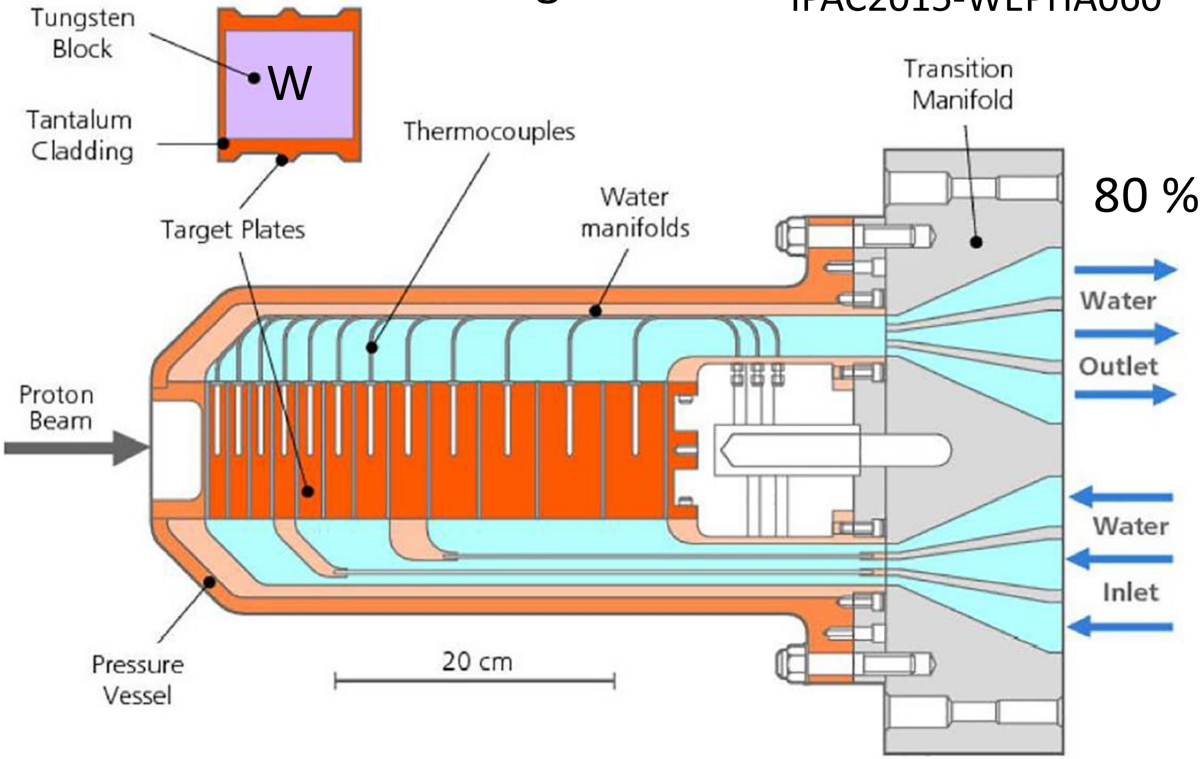
- Channels for cooling in between
  + additional space for thermal expansion
  → Dilution of target material

- Sometimes cladding required: reaction with cooling agent
  → needs good thermal contact with target material inside
  → additional stress, if thermal expansion coefficient different

Neutron spallation targets TS1 @ ISIS

C. Bungau, IPAC2015, doi:10.18429/JACoW-IPAC2015-WEPHA060

Ta-cladding



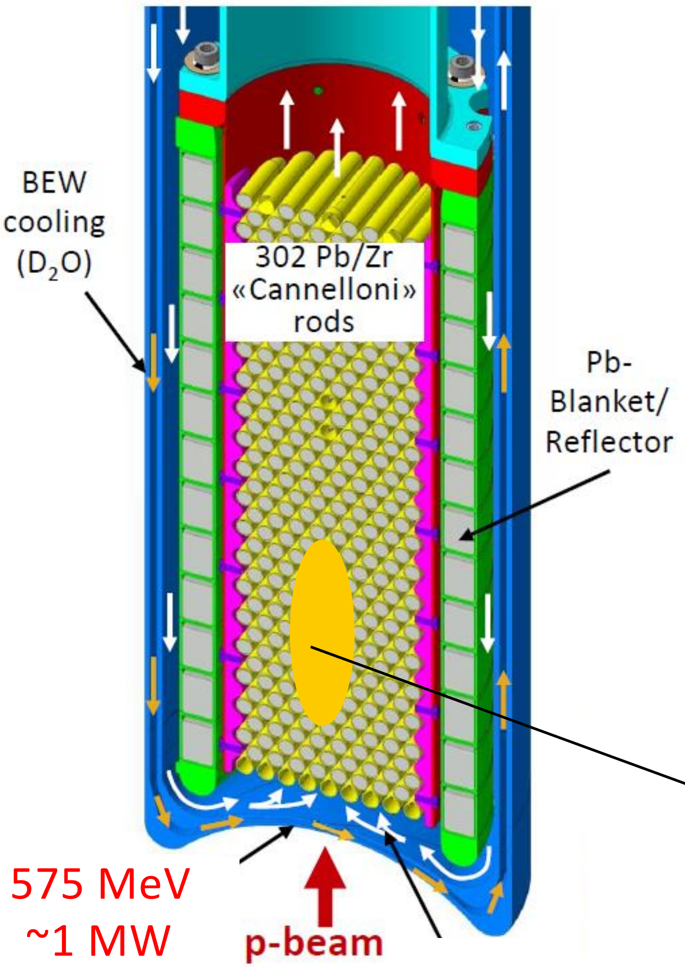
80 % D2O/20% H2O

800 MeV,
200 μA (40 Hz)
→ 0.16 MW

Similar design for TS2

- Size of W blocks according to energy deposition
- Successful operation and experience since 1984
- Plans for upgrade: 2 MW short pulse target in 2035
  → Design study: TS1 type works up to 0.4 MW
  (power limit due to thinnest plate)

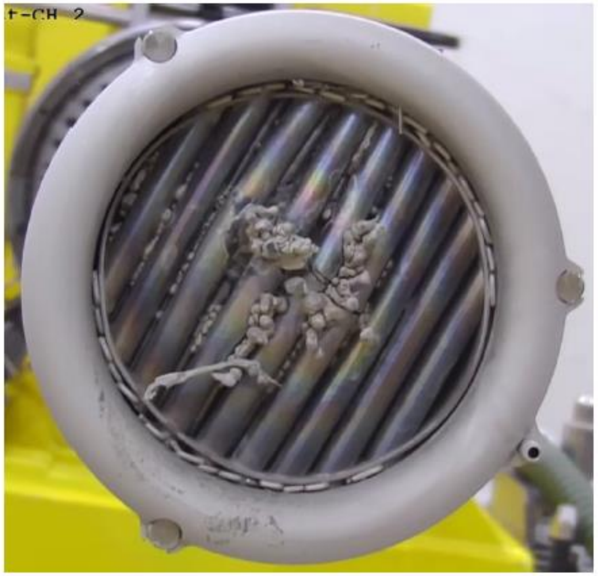
SINQ target @ PSI



- Separate cooling of window & target (D_2O)
- Double shell window → better cooling & safety

Cladding: Zr
Target: Pb
Cooling: D_2O

Melting down (2016)



ICANS XXIII, 14th October 2019, B. Blau

Improvements for safe operation:

- **Hot zone with fluid Pb** replaced by full Zr rods → 10 % less neutrons
- **Monitoring beam position & size in target** → Thermocouples in tubes and in front:
- **Improved beam instrumentation** to avoid overfocussing & missteering

Strategies of successful High Power Targets (3)

3) **Rotating targets:**

→ Distribute power on a larger area

→ Reduce power density

→ Distribute radiation damage → larger life time

Disadvantages:

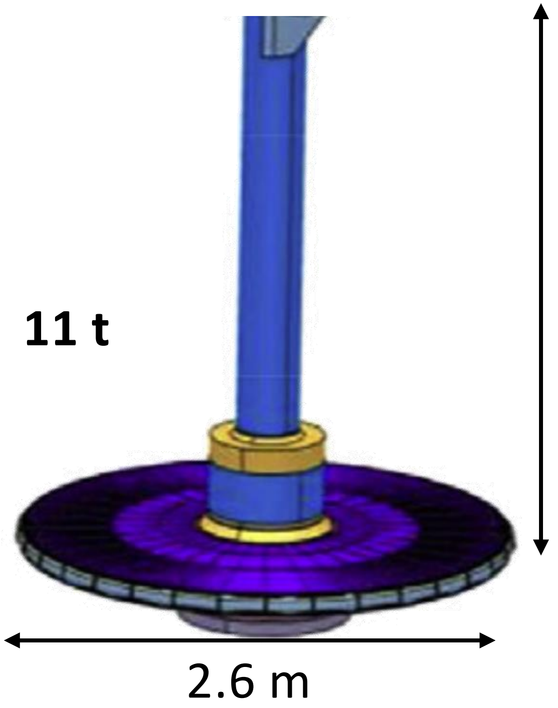
- Rotating target is much larger → more difficult to exchange
  → large(r) amount of waste & cost (fabrication & disposal)

- Bearing: often fails first
  no lubrification (grease, oil) in high irradiation area
  → (remote) procedure for exchange recommended

ESS neutron spallation target

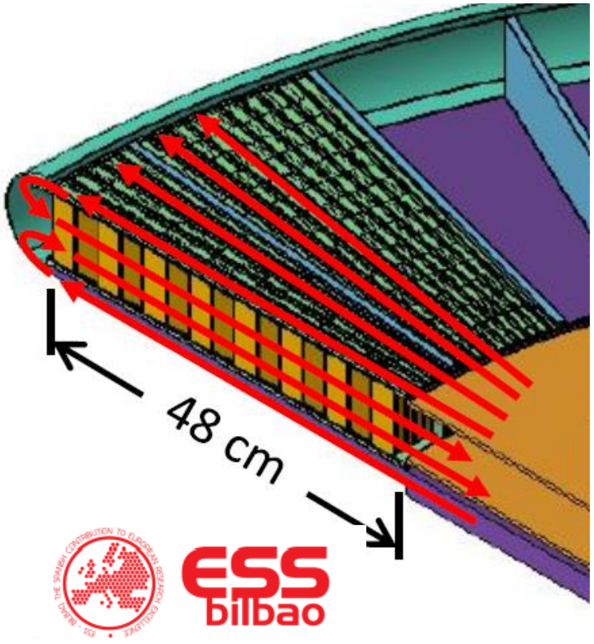
designed for 5 MW

$\Delta T = 100^{o}C$ per pulse, max. T ~$450^{o}C$



T. Shen, JNM468, 348(2016)

ESS Target: ø 2.6 m
Rot. Speed: 0.4 Hz



Weight: wheel + shaft: 11 t
He cools 7000 blocks of W
→ Segmentation for free thermal expansion

Combination of segmented & rotating target

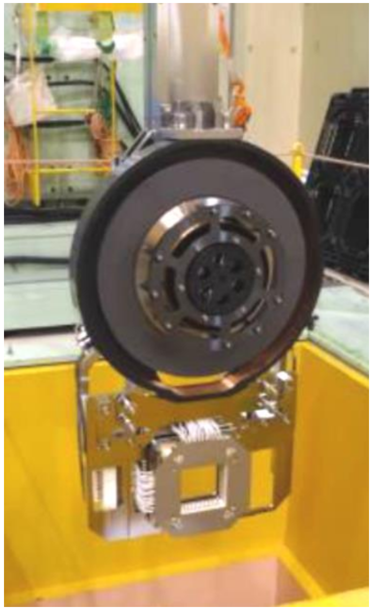
expected lifetime: 5 y

Meson production targets at J-PARC

From a fixed to a rotating target

Life time:
6 y

20 mm
effective
thickness



life time: > 30 y
operating at 940 K

S. Makimura et al.,
µSR2017 Conf.,
JPS Conf. Proc. 21,
011058 (2018)

300 kW beam power
4 kW on target

→

1 MW beam
12 kW on target

Every 700 h beam spot
had to be moved due to
radiation damage

Koyo/JTEKT, J-PARC,
expected life time:
22 y @ 390 K
WS_2 as lubricant

Rotating targets also require reliable, long lasting bearings

Meson production target E at HIPA (PSI)

Power deposition: ~ 50 kW on Target E

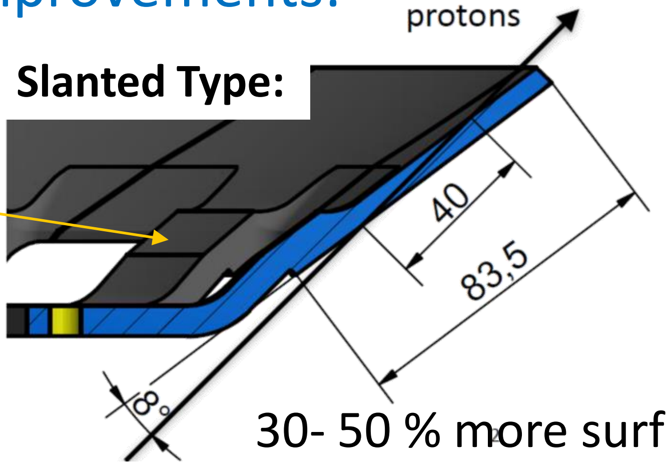
at 2.4 mA, 590 MeV, 1.4 MW protons

Approach:

- Polycrystalline graphite → isotropic properties
- Hollow spokes & Slits for thermal expansion,
  hollow to avoid high temperature at bearing
- Cooling by thermal radiation:
  - independent of conductivity (radiation damage!
  - requires large emissivity & temperature

Improvements:

Slanted Type:

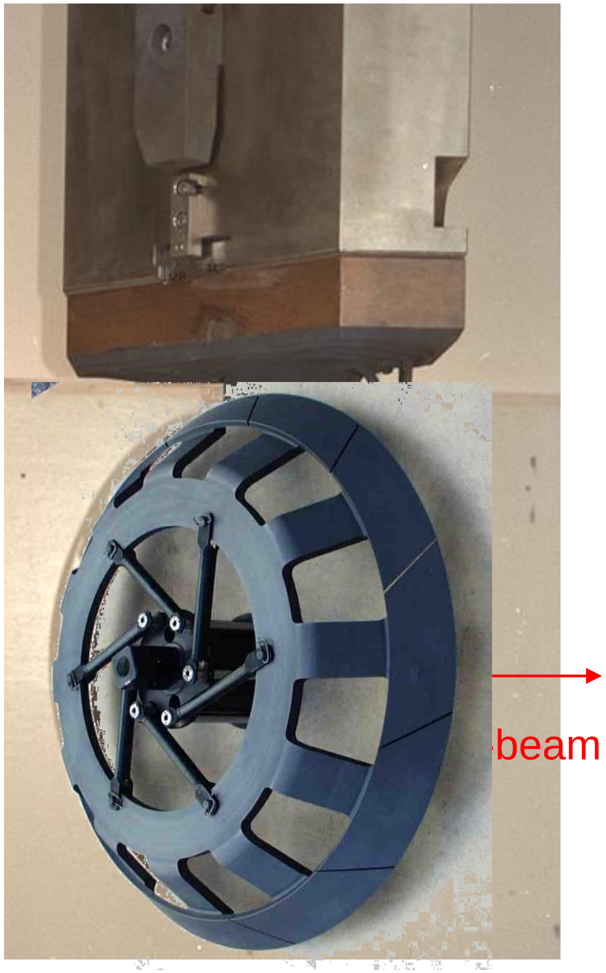


Cu cooled by water

Bearings can be exchanged in service cell

30- 50 % more surface muons

Target E



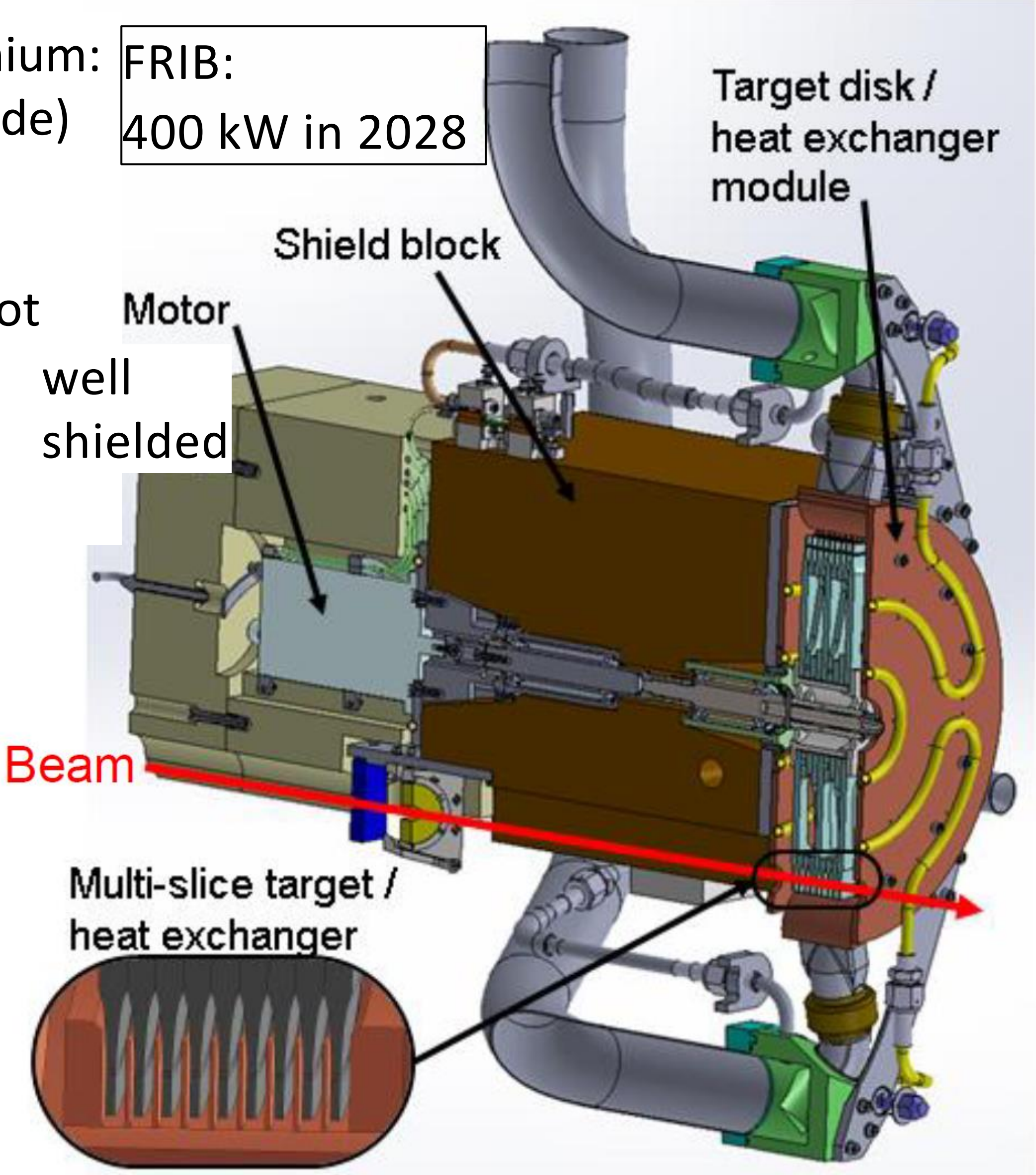
1700 K, 1 Hz

FRIB: Production target for radioisotopes

- Primary beam from Oxygen to Uranium: 200 MeV/u (400 MeV/u after upgrade)
- Graphite wheel, 5000 rpm
- Thickness: mm to 5 cm
- up to 100 kW absorbed on 1mm spot
- multi-slice target
- cooled thermal radiation and by Cu jacket → max. 1900°C

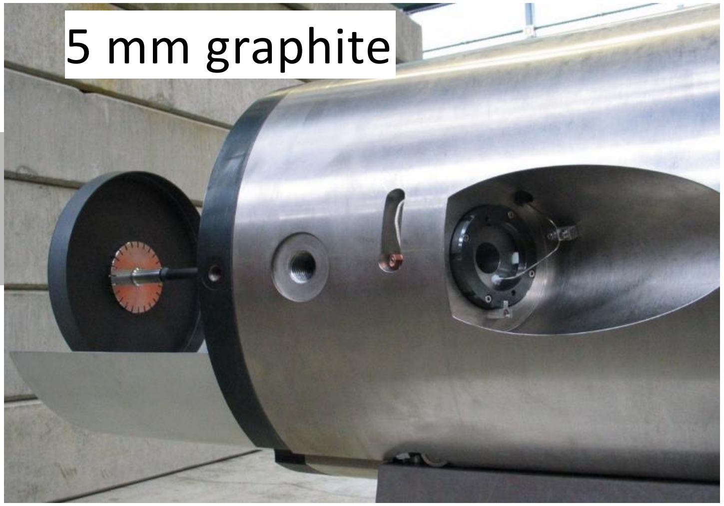
FRIB:
400 kW in 2028

well shielded

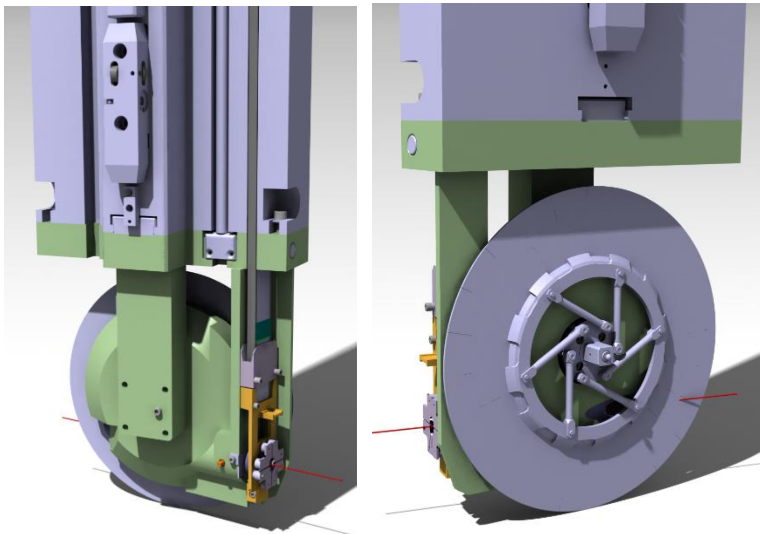


D. Georgobiani, HPTW2018

Upgrade of TgM to TgH: IMPACT-HIMB @ PSI

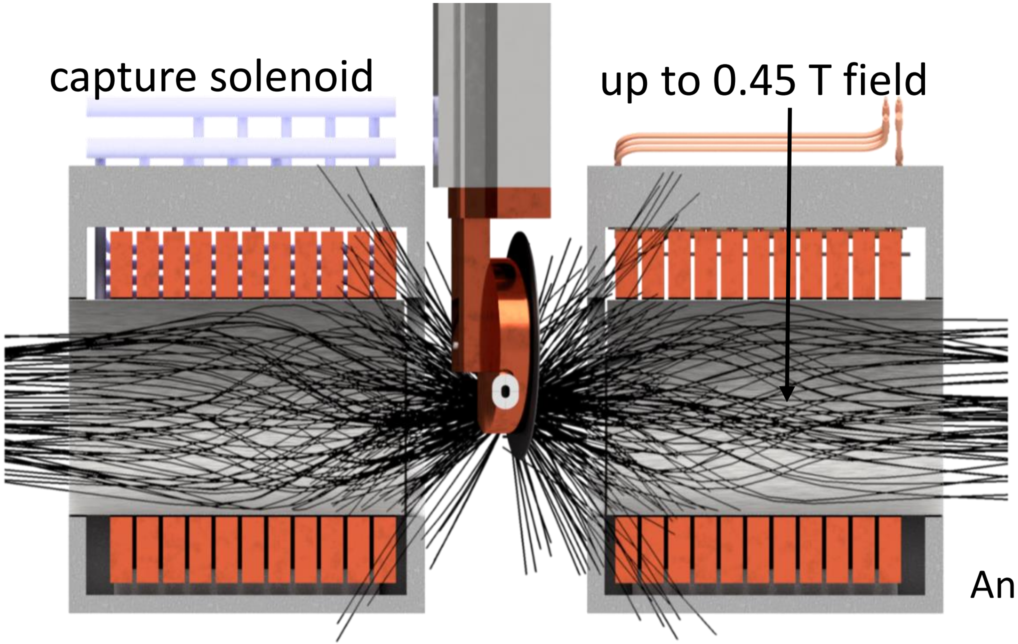


Planned for → 2027/28



20 mm Target E like target

HIMB = High-Intensity Muon Beams



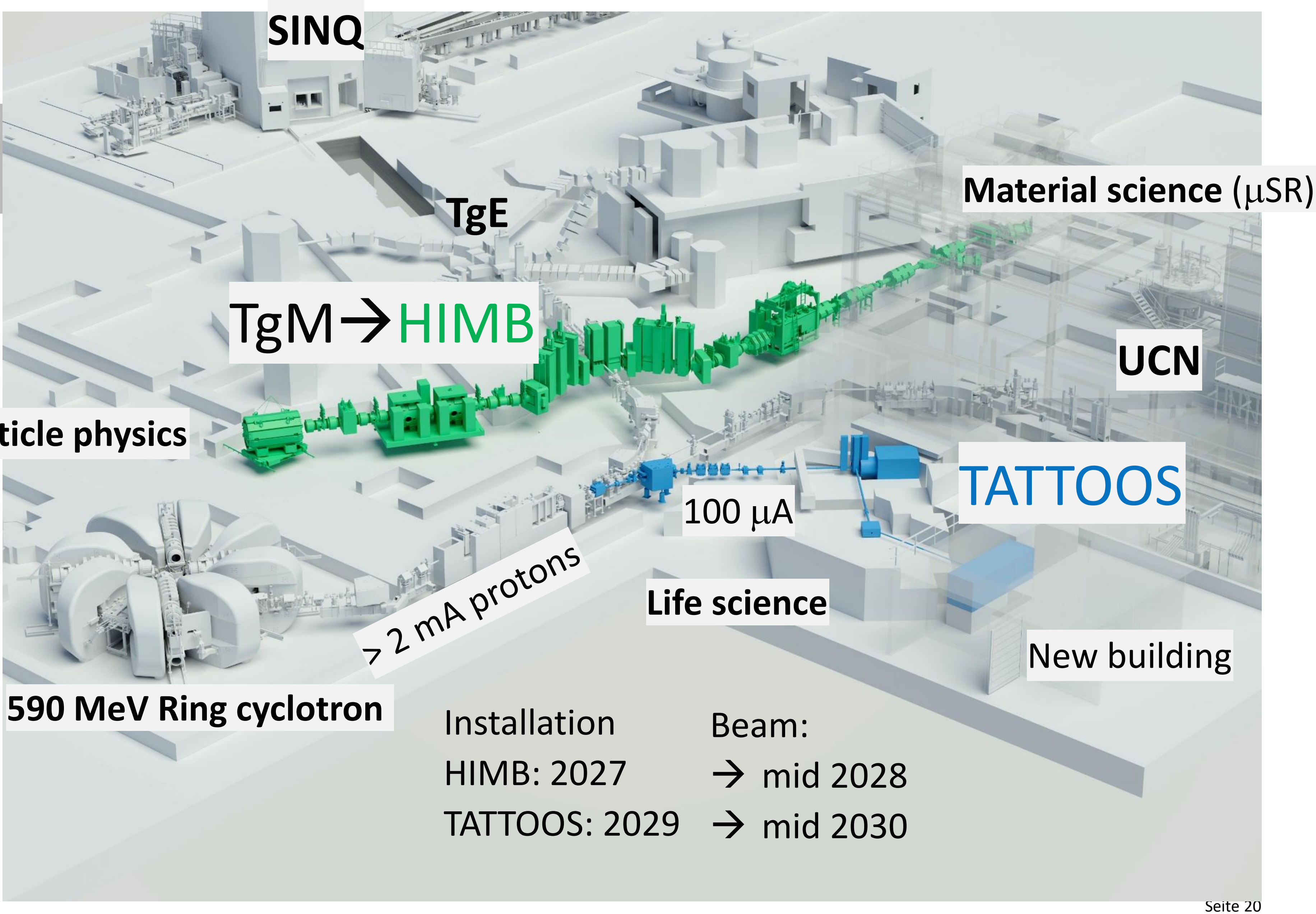
10^{10} <u>surface muons/s</u>

for particle physics & material science

- Capture solenoid:
- Close distance to the target (+/- 250 mm)
- X 100 increase in surface muons

Andreas Knecht, PSI

HIPA with IMPACT (= HIMB & TATTOOS)



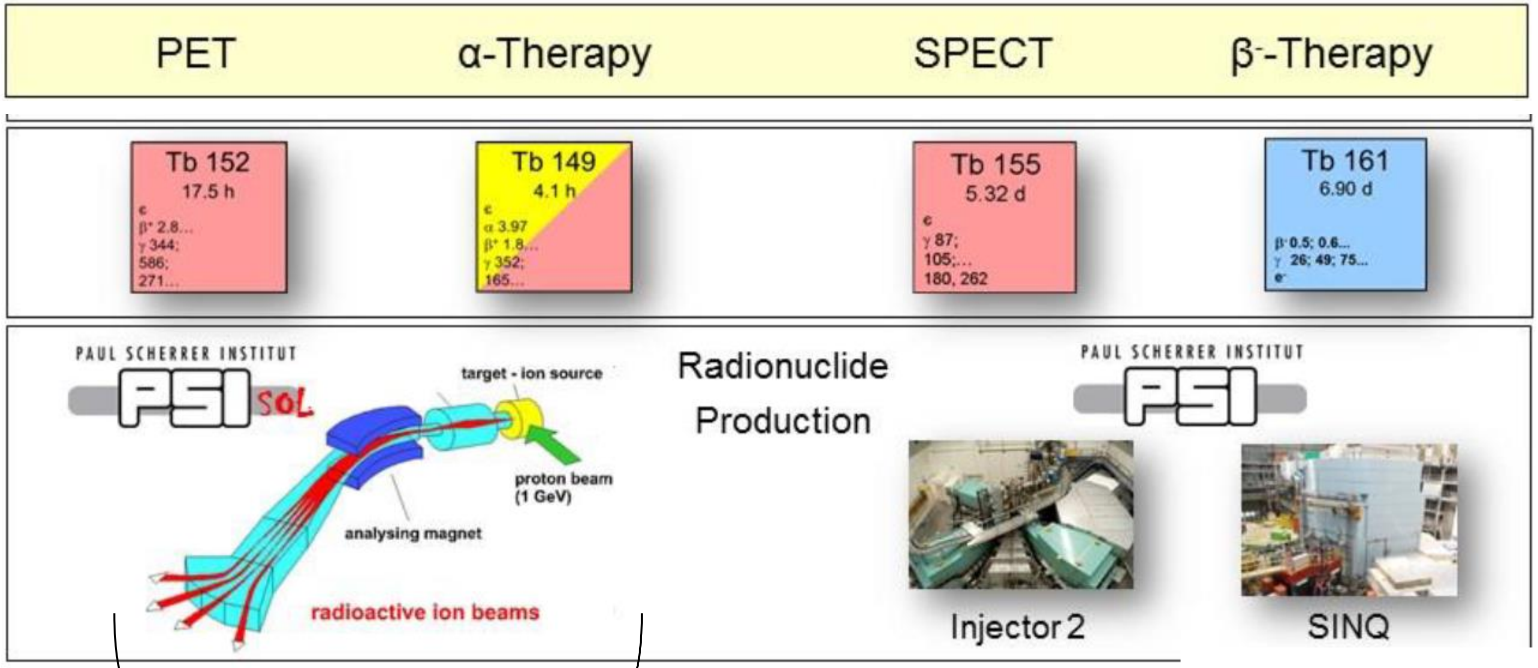
Installation	Beam:
HIMB: 2027	→ mid 2028
TATTOOS: 2029	→ mid 2030

TATTOOS: Targeted Alpha Tumour Therapy and Other Oncological Solutions

Life science:

Producing enough radioisotopes with 590 MeV p (100 μA)

- for cancer treatment & diagnostics (theragnostics) in quantities needed for clinical studies on human beings
- research only, no commercial production planned.



TATTOOS

590 MeV protons on Ta

IP2 (72 MeV)

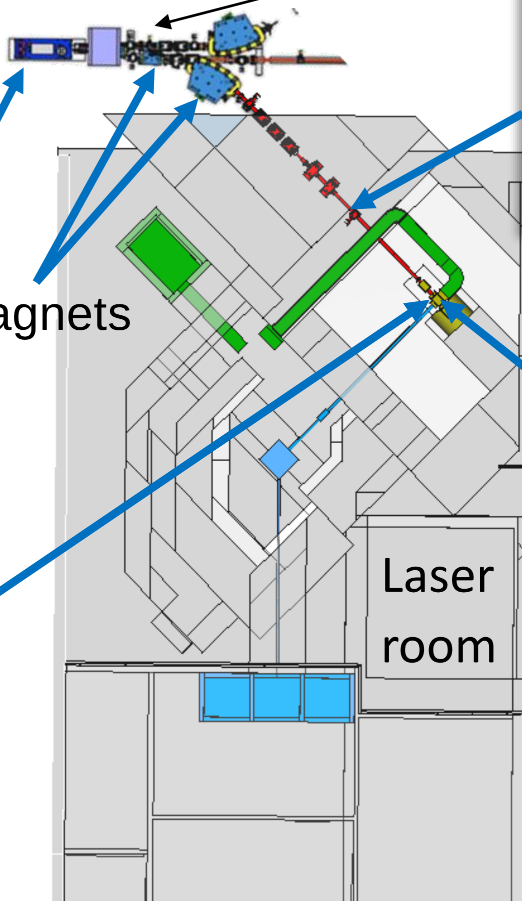
^{155}Gd target

$^{160}\mathrm{Gd}(n,\gamma)^{161}\mathrm{Gd} \rightarrow {}^{161}\mathrm{Tb}$

TATTOOS target station

Poster: J. Snuverink M-protection
M. Hartmann: beam simulation

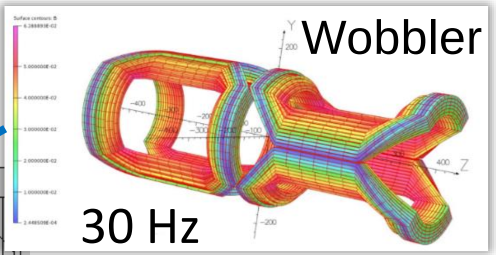
proton beam



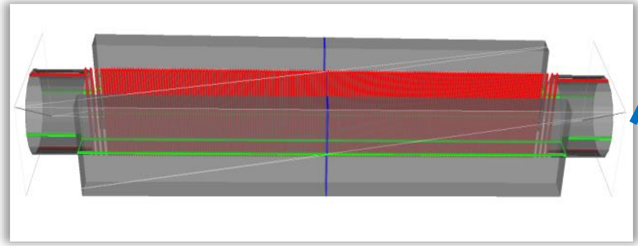
Magnets

Wobbler

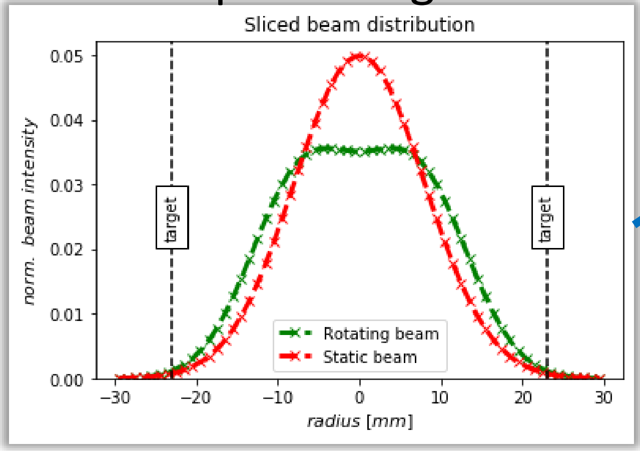
30 Hz



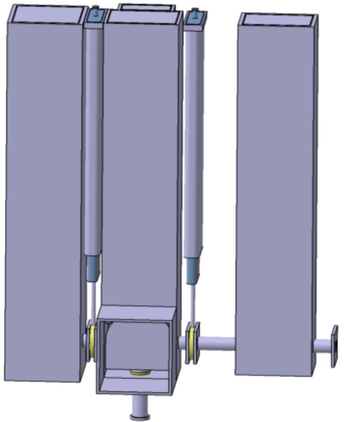
Beam splitter for 100 μA 590 MeV p



Beam shape on target



Vacuum chambers



insert can be pulled
by exchange flask

Target: 10 cm Ta

A challenge to cool the 100 μA proton beam, ~ 26 kW on target

Operation temperature: ~ 2000 – 2800 °C

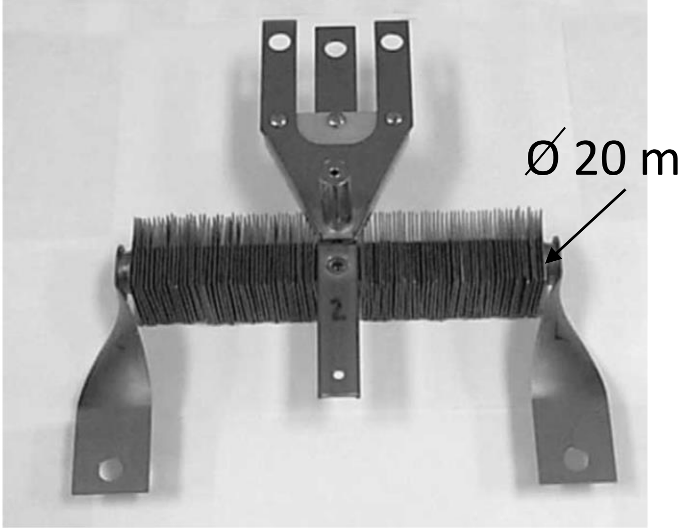
→ required for good diffusion of the radioisotopes out of the target

Experience from ISAC-TRIUMF

Operation temperature: ~ 2000 °C → Cooling by thermal radiation

TRIUMF High Power Target

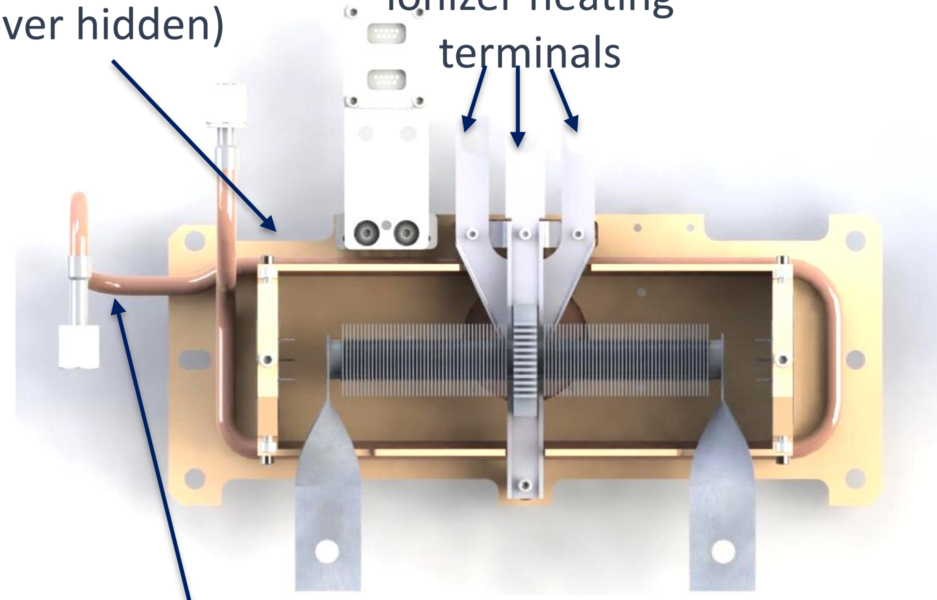
Target for 500 MeV, 100 μA,
= 25 kW in target



Ø 20 mm

90 fins (55 x 55 mm) increase effective emissivity from 0.35 to 0.92

Bricault et al, NIM B204, 319 (2003)



heat shield
(cover hidden)

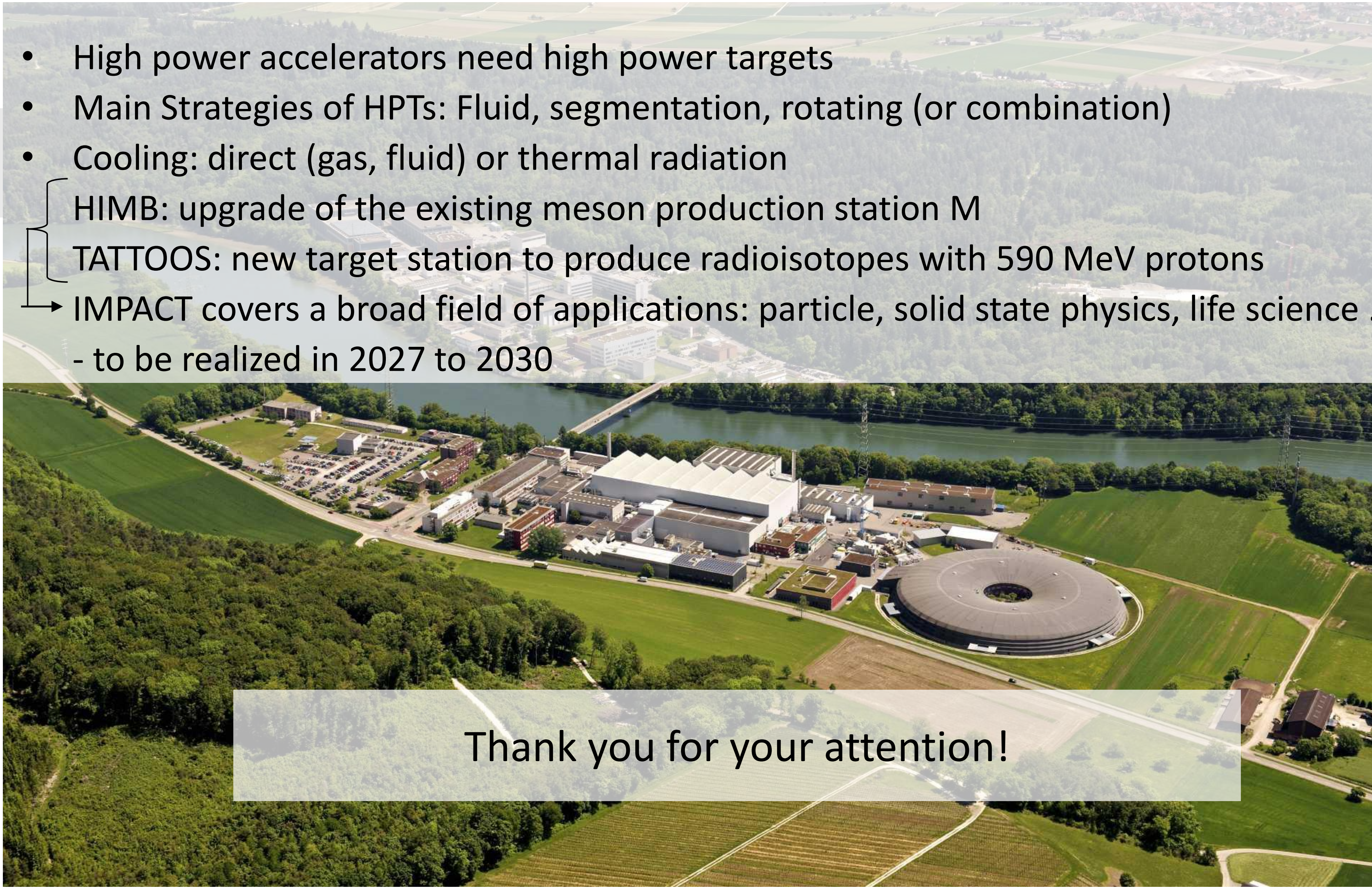
ionizer heating
terminals

cooling-water
supply

A. Gottberg, INTDS2022 @PSI

ISOLDE@CERN: > 50 years experience. model for all later radionuclei production

Summary



- High power accelerators need high power targets
- Main Strategies of HPTs: Fluid, segmentation, rotating (or combination)
- Cooling: direct (gas, fluid) or thermal radiation

HIMB: upgrade of the existing meson production station M
TATTOOS: new target station to produce radioisotopes with 590 MeV protons
→ IMPACT covers a broad field of applications: particle, solid state physics, life science
- to be realized in 2027 to 2030

Thank you for your attention!