Daniela Kiselev :: 8100 :: Paul Scherrer Institut

High-Power Targetry and the IMPACT Initiative @ PSI

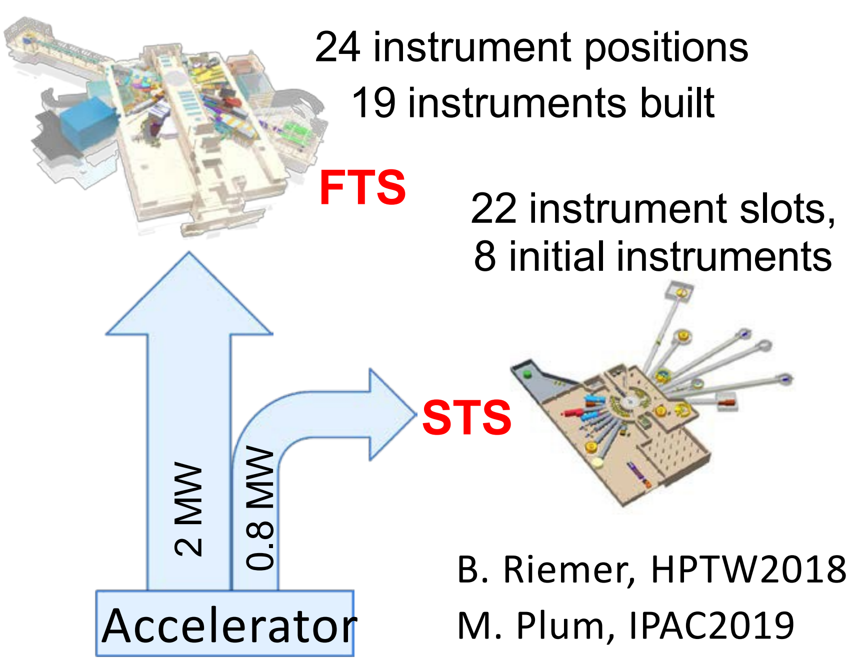
HB2023 workshop, CERN, 9-13.10.2023

The need for high power targets

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

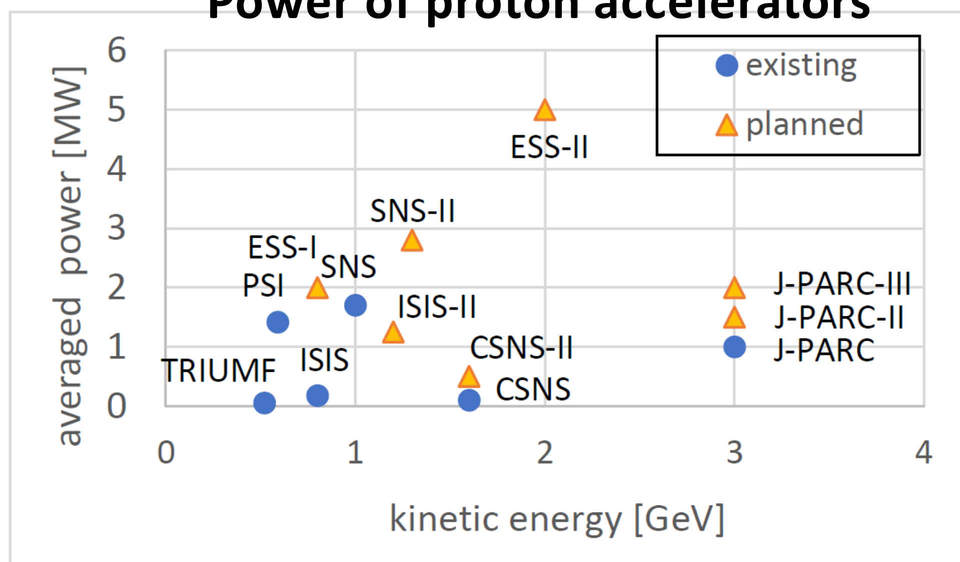
- Feasible due to faster detectors (segmented), electronics, DAQ/computers
  → processing of larger rate

- driven by: More powerful accelerators



B. Riemer, HPTW2018
M. Plum, IPAC2019

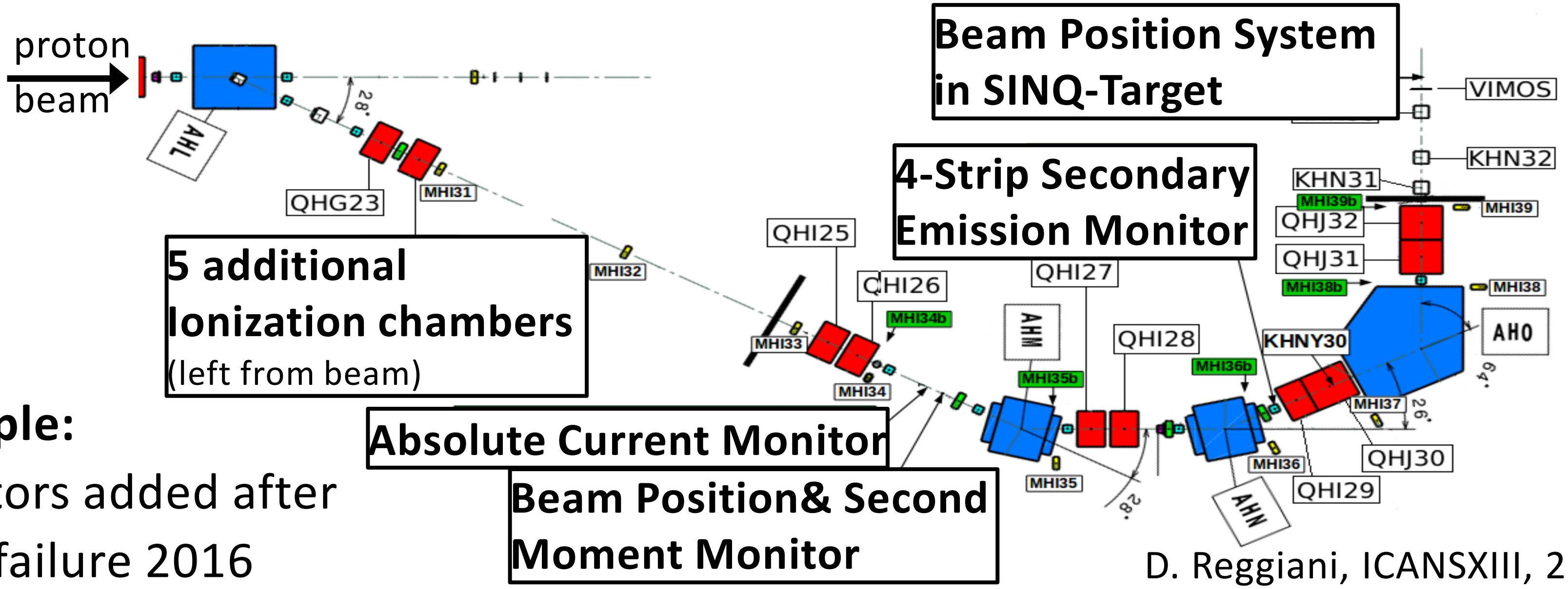
Power of proton accelerators



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

Challenges on the accelerator side

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



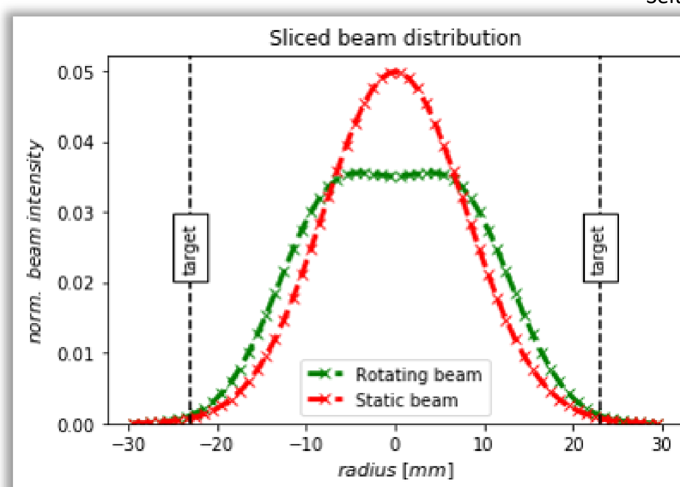
Example:
Monitors added after SINQ failure 2016

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

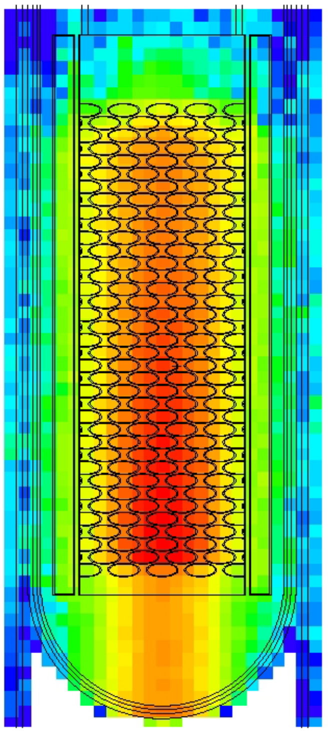
(Many) Challenges on the target side

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

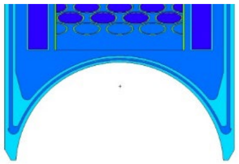
- **Replacement/repairing/disposal** of the target:
  very high dose (~ several Sv/h)
  → remote handling in a shielded cell,
  special tools

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

SINQ:
energy deposition



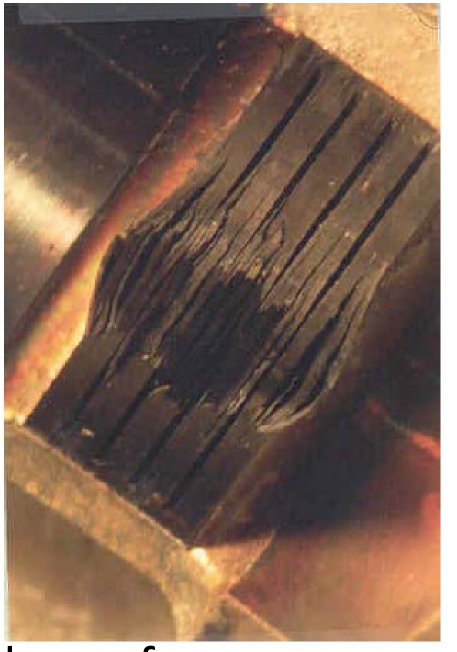
New window



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

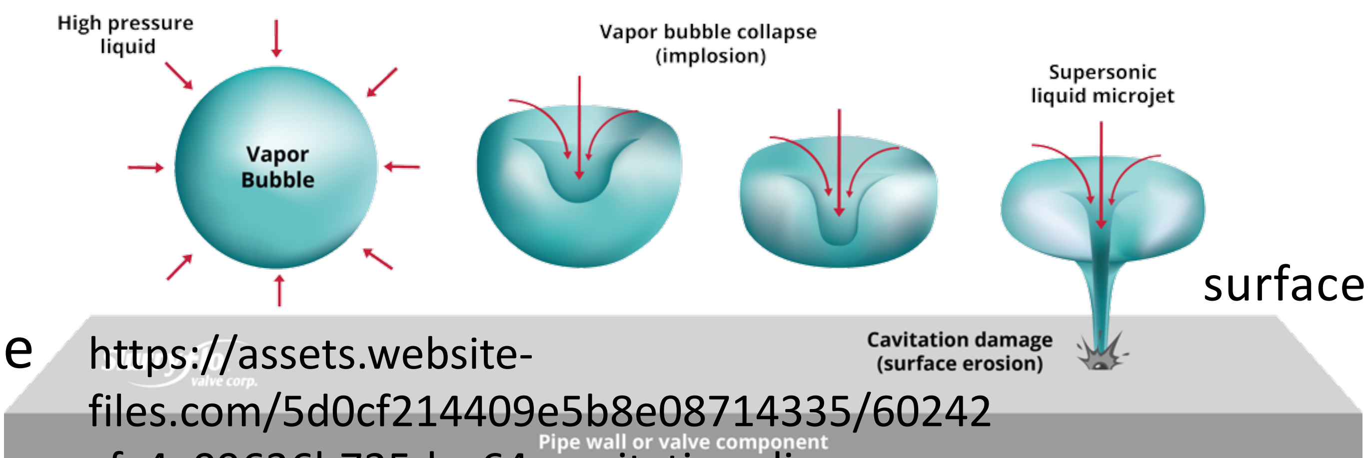
Pulsed sources

- **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



surface erosion/ pitting

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

PAUL SCHERRER INSTITUT PSI

Strategies of successful High Power Targets (1)

1) **Fluid material:**

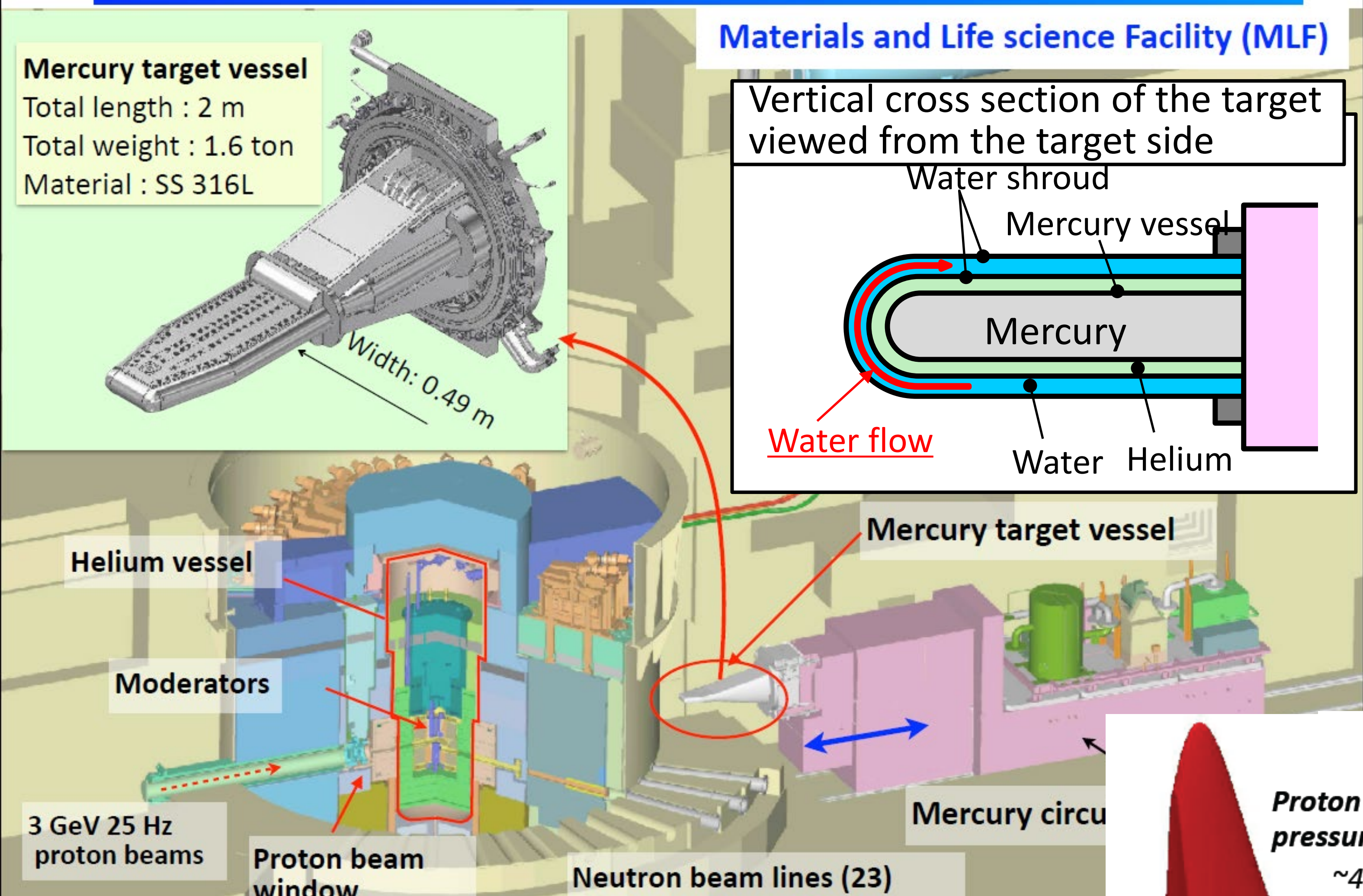
- used as target material as well as for cooling
  → particular efficient:
  no dilution of effective target density

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

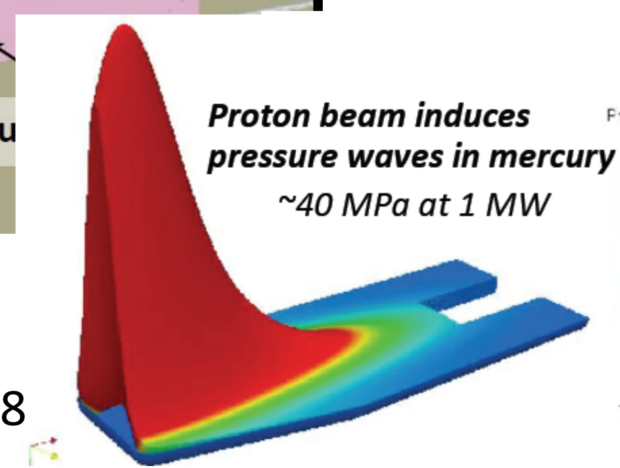
- Difficult to handle (remotely) → usually own specialized shielded cell
  to ensure containment
  to dispose (needs solidification)
  to license (approval of the authority)

Solution: reuse!

J-PARC 1MW spallation neutron source



Mitigation of cavitation damage



K. Haga HPTW2016

H. Kinoshita, HPTW2018

T. Naoe, HPTW2018

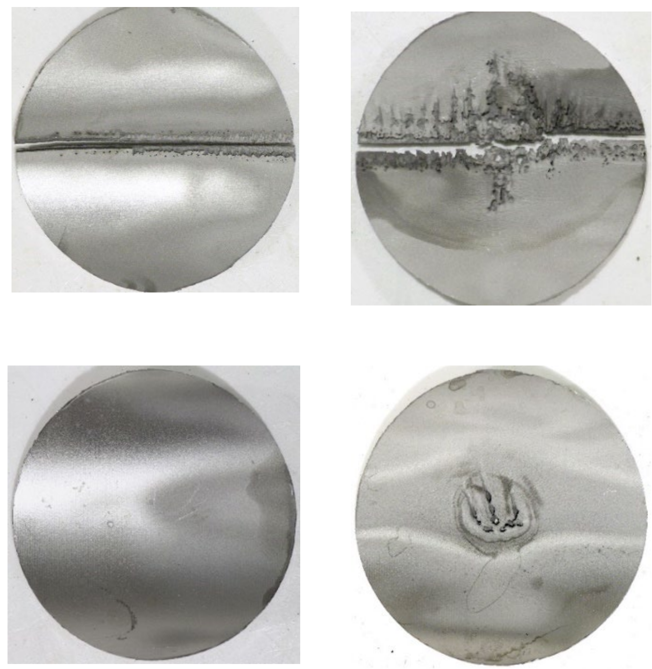
Cavitation: Mitigation by He

Post irradiation core samples indicate clear reductions in cavitation damage

SNS: TS1

Helium off:
(Target 17)

Helium on:
(Target 18)

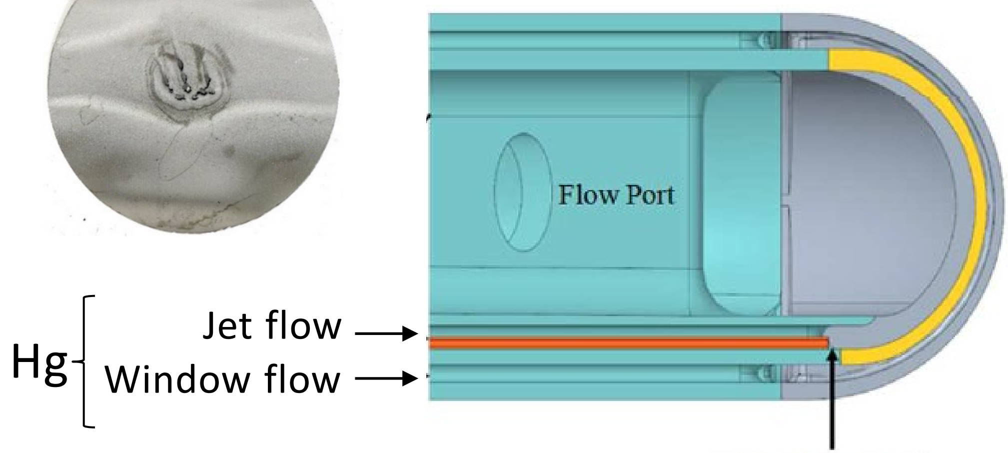


Experience from previous targets and J-PARC target operation.

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



Nose Gas supply
He, up to 10 l/min

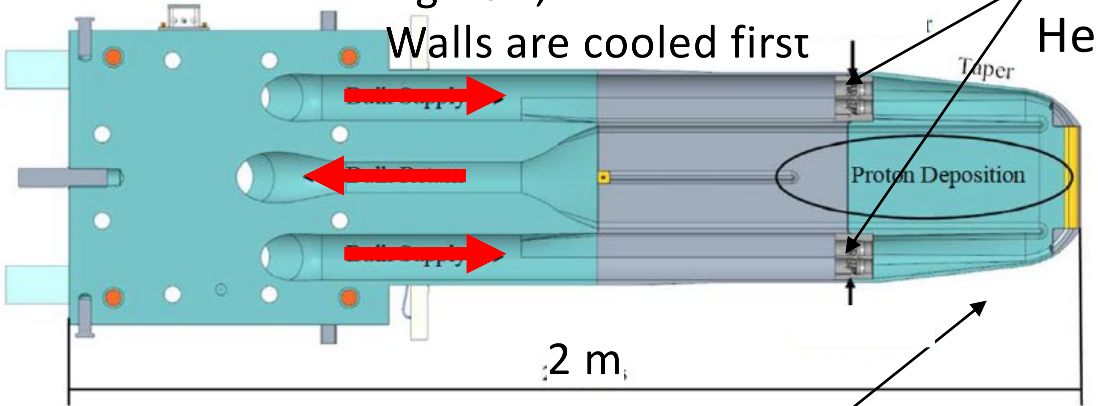
K. Johns et al., NIMA 1018, 165799 (2021)

Mercury targets in pulsed beam

SNS target (TS1):

Hg flow,
Walls are cooled first

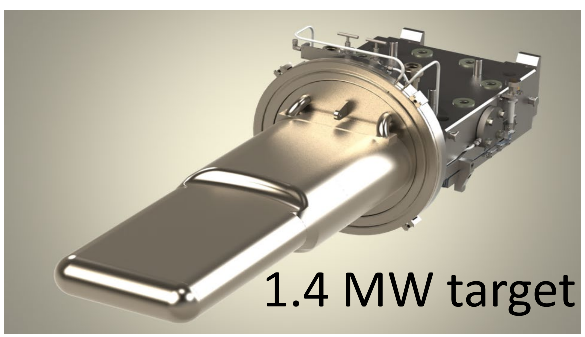
Swirl bubblers,
He, 5 l/min each

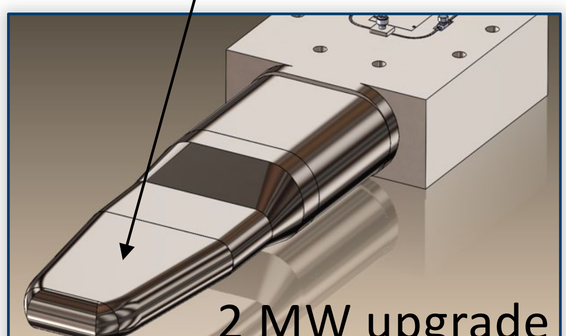


Proton beam
1.0 → 1.3 GeV
1.4 MW → 2 MW

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

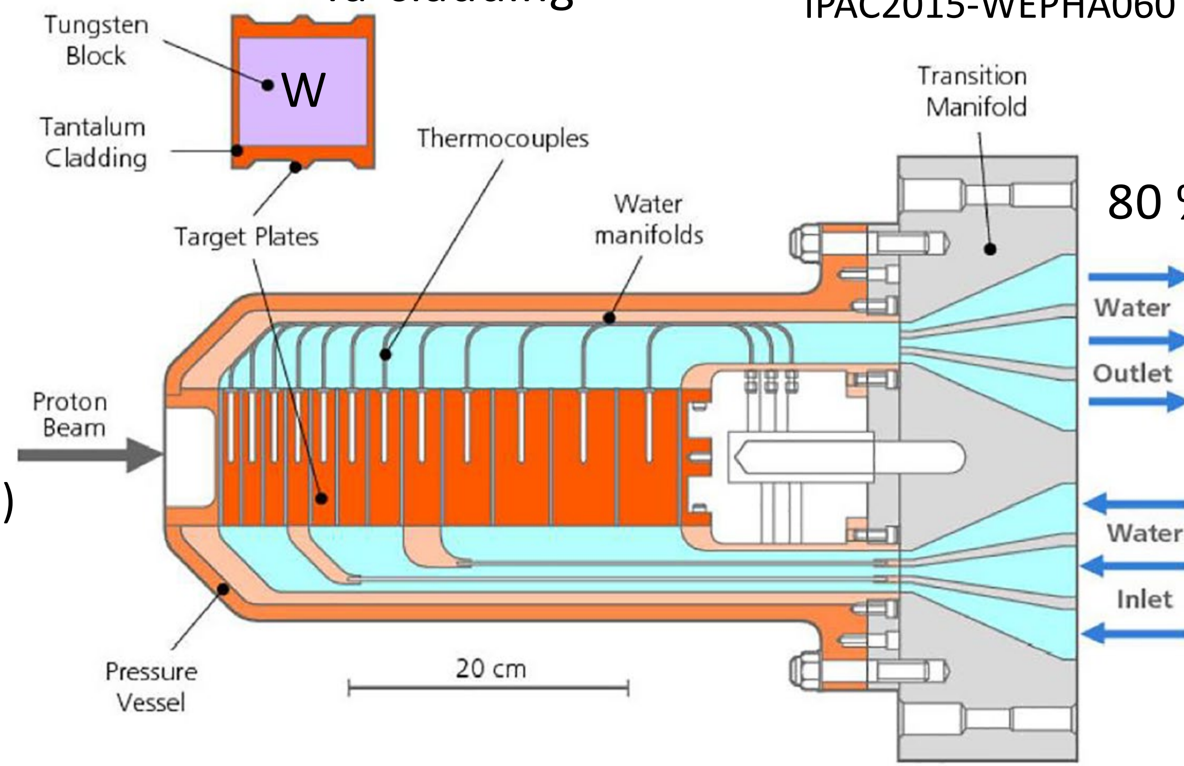
Neutron spallation targets TS1 @ ISIS

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

Ta-cladding

80 % D2O/20% H2O

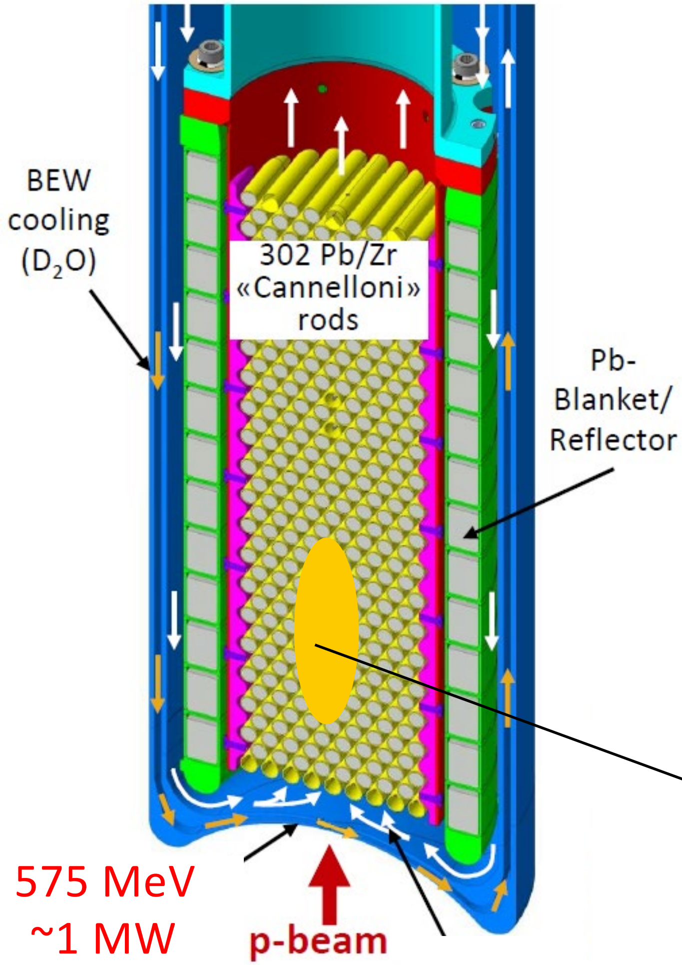
800 MeV,
200 μA (40 Hz)
→ 0.16 MW



Similar design for TS2

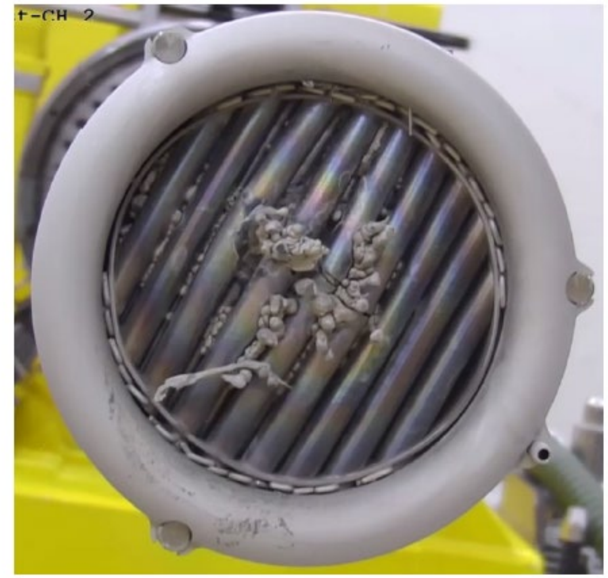
- Size of W blocks according to energy deposition
- Successful operation and experience since 1984
- Plans for upgrade: 2 MW short pulse target in 2035
  → Design study: TS1 type works up to 0.4 MW
  (power limit due to thinnest plate)

SINQ target @ PSI



Cladding: Zr
Target: Pb
Cooling: D_2O

Melting down (2016)



ICANS XXIII, 14th October 2019, B. Blau

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

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

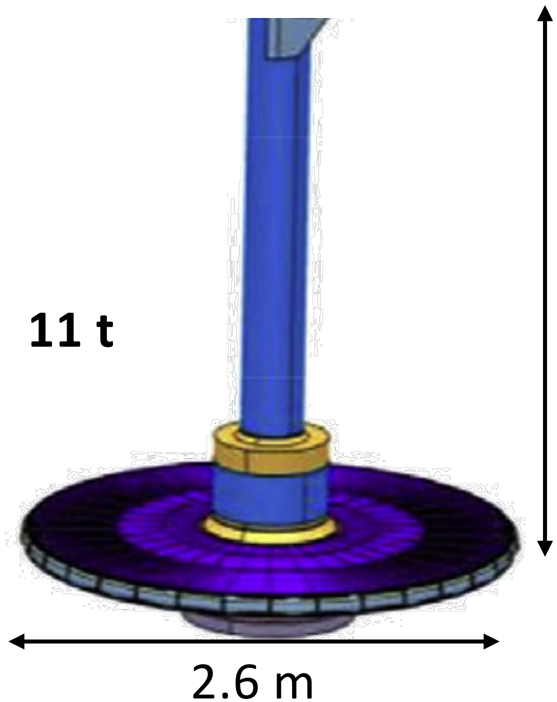
→ Distribute radiation damage → larger life time

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



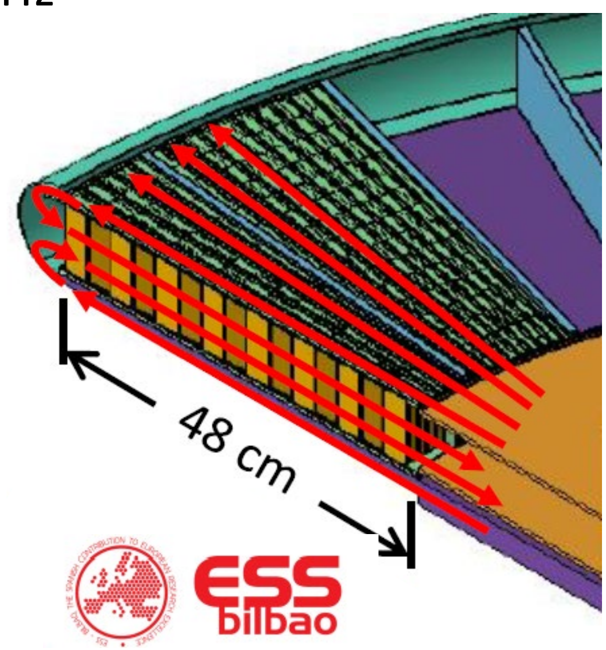
5 m

designed for 5 MW

ΔT = 100°C per pulse, max. T ~450°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

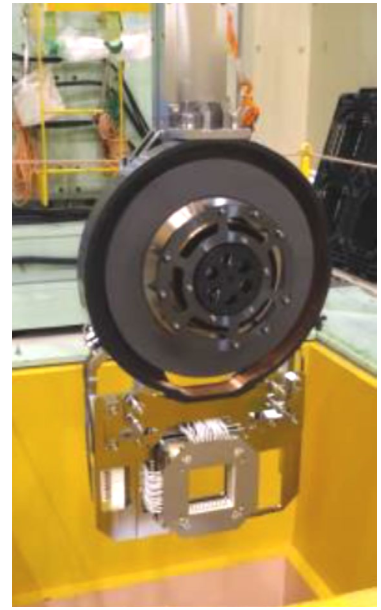
expected lifetime: 5 y

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

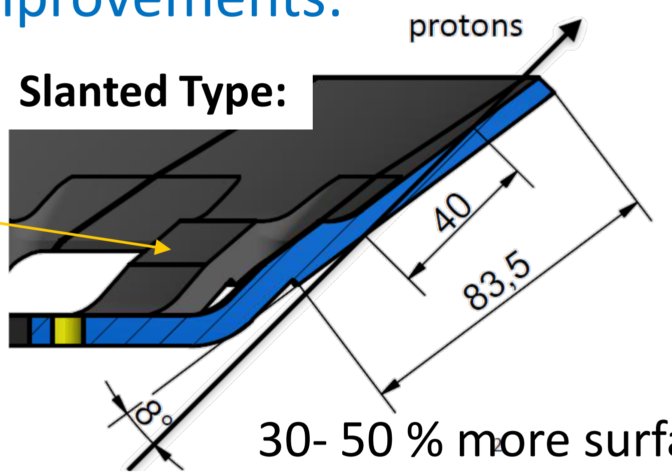
Approach:

- 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:

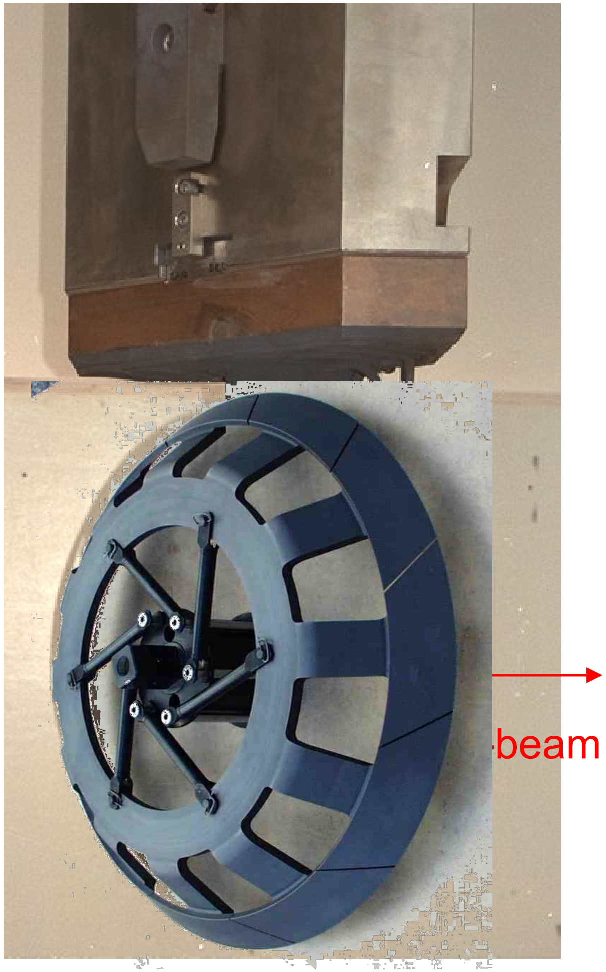
Cu cooled by water



Bearings can be exchanged in service cell

30- 50 % more surface muons

Target E



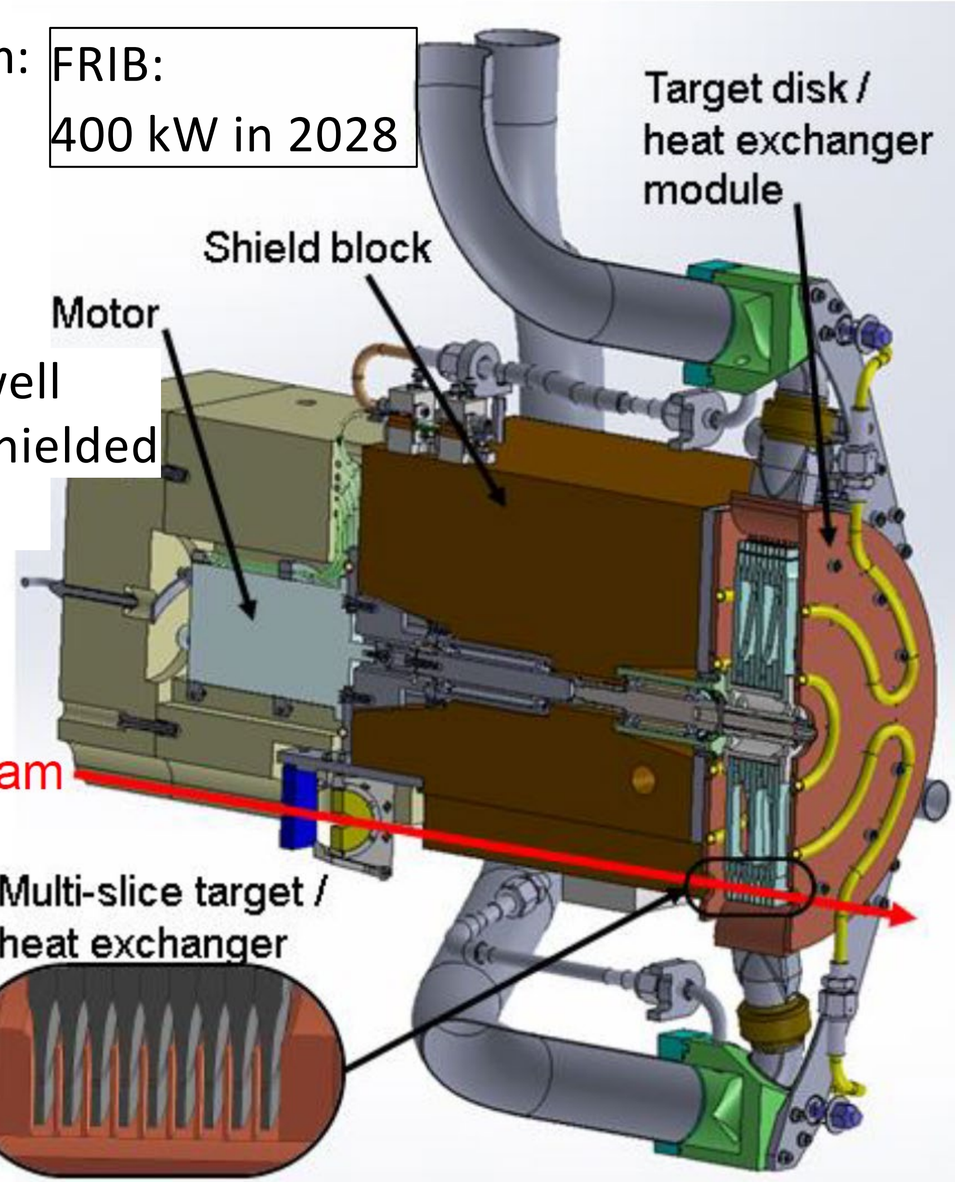
1700 K, 1 Hz

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

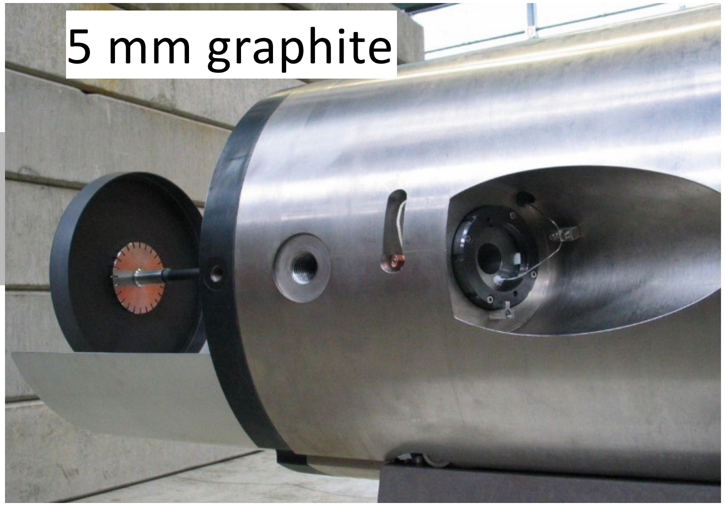
FRIB:
400 kW in 2028

well shielded

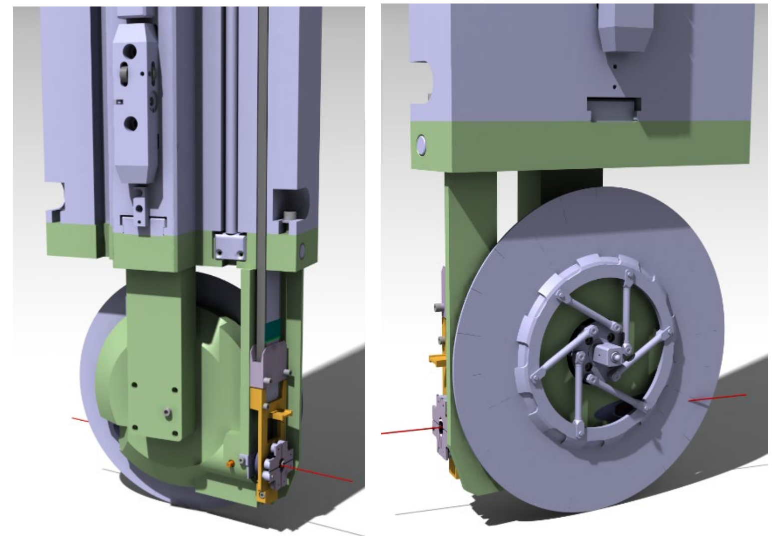


D. Georgobiani, HPTW2018

Upgrade of TgM to TgH: IMPACT-HIMB @ PSI

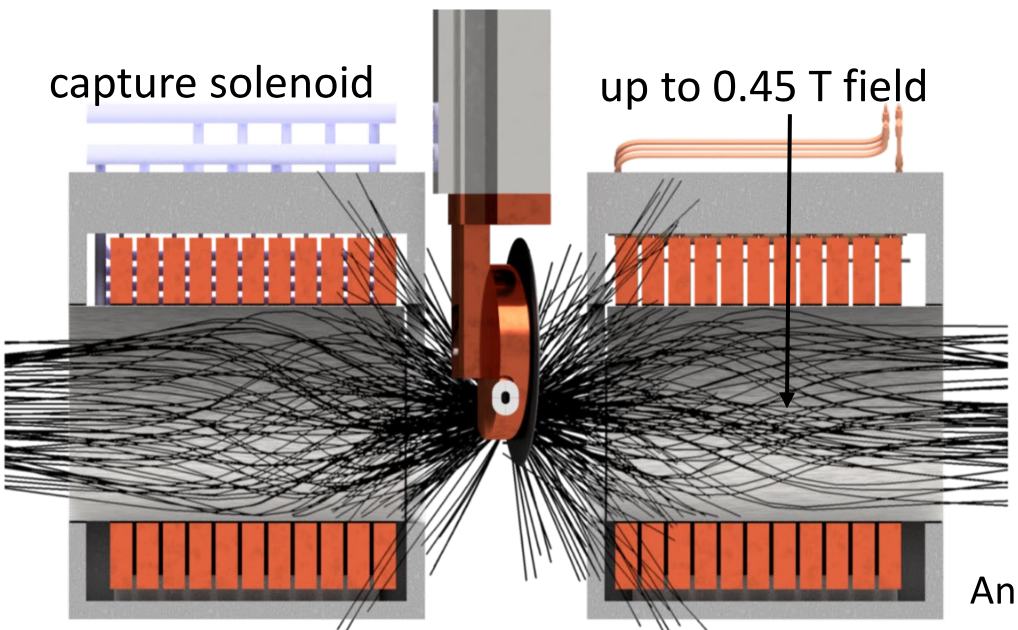


Planned for 2027/28 →



20 mm Target E like target

HIMB = High-Intensity Muon Beams



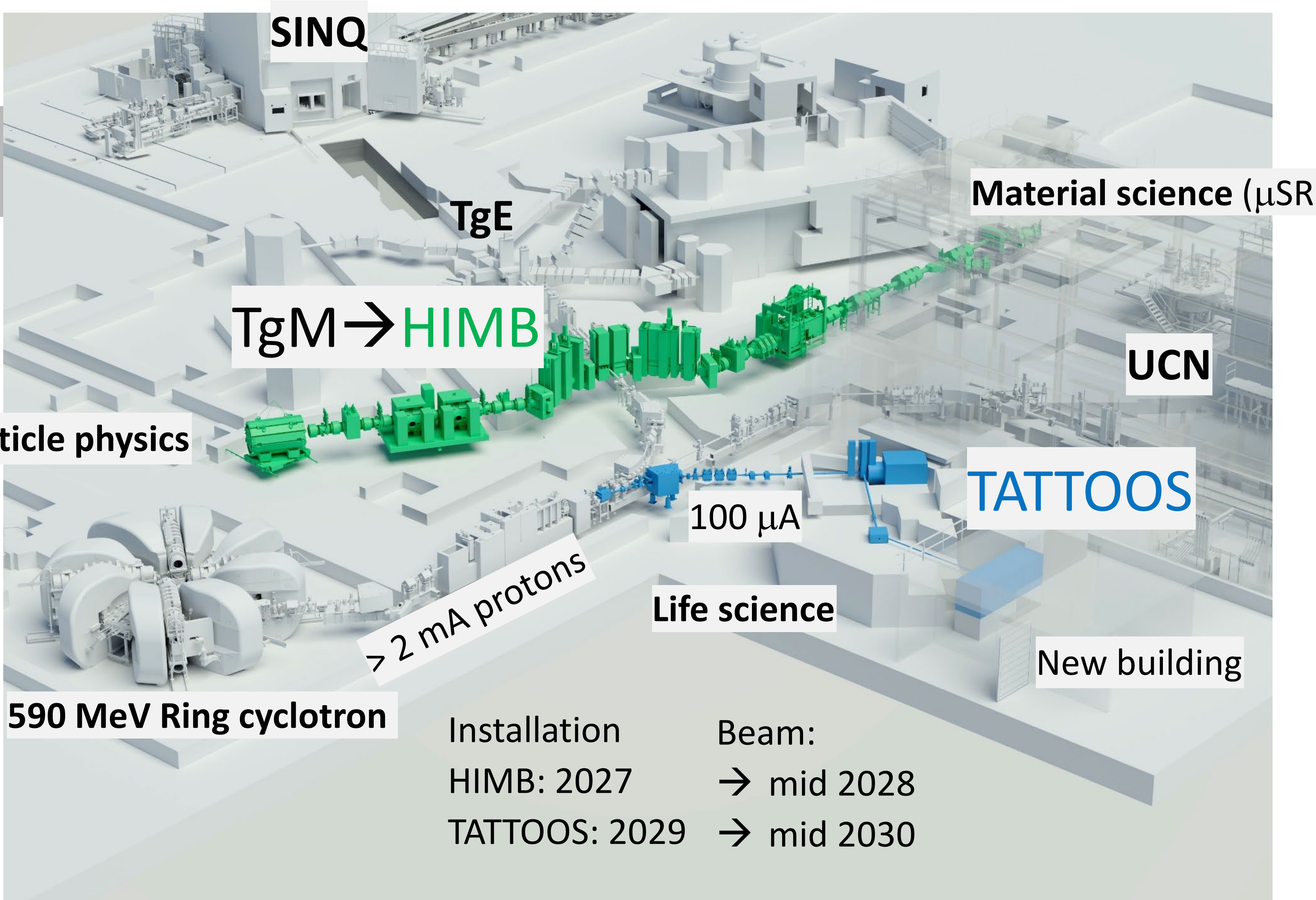
10^{10} surface muons/s

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)



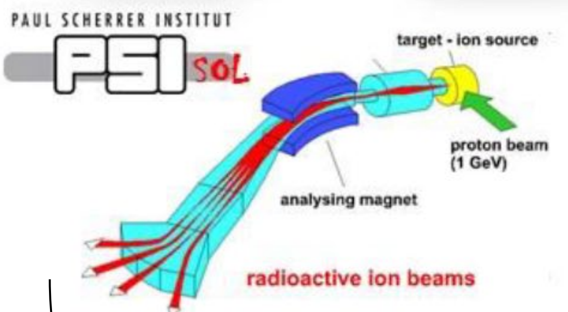
TATTOOS: Targeted Alpha Tumour Therapy and Other Oncological Solutions

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.

PET	α-Therapy	SPECT	β^--Therapy
Tb 152 17.5 h ε β^+ 2.8... γ 344; 586; 271...	Tb 149 4.1 h ε α 3.97 β^+ 1.8... γ 352; 165...	Tb 155 5.32 d ε γ 87; 105;... 180, 262	Tb 161 6.90 d β^- 0.5; 0.6... γ 26; 49; 75... e^-



Radionuclide Production

Injector 2

SINQ

TATTOOS
590 MeV protons on Ta

IP2 (72 MeV)
^{155}Gd target

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

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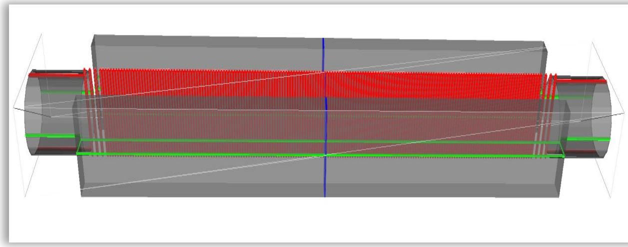
TATTOOS target station

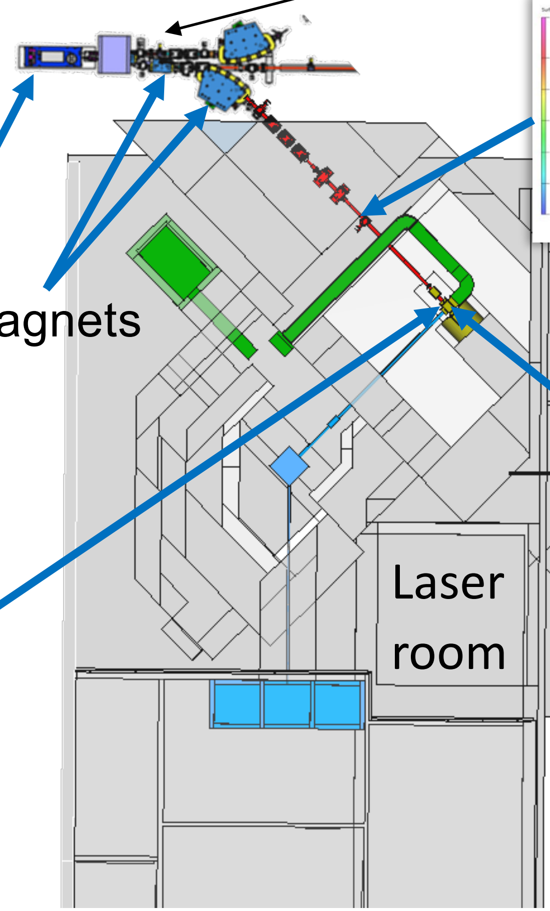
Poster: J. Snuverink M-protection
M. Hartmann: beam simulation

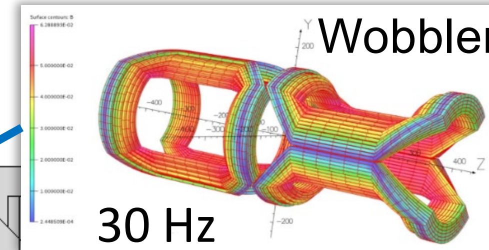
proton beam

Beam splitter for 100 µA 590 MeV p



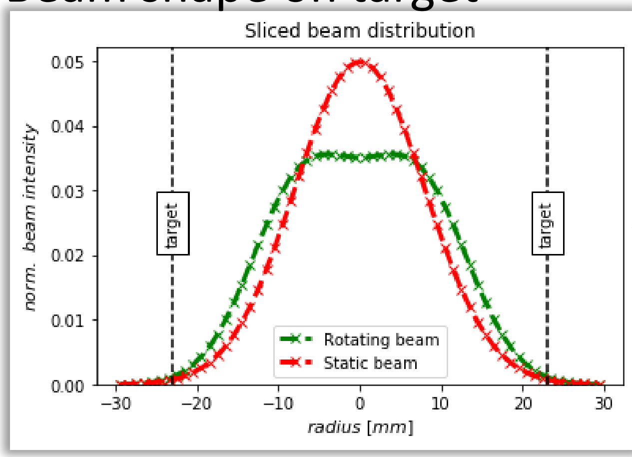
Magnets

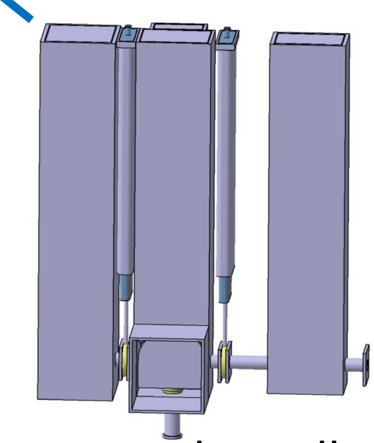




Vacuum chambers

Beam shape on target





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

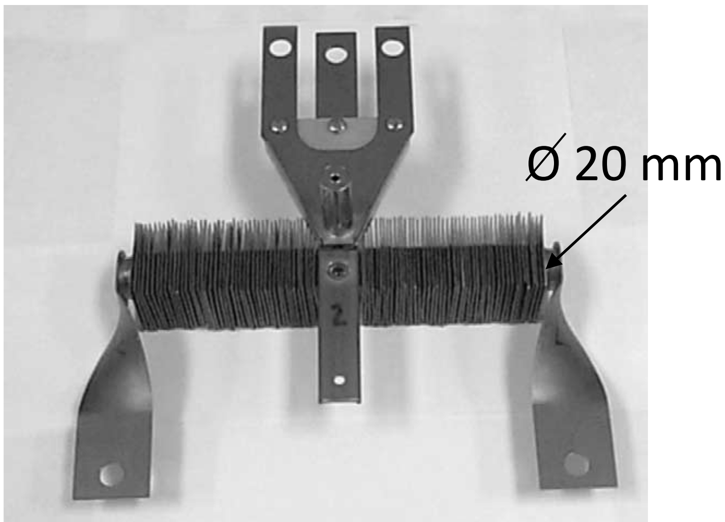
Experience from ISAC-TRIUMF

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

TRIUMF High Power Target

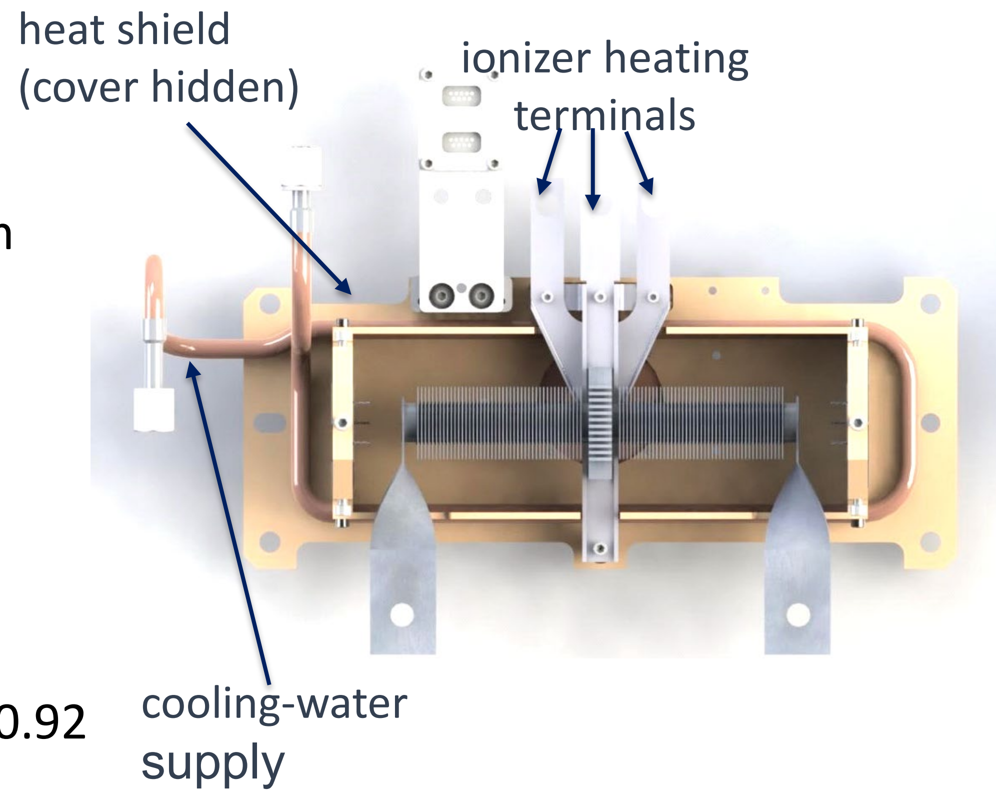
Target for 500 MeV, 100 μA,

= 25 kW in target



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

Bricault et al, NIM B204, 319 (2003)



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!