Beam Loss Simulations for the Proposed TATTOOS Beamline at HIPA

HB 2023 workshop

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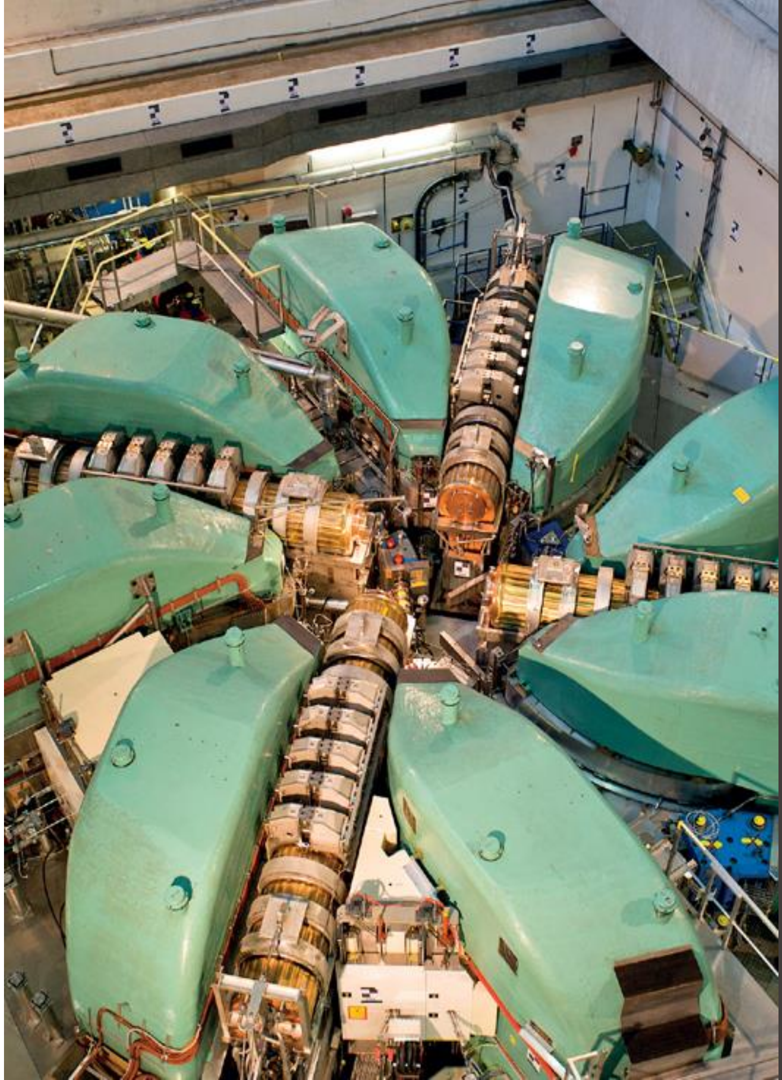
11th October, 2023



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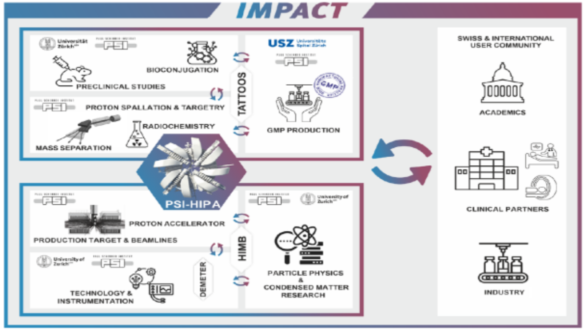
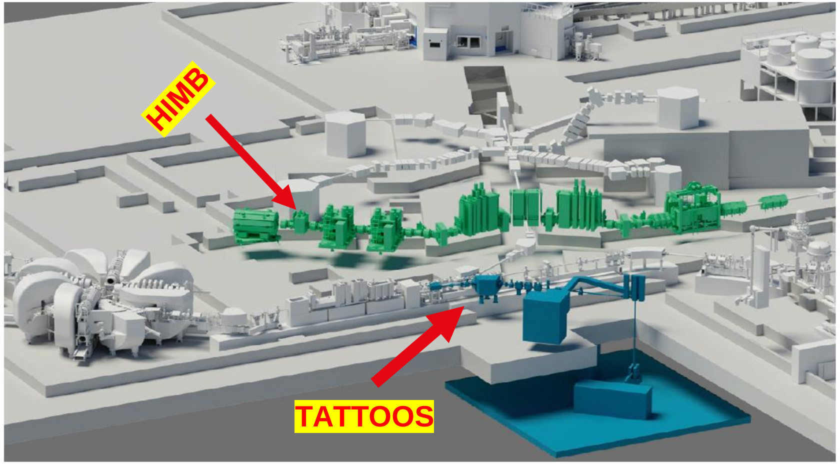
Outline of the TATTOOS Initiative

- High Intensity Proton Accelerator (**HIPA**) at PSI – 590 MeV CW proton beam, currents up to 2.4 mA.
- **IMPACT** (Isotope and Muon Production with Advanced Cyclotron and Target Technologies) – proposed initiative for HIPA.
- IMPACT:
  - ➢ HIMB (High Intensity Muon Beams) – Replacing existing target to increase surface muon production.
  - ➢ **TATTOOS** (Targeted Alpha Tumour Therapy and Other Oncological Solutions) – new beamline to produce **promising radionuclides** for therapeutic and diagnostic purposes.
- TATTOOS beamline intensity – **100 µA** → Requires continuous splitting of main HIPA beam via electrostatic beam splitter.

Overview of IMPACT initiative (TATTOOS and HIMB).



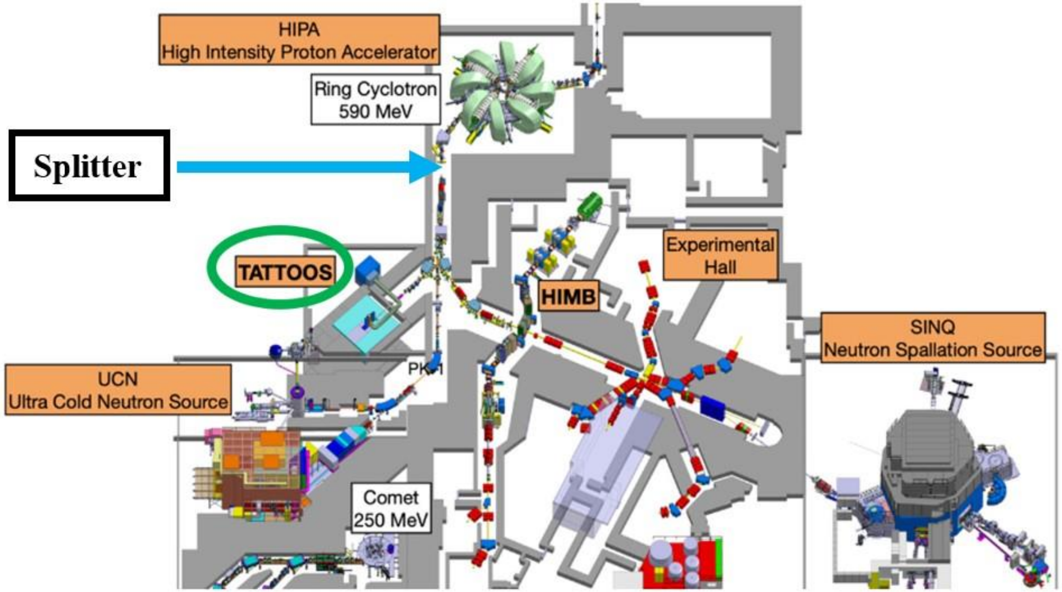


R. Eichler et al., "IMPACT conceptual design report", Paul Scherrer Institute, Villigen PSI, Switzerland, PSI Rep. No.22-01, Jan. 2022.

Overview of the HIPA facility

- Proton beam extracted from the Ring Cyclotron and delivered to :
  - ➢ Two meson production targets (TgM and TgE).
  - ➢ Two spallation sources:
    1. Swiss Spallation Neutron Source (SINQ).
    2. Ultra Cold Neutron source (UCN).
- Beamline from extraction to SINQ : P-Channel.
- Kicker magnet diverts beam from TgM, E and SINQ to UCN.
- Beam splitter, peels off small portion of beam, to be sent to TATTOOS target.

HIPA facility and foreseen TATTOOS location.



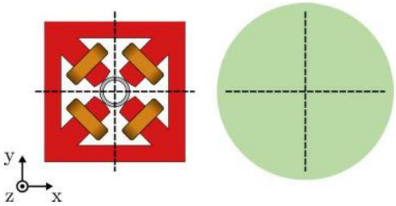
R. Eichler et al., "IMPACT conceptual design report", Paul Scherrer Institute, Villigen PSI, Switzerland, PSI Rep. No.22-01, Jan. 2022.

Main Requirement and Challenges for TATTOOS Beamline

- Requirement → transport beam without large losses to allow "hands-on" maintenance (loss levels should be < 1 W/m to limit activation of components).
- Main physics challenge and innovation → unprecedented power of split beam (60 kW beam power).
- Residual activity by lost beam particles is :
  - Source of exposure for personnel.
  - Source of damage and reduced lifetime of radiation sensitive components.
- For TATTOOS:
  - Splitter has to withstand significant power deposition.

Beam Delivery Simulation (BDSIM)

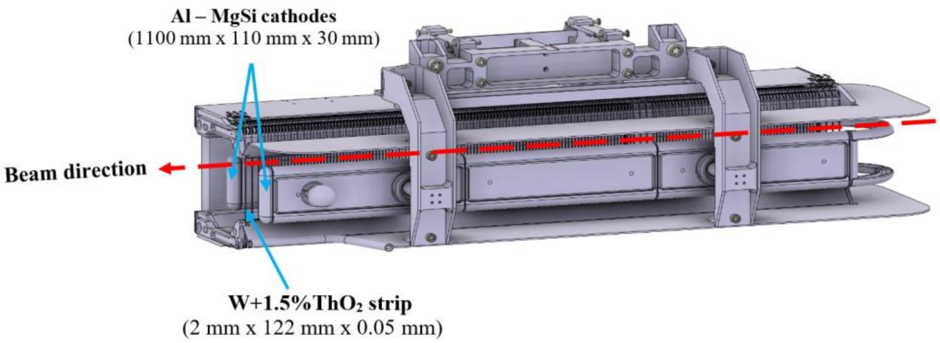
- Need to perform tracking simulations in EM fields and accurately predict interaction processes with TATTOOS components.
- → BDSIM (Geant4 based) delivers optimal and complete simulation from beam splitter to TATTOOS target.

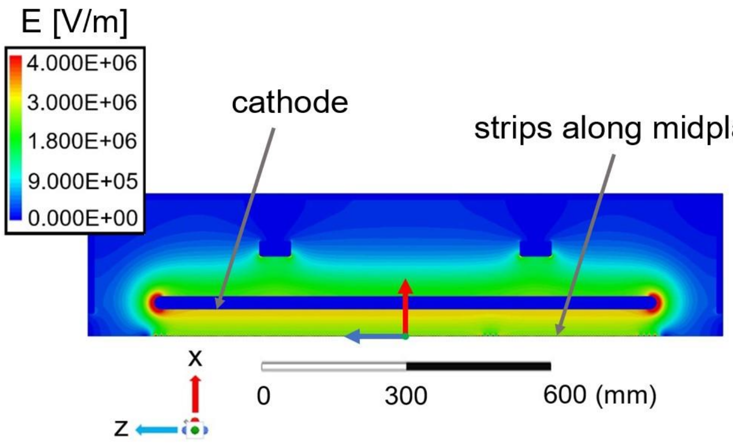


Beam Splitter

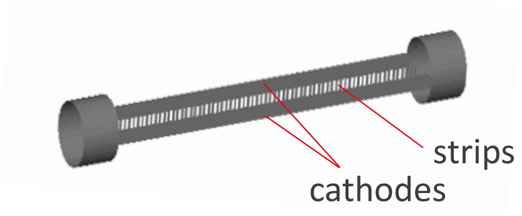
- Peels off high power beam in the horizontal plane.
- Septum : series of 175 electrically grounded tungsten alloy strips (2 mm x 122 mm x 0.05 mm).
- 2 cathodes at -172 kV create E-fields on either side of strips.
- Protons pulled away from strips for each beam.
- Detailed electric field map with ANSYS and implemented in BDSIM.
- Viability of the splitter - Splitter can withstand power deposition (first strip can handle max. 20 W).
- At the moment, splitter not used in normal operation.

Computer aided design (CAD) of splitter (courtesy of D. Goetz).





Splitter electric field map, resolution : 25 μm by 3000 μm by 500 μm.

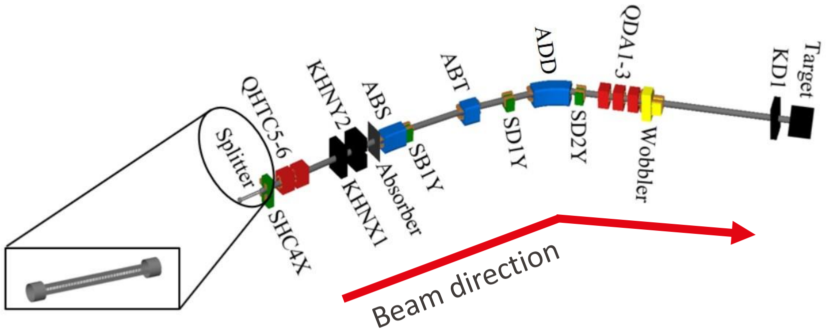


Splitter geometry (GDML) implemented in BDSIM.

TATTOOS Beamline Description

Component	Use for TATTOOS
ABS	Septum magnet. Diverts peeled beam to the UCN beamline (6.5° bend).
ABT	Dipole magnet. Diverts peeled beam from UCN line into TATTOOS (6.5° bend).
ADD	Dipole magnet. Bends beam by further 32°.
QDA1-3	Quadrupole triplet shapes beam on target.
SB1Y, SD1Y , SD2Y	Steering magnets. Steer the beam in vertical plane.
“Wobbler”	Two fast dipole magnets driven by AC current. Flattens beam footprint to homogenise target temperature (frequency ~ 30 Hz).
KHNX1, KHNY2	Jaw collimators acting in *x* and *y* planes.
KD1	Protection collimator for off-axis beams.

Complete TATTOOS beamline implemented in BDSIM.

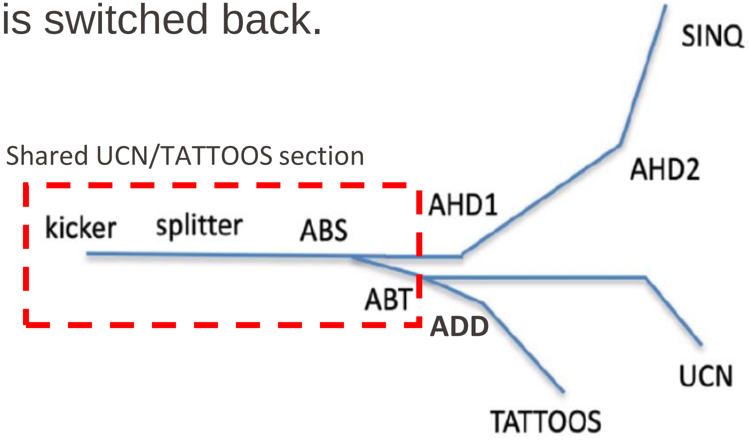


TATTOOS Operation

- First section of TATTOOS beamline is shared with the UCN beamline.

→TATTOOS and UCN cannot operate simultaneously.

- To switch from TATTOOS to UCN operation and vice versa:
  - Retract splitter from beam while ABT changes its polarity.
  - Kicker is activated for usual UCN operation.
  - Polarity of ABT is switched back.

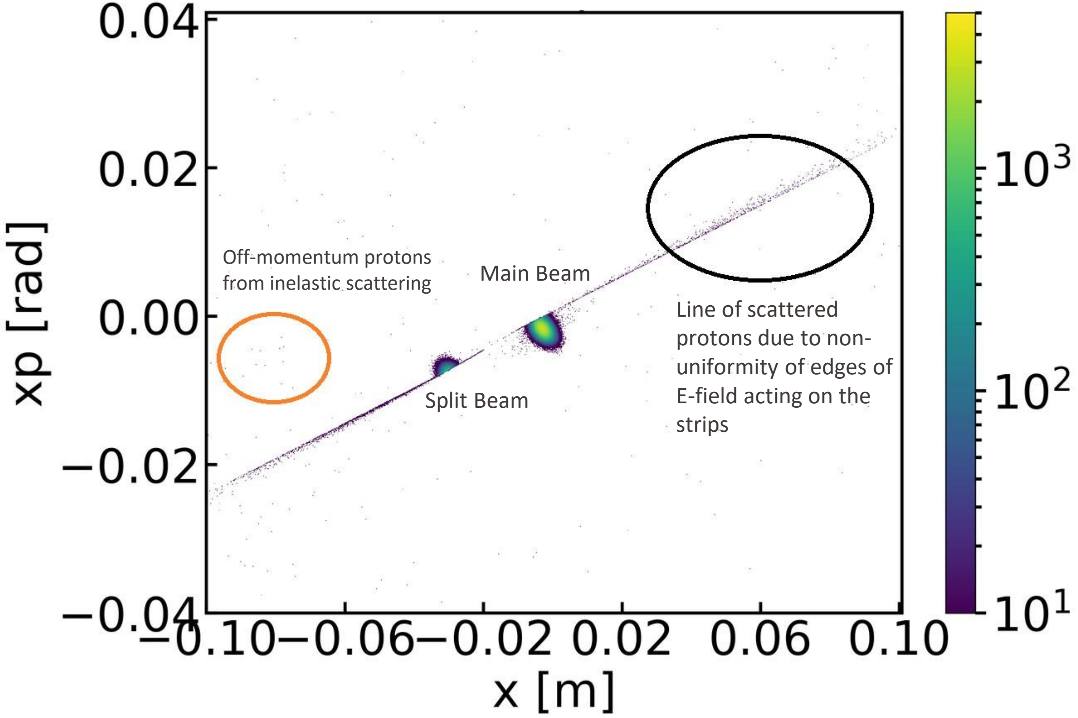


UCN/ TATTOOS alternating beam operation.

Input File and Horizontal Beam Profile

- Initial beam – Gaussian distribution.
- In BDSIM - wide range of physics processes included.
- Clear distinction between main and split beams.
- Various scattering processes visible.

Horizontal phase space approximately 4 m downstream of splitter.

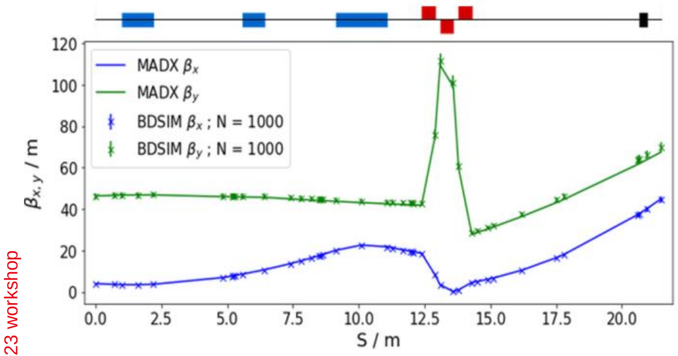


Beamline Optics Validation

- Beamline lattice designed with TRANSPORT code.
- Beam optics from BDSIM benchmarked with MAD-X.
- Excellent agreement between BDSIM and MAD-X.
- Beam size and transmission calculated from splitter to target for different split beam currents.

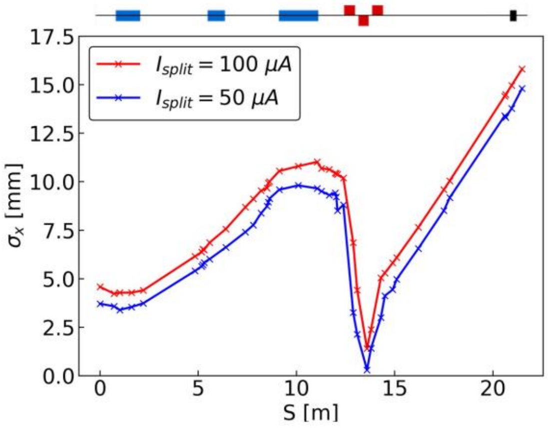
→ For a larger split beam current, beam size is larger as core of beam is more dense than halo → higher transmission to target.

Benchmarking between BDSIM and MADX - beta function validation

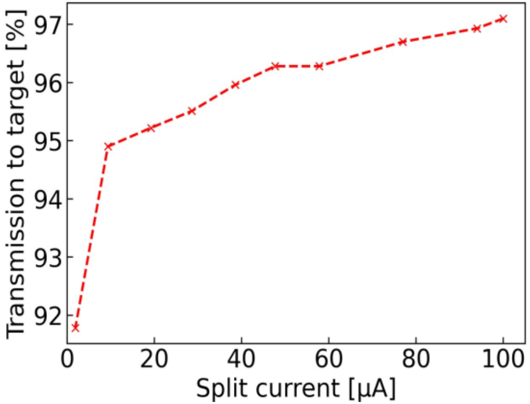


M. Hartmann et al., “Design of the 590 MeV proton beamline for the proposed TATTOOS isotope production target at PSI”, in Proc. IPAC’22, Bangkok, Thailand, Jul. 2022, pp. 3000- 3003. doi:10.18429/JACoW-IPAC2022-THPOMS02

Horizontal beam size along the TATTOOS beamline.



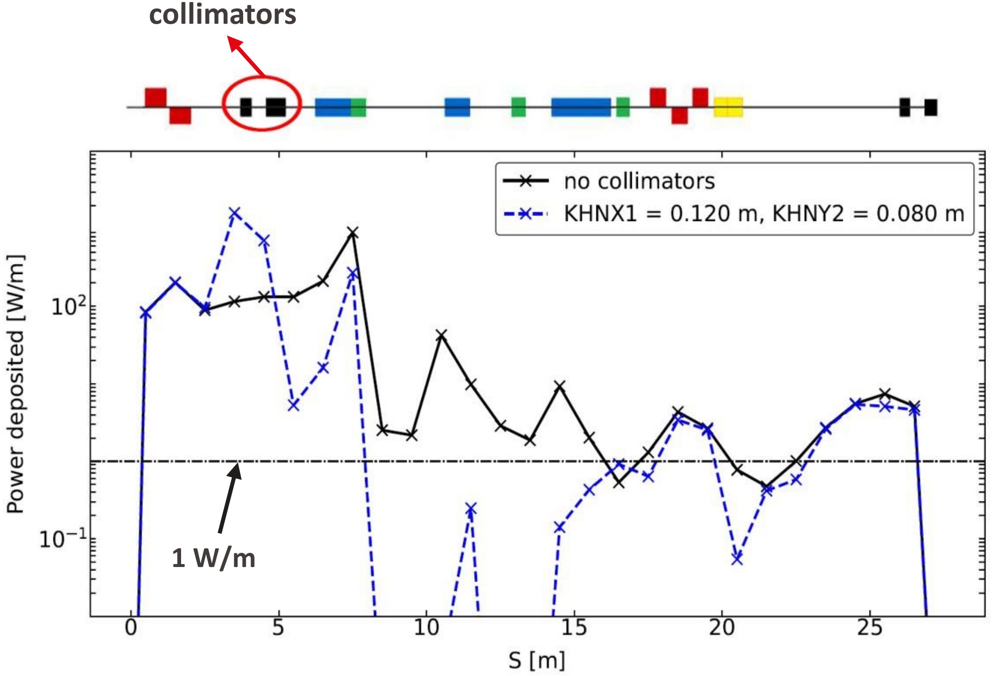
Transmission of split beam to target vs split beam current.



TATTOOS Beam Loss Simulations

- Main source of beam losses: proton head on collisions with splitter strips → scattered particles lost downstream.
- Apertures of collimators KHNX1 and KHNY2 optimised to reduce power deposition.
- Power deposited is highest at collimators (indicated with an arrow).
- Lower power deposited when collimators present compared to when there are none.

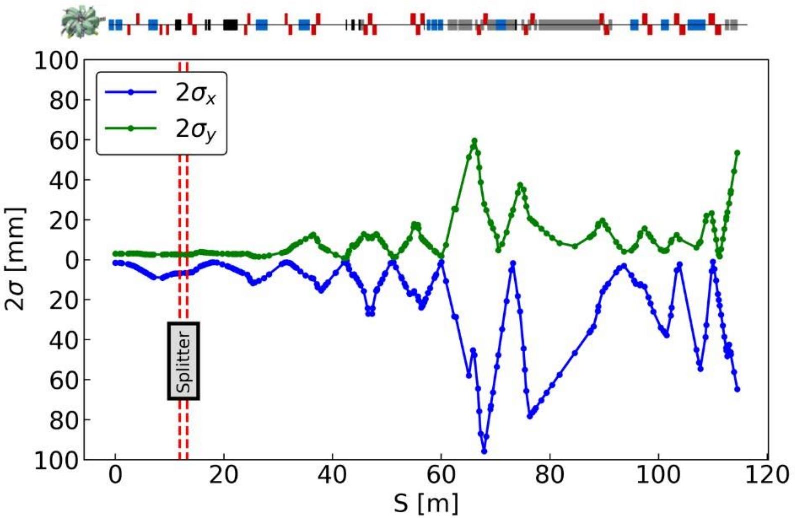
Power deposition from splitter to target with optimised collimator settings.



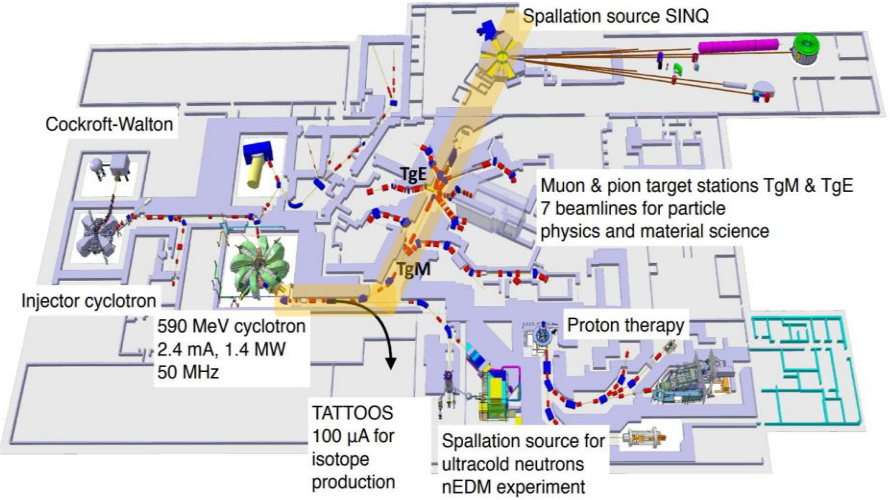
P-Channel Model and Beamline Optics

- P-channel simulated with BDSIM from extraction to SINQ.
- Goal: losses in P-Channel with splitter not significantly larger compared to current situation without splitter.

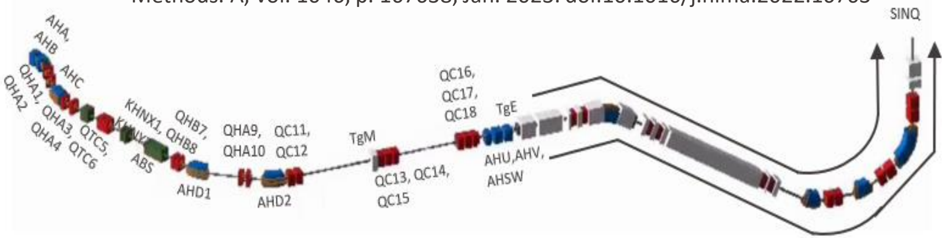
Beam sizes from extraction to SINQ target (splitter location marked with dashed lines).



HIPA facility and P-channel location.



M. H. Tahar et al., "Probing the losses for a high power beam", Nucl. Instrum. Methods. A, vol. 1046, p. 167638, Jan. 2023. doi:10.1016/j.nima.2022.16763

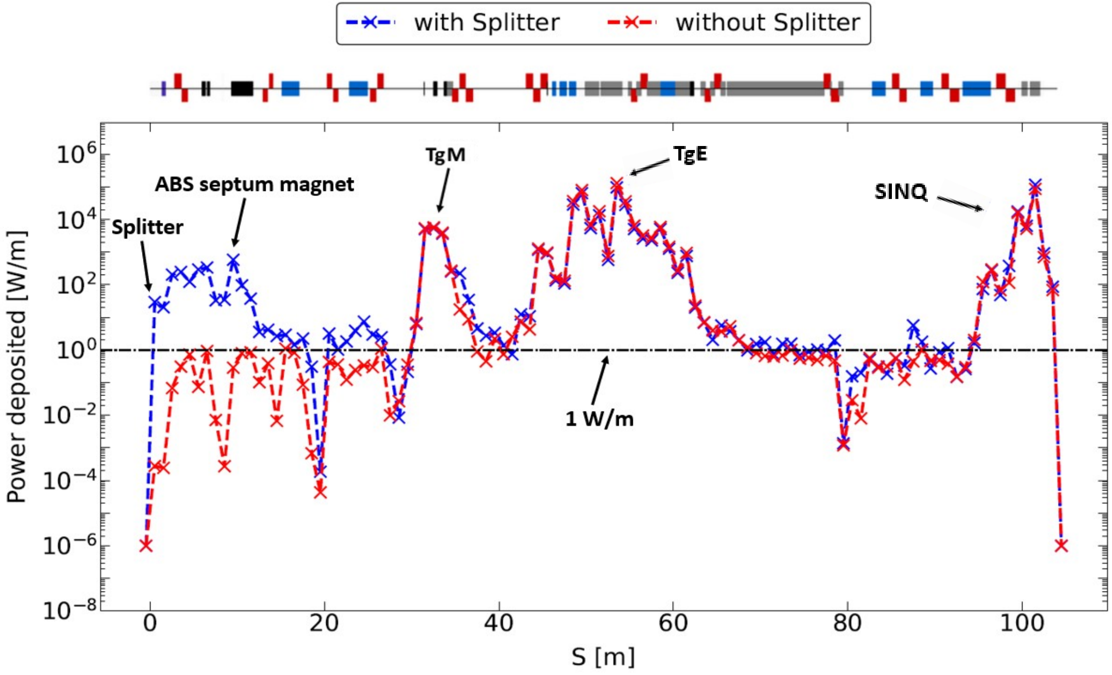


Overview of P-Channel beamline in BDSIM.

P- Channel Beam Loss Simulations

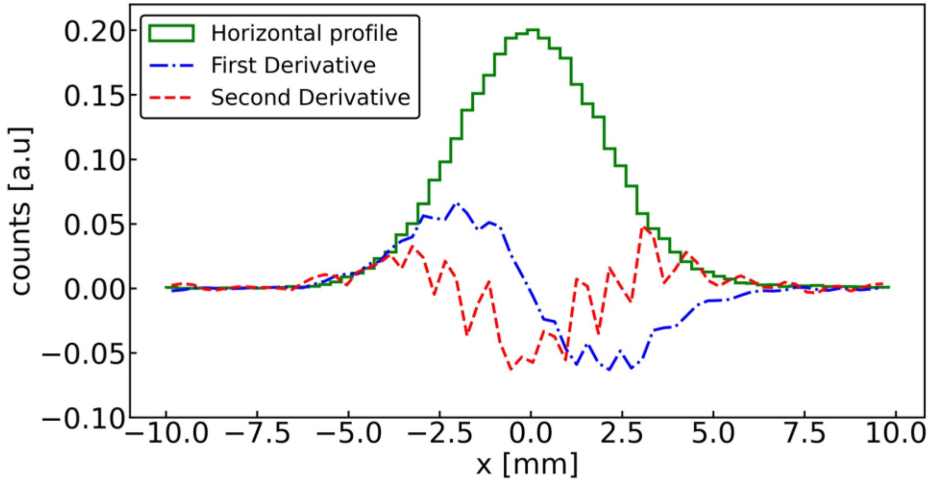
- Losses calculated in P-channel calculated with and without splitter.
- Losses up to TgM are larger with splitter, as expected → further studies needed.
- Up to SINQ → losses dominated by beam scattering on targets→ losses with and without splitter are comparable.

P-Channel losses for a 2 mA beam with (100 µA split current to TATTOOS) and without splitter.



Beam halo - Definitions and Characterisation Methods

- High intensity beams produce beam halo → beam losses.
- "Distribution method" : beam core-halo limit defined only by 2D phase space distribution.
- Typically : $\frac{m\ RMS}{n\ RMS}$ (n = 1, m = 3) with reference Gaussian distribution.
- However, split beam is not Gaussian – beam tail can be more or less significant compared to standard Gaussian.
- "Second derivative method": beam core-halo limit defined by location of steepest density gradient, i.e. max. of 2nd derivative in 1D.
- Visually halo location corresponds to tails of the beam distribution.



Normalised horizontal beam profile after the ABS septum magnet (about 8 m downstream of the splitter).

Beam Halo - Method Comparison

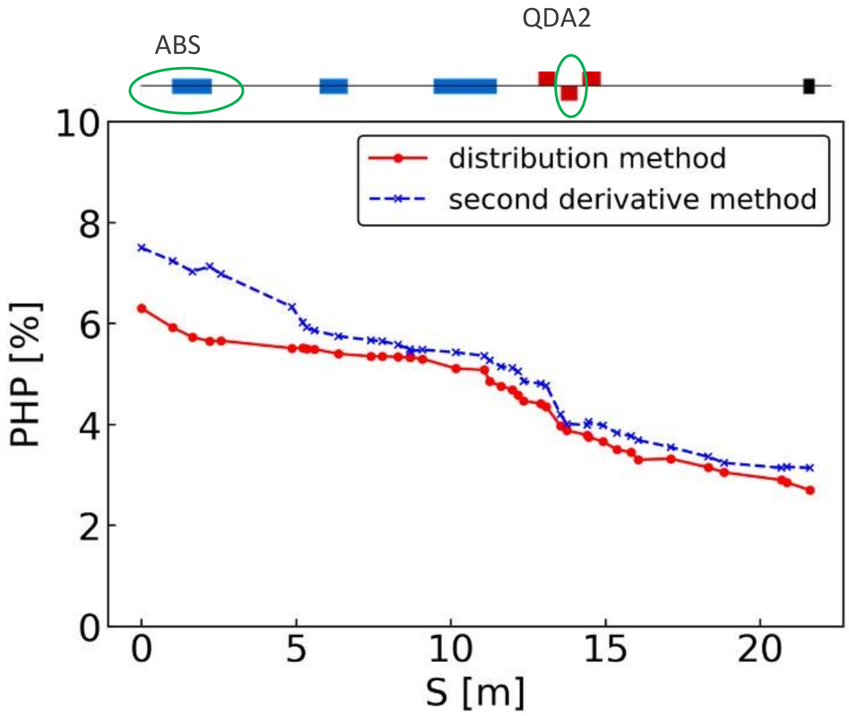
- Percentage of halo particles (PHP) :

$$PHP = 100 \cdot \frac{N_h}{N_c}$$

- Significant decrease in halo at :

1. ABS septum magnet (where main and split beam separate).
2. QDA2 quadrupole where phase advance changes abruptly.

→ These locations correspond well to peaks in power deposition.



Evolution of beam halo along the TATTOOS beamline for 100 μA split beam current using two different methods.

Conclusion and Outlook

- TATTOOS beamline lattice designed and simulated with BDSIM.
- Biggest challenge for TATTOOS beamline is high beam power → Extremely important to simulate losses along beamline.
- Power deposits both for TATTOOS and P-Channel calculated.
- Beam halo characterised using two independent methods.
- Simulations will serve as model predictions for future TATTOOS beamline measurements.
- Activation calculations to be performed in the splitter – TgM regions. Realistic shielding to be introduced and effects on power deposition to be determined.

Thank you!

Backup

Applied radionuclide sciences – Terbium radionuclides

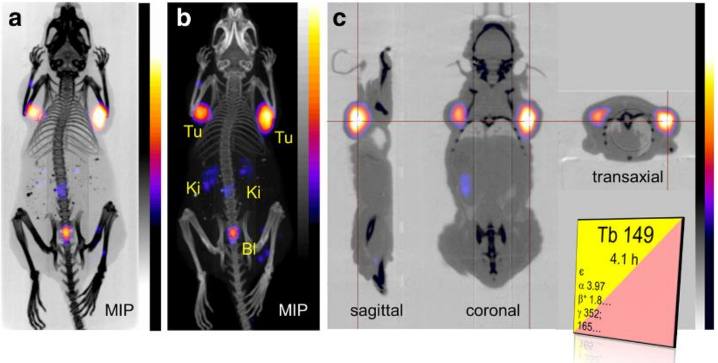
- Target containing high Z irradiated by a high energy proton beam → Spallation reactions → **Plethora of elements produced**.
- For TATTOOS, **Tantalum (Ta) target** → Large Tb production rates.
- Terbium (Tb) - one of the initial main production goals of TATTOOS.
- **3 main isotopes**:

1. ^{155}Tb emits γ-radiation suitable for SPECT.
2. ^{152}Tb decays, emission of β^{+}-particles useful for PET.
3. **^{149}Tb**, "flagship" nuclide for this project - promising properties for α-radionuclide therapy and PET.

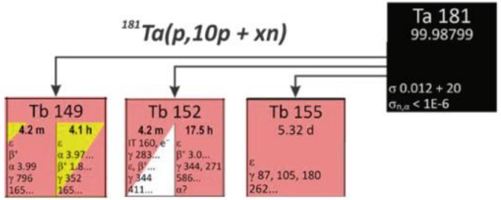
"Swiss knife" elements

- Alpha decay effective in treating small isolated tumours (short path length ~1-3 cell diameters).

A mouse bearing tumor xenografts, treated with ^{149}Tb-DOTANOC → PET/CT scans performed 2h later. 89% survival over 120 days [1]



Tb radionuclides produced from spallation with Ta target [4]



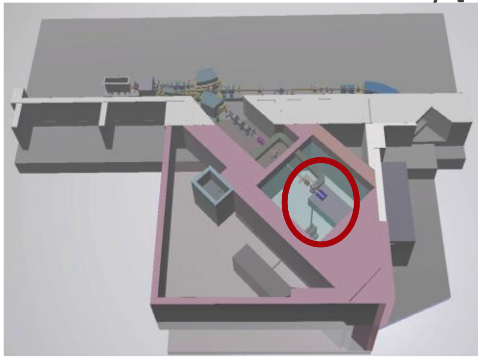
Spallation reaction in TATTOOS

- For TATTOOS, **Tantalum (Ta) target** → Large lanthanide (e.g. Terbium) production rates.
- Extraction system :

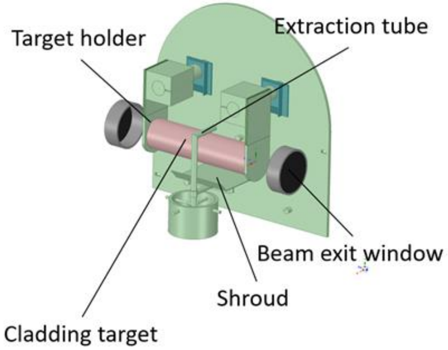
1. Selection of designated radionuclides
2. Diffusion out of the heated target + high potential difference
3. Ionisation by Laser-Resonance Ionisation (RILIS)
4. Mass purification via mass separator (collection of radionuclides of specific mass)

- 50 x higher beam intensity than ISOLDE → Pure radionuclides of unprecedented activities.
- Beam energy is degraded from 590 MeV to 300 MeV, remainder of beam goes to beam dump.
- Target operates in vacuum. Temp has to be high enough to achieve good releases of radionuclides but below melting point.

CAD overview of TATTOOS facility [1]



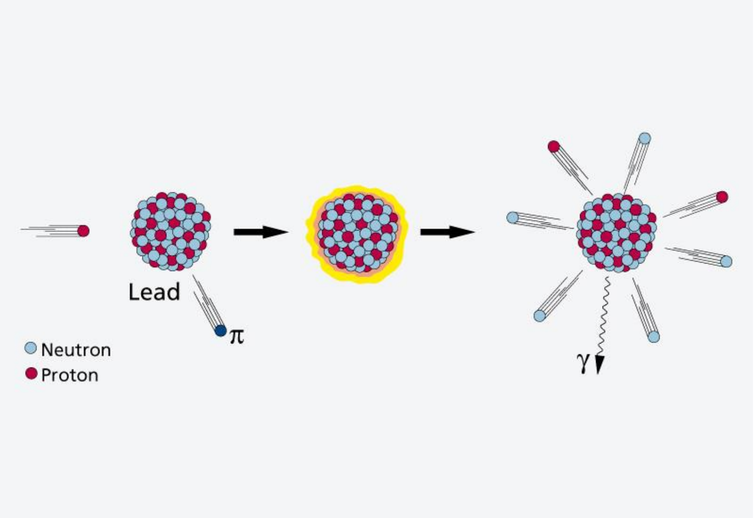
Simplified CAD Ta target (courtesy of S.Jollet)



Applied radionuclide sciences – Spallation reactions

- **Goal :** Production and delivery of radionuclides for pharmaceutical use.
- For cyclotrons with proton energies of 18-70 MeV – only proton rich radionuclides produced.
- **Spallation reactions** lead to radionuclide lighter than the target material.
- Target containing high Z is irradiated by a high energy **(600 MeV – 1GeV)**, low intensity proton beam → Spallation reactions → Plethora of elements produced.

Spallation reactions for SINQ target (lead) [2]



BDSIM input distribution

One of the most important parameters to give BDSIM to create a realistic simulation is the protons incoming distribution. BDSIM lets the user choose between several classes distributions and in this code we use several depending on the use case. For details on these classes, see BDSIM's documentation.

Since we are not simulating the whole beamline but only from EHT to, at most, TATTOOS' target, we need a starting distribution. Fortunately, analyses have been made before, using TRANSPORT, to simulate the optics along the whole beamline, and one can easily obtain the proton distribution at any point of the beamline.

An important remark on the translation between a typical TRANSPORT output and a BDSIM input : TRANPORT outputs a distribution under a very specific form. More details can be found in the TRANSPORT manual from 1980, but in short it has this form :

$x_{\max}$ MM

$\theta_{\max}$ MR r_{21}

$y_{\max}$ MM r_{31} r_{32}

$\phi_{\max}$ MR r_{41} r_{42} r_{43}

$l_{\max}$ CM r_{51} r_{52} r_{53} r_{54}

$\frac{1}{2}\frac{\Delta p}{p}$ PM r_{61} r_{21} r_{63} r_{64} r_{65}

The closest distribution class that BDSIM takes into input is `gaussmatrix`. It has some differences that need to be taken into consideration. The user must supply the diagonal and under-diagonal terms of a covariance matrix. The main thing to keep in mind when translating from TRANSPORT to BDSIM is that $x_{\max}$, the maximum half-width of the beam, corresponds to $2\sigma_x = 2\sqrt{\sigma_{11}}$. The interpretation one has to keep in mind is we keep 95% of the beam within $[-2\sigma,\ 2\sigma]$ for all coordinates.

BDSIM's input is also 6D but **Most quantities are actually different**.

- The first and third coordinates are still x and y [m].
- Second and fourth are x' and y', [ ]. Note TRANSPORT gives $\theta_{\max}$ [rad or mrad] in lieu of $2\sigma_{x'}$ [ ]. The relationship between these quantities is actually just a $\sin$ that the user can safely forget about since the values are usually < 1 mrad.
- Fifth is t. This is a big difference but mostly irrelevant. To go from packet length to time spread one must divide by the proton' velocity, easily obtained from their mass and kinetic energy.
- Sixth is E. To go from half relative spread in momentum to absolute spread in energy, the formula is $\sigma_E = \frac{1}{2}\frac{\Delta p}{p} \times p \times \beta$. This is also largely irrelevant.

Finally one must think of translating correlations to off-diagonal covariances : $\sigma_{ij} = r_{ij}\sqrt{\sigma_{ii}}\sqrt{\sigma_{jj}}$.

Advantages of BDSIM w.r.t to Geant4 and Fluka

- **Geant4 and FLUKA** provide capability to simulate passage of particles in matter
- In both codes, **significant effort is required to describe the geometry** and materials of a simulated accelerator
- **Both codes rely on numerical integration** (e.g. 4th order Runge Kutta integrators) to calculate the particle motion in an arbitrary field → **Can suffer from small numerical errors that get amplified** and lead to gross inaccuracies
- Geant4 includes examples of beamline simulations BUT typically less than 10 components, uses only numerical integration for particle motion, components are hardcoded to that beamline experiment in C++. A developer must write their own C++ to insatiate classes representing geometries etc.
- BDSIM creates a **3D model using Geant4 library** with the **addition of accelerator tracking routines**
- **BDSIM has advanced scalable output and per-event analysis**
- BDSIM provides a library of scalable and customizable 3D components that **provide most common magnets and apertures** (description includes the length, type, strength of each magnet in sequence)
- User may progress **from a generic model to a more specific model by adding provided geometry for particular elements**
- Users can **overlay their own field maps** on top of parts or all of components
- Allows **energy deposition to be calculated**

BDSIM - physics processes

- **Large library of physics properties.**
- If no process selected, particles pass unimpended through matter.
- **Sampler** = a thin box (~1nm) recording any particles passing through it.
- **The particle coordinates are recorded** on the sampler, which is placed after the element with a 1 nm gap between each surface.

Bertini model:

- Implemented as part of the Geant4 **hadronic shower framework**. It contains an intra-nuclear cascade model with exitons, as well as a pre-equilibrium model, a nucleus explosion model, a fission model, and a evaporation model.
- May be used to simulate pion-, proton-, and neutron-induced reactions in nuclei. It is valid for **incident energies up to 10 GeV**
- **Secondaries are activated for power deposition** studies but not for transmission.
- **No physics list** for optics validation as none are required (not interested in secondaries).

BDSIM - calculating losses

- **Purpose of BDSIM** is not to perform long term tracking but **to simulate losses.**
- **Impact location** is the **first point where a physics process is invoked** along the step of a particle.
- **Loss point is the end of the trajectory** of the primary proton (due to inelastic collision and subsequent fragmentation, or absorption).
- **All histograms are made on a 'per-event' basis** (1 event is 1 particle) and the energy deposition histograms are the mean of the sampled number of events. Uncertainty of for each bin is the standard error on the mean.

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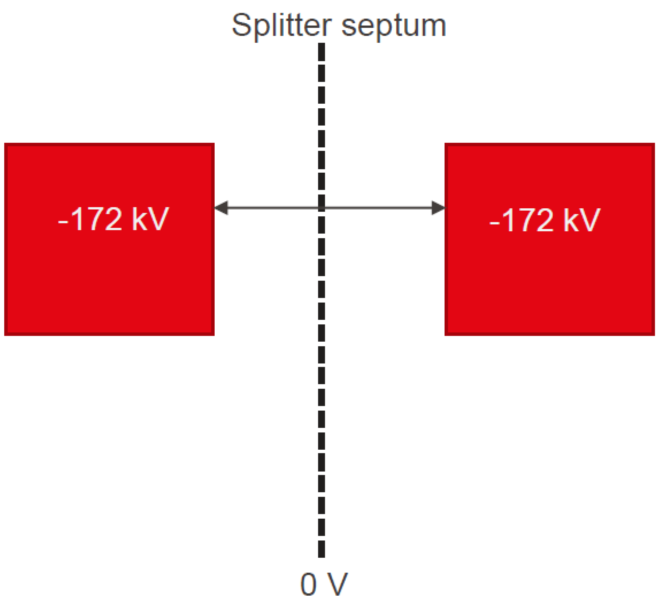
Splitter (1)

- The **peeled beam passes through the channel between the septum and the cathode -- > gets a kick towards the cathode**.
- **The septum is set to x=0**, while the **beam direction is parallel to the z-direction**.
- **Simulation starts at entrance of beam splitter** → beam centroid has to be shifter to a negative position x0
- Only protons hitting the septum or passing through the channel between septum and cathode will be tracked

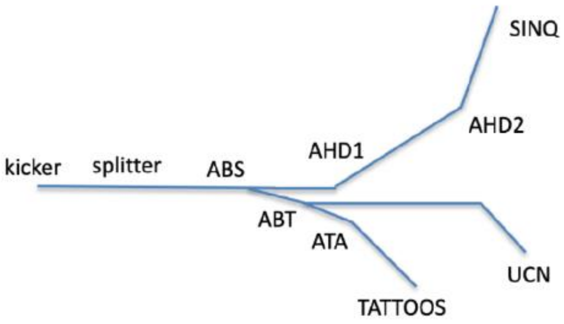


To find the position of the septum corresponding to the desired cut off proportion c, one needs to solve the following for x_0 :

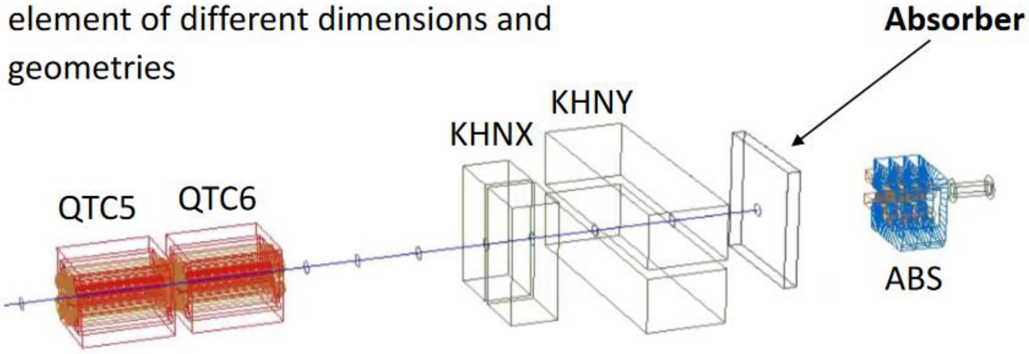
$$\int_{-\infty}^{x_0-w} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}} dx = c \quad (1)$$

Absorber

- Want all particles of the beam going into SINQ to be removed before ABS septum
→Left with 5 % of initial number of protons reaching TATTOOS target



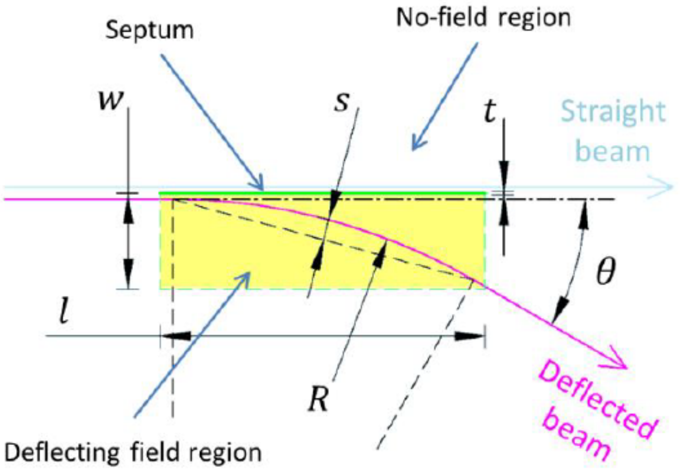
- BDSIM offers a movable "absorber" element of different dimensions and geometries



(size of elements exaggerated)
purple line : proton trajectory

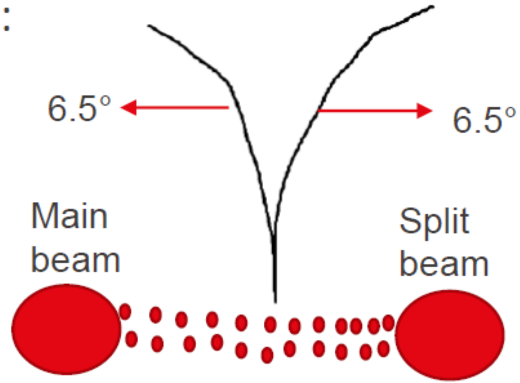
Septum magnet and steerer magnets

- **Septum magnet** = A magnetic septum has a lot in common with dipole (bending) magnets but it is more complex due to
  the necessity of having an **abrupt field change**.



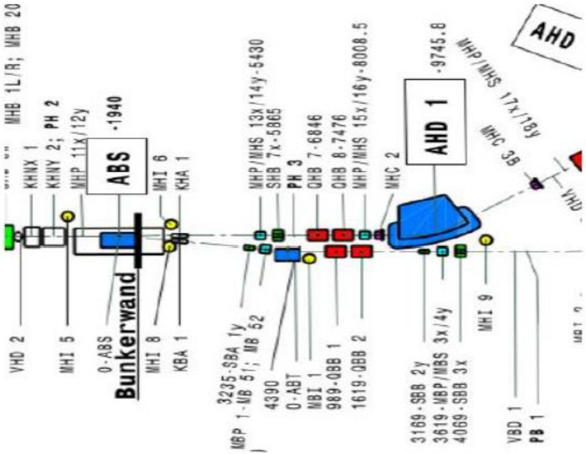
- **Steering magnets** = **small-angle corrections** of charged particle beam trajectories

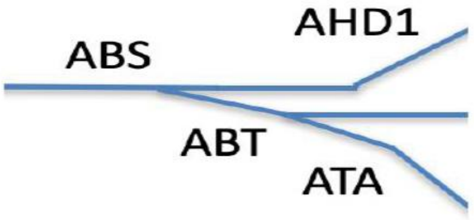
- ABS functioning :



ABT

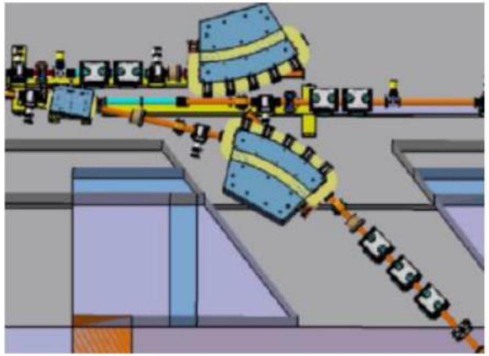
- Bends back to UCN
  - 6.5 degrees
  - effective length 823 mm
  - pole tip field 5.54 kG
- Should with reversed polarity bend beam to TATTOOS
- Ramping < 30 seconds
  - reproducibility (no strong hysteresis effects)
- Can existing magnet be reused / modified?





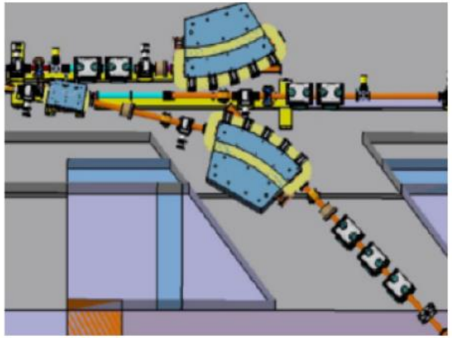
ADA

- Large bend
  - 32 degrees (or rather 45 - ABS - ABT)
  - 2042 mm effective length
  - Pole tip field 11 kG
- Could be very similar to AHD1

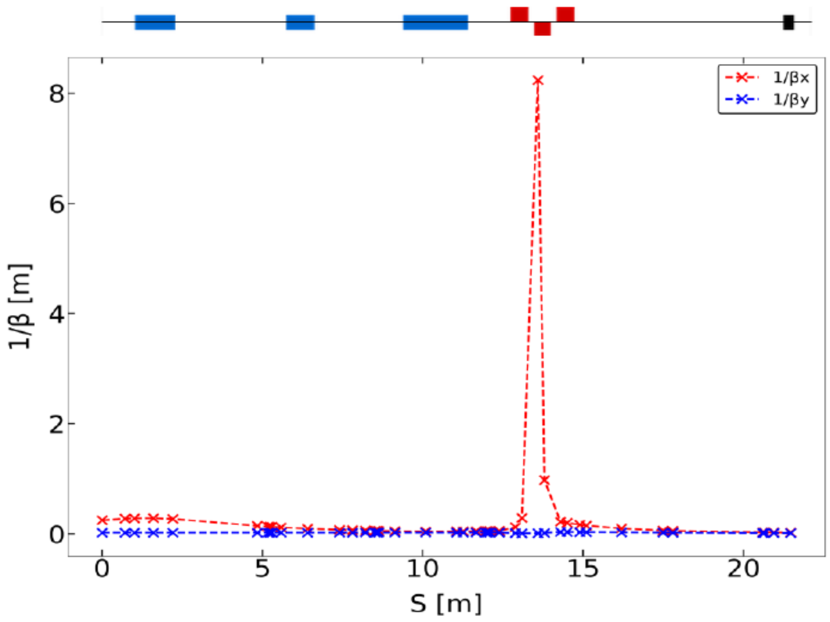


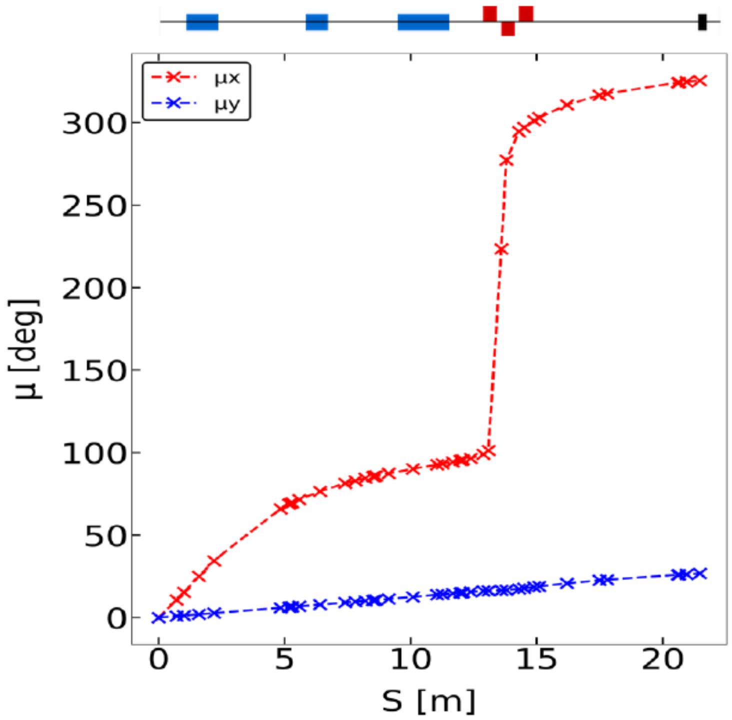
Quadrupole triplet

- To shape the beam on the target
  - 500 mm effective length
  - pole tip field 9 kG
    - only 3rd magnet
- After ATA bend

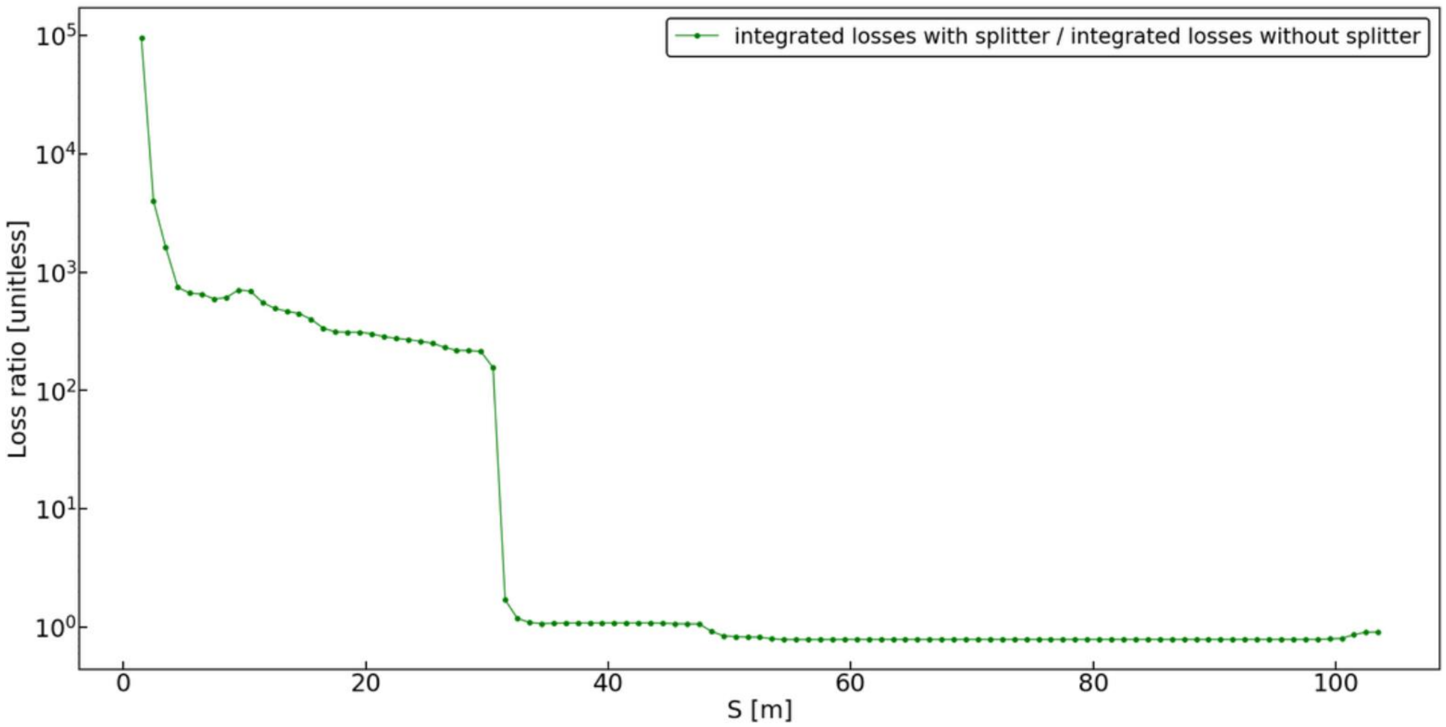


TATTOOS phase advance





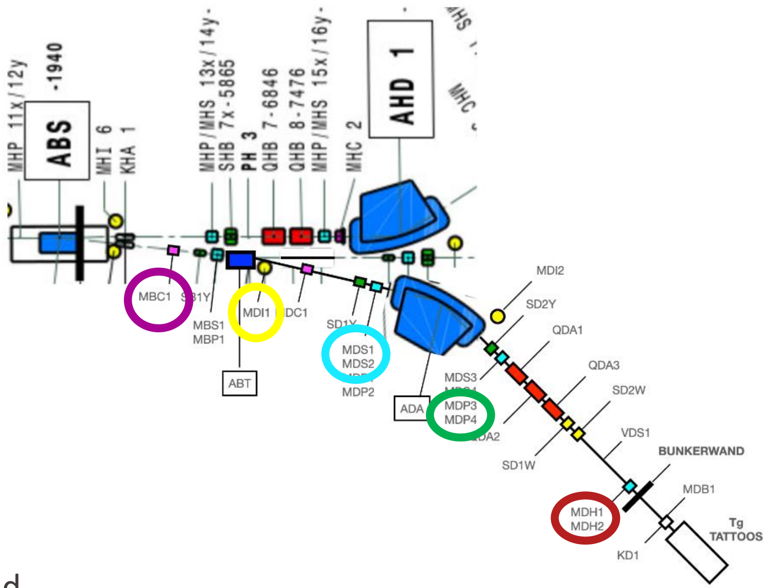
P-Channel losses (continued)



Diagnostic elements for TATTOOS beamline

Diagnostic element	Use for TATTOOS
2 Beam current monitors	Absolute measurement used to calibrate relative monitor. Provides more stability over time
2 Beam loss monitors	Detect beam losses in the sub-nA level. Coupled to machine protection
4 Beam position monitors (BPMs)	Provide the means to steer the beam through the beamline (resolution at 100 µA is ~0.2 mm)
4 Beam profile monitors	Measure and verify the optics (placed in same vacuum chamber as BPMs)
Harp for each plane before target chamber	Measures both beam profile and position in a continuous manner

Diagnostic elements along TATTOOS beamline (courtesy of J.Snuverink)



+ 4 segment aperture foil in front and after target – collimator and beam dump equipped with thin sheet metal (100 µA) that provide beam halo measurements in 4 directions

Splitter moving in process

- Each splitter move takes 15 s
- UCN kick procedure takes 20 s
- TATTOOS target irradiated for 240 s every 320 s.
- The ABT ramping time will have to be short enough in order to make it possible to power the magnet right after the UCN kick before the beam current reaches its nominal values (roughly 30 s)

Why not use a kicker instead of splitter?

- Device would need a high repetition rate
- From a beam dynamics standpoint there exists a difficult tradeoff between increasing the beam losses (with increased repetition rates) and target damage (with reduced repetition rate)
- Such a device will take a considerable amount of space in the experimental hall for the power supplies

Machine protection system – splitter operation for TATTOOS and kicker operation for UCN

- Fast kicker magnet diverts full intensity beam to UCN for max. 8 s.
- **Solution:** Run TATTOOS between 2 UCN pulse (one UCN pulse ~ 8 seconds, time between 2 pulses ~300 s)
- There should be no beam while ABT dipole magnet is ramping. Kicker is disabled and splitter is in park position.
- There should be no UCN kick to TATTOOS – kicker is disabled when ABT is bent towards TATTOOS.
- There should be no split beam to UCN – splitter is in park position when ABT is bent towards UCN.
- To ensure the correct ABT polarity short UCN test pulses are sent before the 8 s UCN kick and split beam is slowly ramped up
- Emergency scenarios :
  → If splitter strips break (the ones in front) : splitter can still function by increasing the applied voltage slightly

  → if many splitter strips break (8 strips) and voltage cannot be increased : splitter exchanged with available spare splitter.