DESIGN OF THE PROTON BEAMLINE FOR THE TRADE EXPERIMENT

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Abstract

The TRADE (Triga Accelerator Driven Experiment) experiment, to be performed in the TRIGA reactor of the ENEA-Casaccia centre consists in the coupling of a 140 MeV-0.5 mA proton beam produced by a cyclotron to a target hosted in the central thimble of the reactor scrammed to sub-criticality. A 27 m long beamline has been designed to transfer the beam injecting it from the top of the pool with special care of having low losses in TRIGA building where a limited shielding of the line is possible. A particular attention was paid to reduce the number and size of elements in the last part of the beamline that are immersed in the pool's water. The paper presents a description of the beam line, the design criteria and the results of a sensitivity to errors study.

THE TRADE LAYOUT

The TRADE “TRiga Accelerator Driven Experiment” - to be performed in the existing TRIGA reactor of the ENEA Casaccia Centre - is an original idea of Carlo Rubbia aimed at a global demonstration of the ADS concept [1,2]. The layout is shown in Fig.1. The cyclotron is located in a shielded area nearby the TRIGA building. It is mounted on concrete columns and steel supports so that the beam output is at the same level off the top of the TRIGA pool. The cyclotron output beam is transferred from one building to the other via a section of the transfer line that is shielded by a massive shielded tunnel. This is a long straight line, with a number of quadrupoles that match the beam to the final bending system that bends the beam 90° from horizontal to vertical direction. This is partially immersed in the pool’s water for shielding reasons. The target is about 4 m down the last dipole.

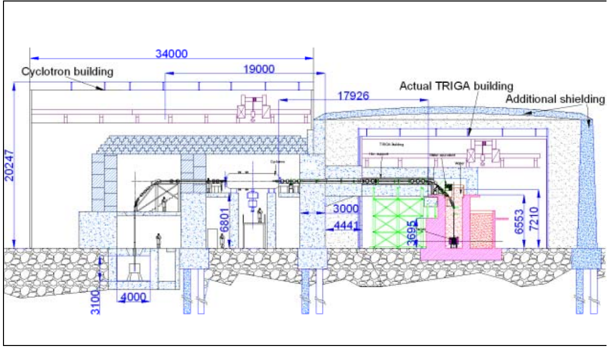

Figure 1: Section of the cyclotron and TRIGA buildings

Two 180° apart beam outputs are foreseen on the cyclotron: the first is the TRADE experiment output while the second is used in the commissioning phase.

Accelerator characteristics

The cyclotron has been chosen as an H^- cyclotron with stripping extraction. An indicative list of parameters is given in Table 1. A modest, tolerable degradation of the beam characteristics is expected from the extraction H^- strippers. Therefore a clean output beam with small emittance (1-4 π mm mrad normalized) is expected.

Table 1: Main parameters of the TRADE cyclotron

Output energy	140 MeV
Abs. Max Current Operating current	500 μA 215- 286 μA
Normalized transverse emittance at 2σ	< 4 π mm mrad
Energy spread	< 1 MeV (90% beam)
Beam dimensions	≤ 7 mm (FWHM in both planes)
Beam temporal distribution	CW Pulsed (30 – 1500 μsec), 0 - 10 Hz
Injected particles	H^-
Cyclotron outside diameter	6.5 m
Total weight	300-400 tons
Extraction	Stripping (carbon foil 70 mg/cm2)

Target characteristics

The target is machined from massive tantalum and has a conical shape, with a useful length of 38 cm. The upper part is connected to the beam line. The target is cooled by flow guides that direct the water flow around the body. The maximum power manageable is 30 - 40 kW. The neutron distribution in the TRIGA core generated by the protons and the power distribution along the target are dependent on the beam shape and dimensions. Therefore a certain commitment is necessary on the beam transport line in terms of beam centroid precision (± 1 mm) and beam size (σ = 8.8 ± 1 mm).

THE TRADE BEAM TRANSPORT LINE

Description

The TRADE beamline (fig.2) includes 12 quadrupoles and two dipoles. It is composed by three main sections: a Matching Section (MS) with 4 quadrupoles Q1-Q4 for matching the cyclotron beam to the rest of the BTL, a Straight Transfer Line (STL) with 5 quadrupoles Q5-Q9, and a final bending section (FB) that bends the beam 90° downward and is composed of two 45° dipoles M3 and M4 with three quadrupoles (Q14-Q15-Q16) in between.

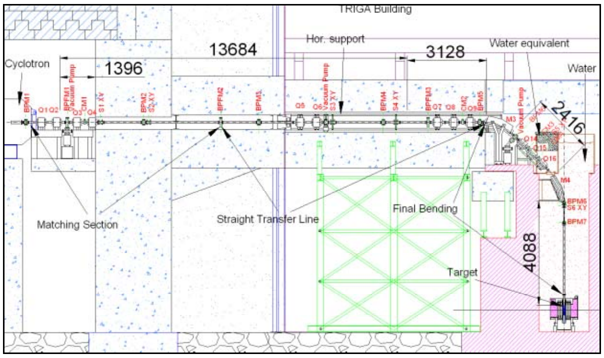

Fig. 2 Layout of the TRADE BTL

The beamline optics has been designed by using TRACE3D code[3] starting from the parameters reported in table 2.

Table 2: Reference input beam parameters

Normalized emittance, π mm mrad	1, 4, 6
x_{max}, y_{max}, mm	7, 7
xp_{max}, yp_{max}, mrad	2.5, 2.5
Bunch half-width (°RF at 70 MHz)	10
Energy spread half-width (keV)	470

However the actual output phase space beam characteristics are dependent on the actual performance of the accelerator and cannot be entirely defined at the design stage. Since the stripper foil is gradually deteriorating in time and even periodically replaced, the precise value of the vertical and horizontal emittances may even slightly vary during the operation. Therefore the beam transport line must be capable of tracking and continuously adjusting with high precision the relation between the beam emittances in each of the two planes and the size of the final spot.

Design criteria

The design criteria for the final part of the BTL were as follows

- Achieve a circular spot of nominally 35.2 mm diameter (2σ) at the target spot
- Double achromatic final bending, i.e. D = D'= 0 at output.
- Point-to-point transport between the centres of M3 and M4.
- Minimum in the beam sizes at the centre of dipoles M3 and M4 in order to reduce the size and therefore the beam losses in the gaps.
- Symmetric expansion in the final drift
- The two dipoles, each of 45°, have been chosen with a relatively conservative magnetic field of 1.3 T corresponding to a curvature radius of 1.36 m.

Figure 3 shows the horizontal and vertical envelopes as computed by TRACE3D for three different values of beam emittance for the same final beam spot.

The quadrupoles length is 250 mm for the first 9 quadrupoles and 300 mm for the 3 quadrupoles placed between the two dipoles of the FB section. In the whole range of emittances the maximum gradient is below 12 T/m for the first 9 quadrupoles and below 15 T/m for the 3 quadrupoles placed between the two dipoles in the FB section (maximum value in Q15).

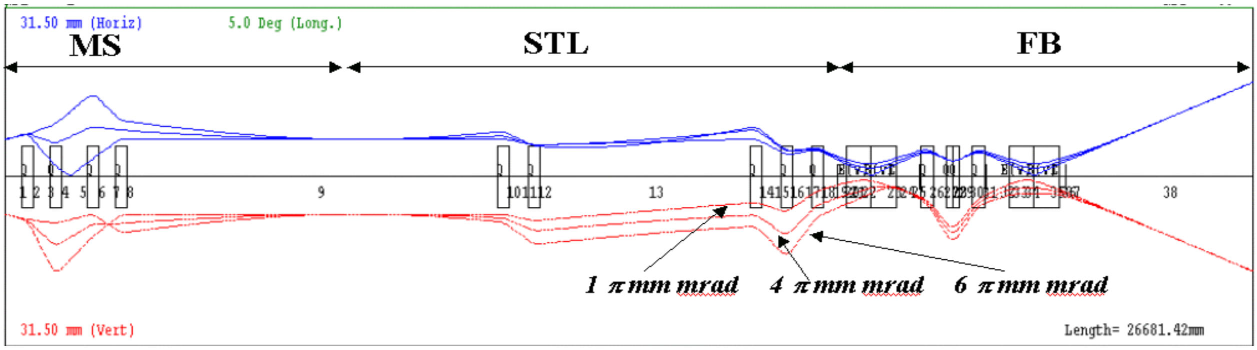

Fig. 3 - TRACE3D outputs for the standard tune: envelopes (2σ) along the BTL tuned for 1, 4, 6 π mm mrad

Spot size tuning

An original "zoom" focussing geometry has been introduced in order to ensure with precision the required spot of the beam at the target position, independently of the actual beam emittances and always keeping a round shape at the target. This is achieved by setting the values in the quadrupoles Q1-Q9 while the values of the final bending elements have been kept constant, pre-set such as to produce a "point to point" transport between the centres of M3 and M4 and a minimum in the horizontal dimension at the centre of the two dipoles M3 and M4. The ratio α/β ($\alpha_{.}$ and $\beta_{.}$= Twiss parameters) is kept constant for both transverse phase planes. In order to elucidate the method, three possible geometries corresponding to 2σ= 1, 2 and 4 cm.are shown in fig. 4.

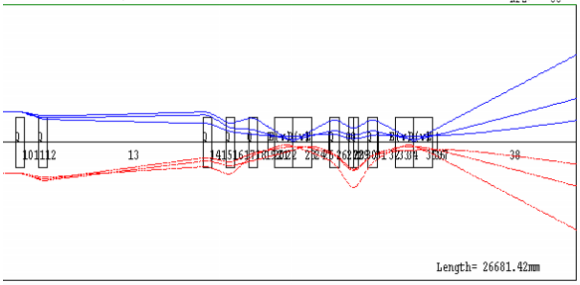

Fig. 4 Variation 1:2:4 in the final spot size at the target for an input normalized emittance of 1 π mm mrad.

SENSITIVITY STUDY

The sensitivity of the optics to different error sources for a normalized emittance of 4π mm mrad (at 2σ) has been studied by using TRACE3D and TRACEWIN [4] codes. For an error amplitude A, the error has an equivalent probability to be between –A and +A.

Focusing sensitivity

The main errors that can affect the final spot size have been considered. The amplitude of the errors and the maximum effect on the spot size in 20 TRACE3D runs are summarized in table 3. About the random gradient error ΔB'/B' the effect is larger for y-envelope due also to the increase of vertical emittance caused by the partial loss of achromatism in the final vertical bending. At the target the maximum change is +0.67 mm in σ_x and +1.82 mm in σ_y. We did not include in our simulations specific diagnostic to correct the gradient errors which cause mainly mismatching. Thus we consider that the error study results below show a worse beam behaviour that the normal operating mode where specific diagnostics are used to match the beam.

Table 3 Effect of different errors on beam spot

Parameter/Amplitude	**Effect on beam spot**
Quadrupole gradient, ± 1%	$\Delta\sigma/\sigma$=20 %, σ_x/σ_y=20%
Quadrupole rotation (Z), ± 1 deg	$\Delta\sigma/\sigma$=7 %
Twiss parameters mismatch, ± 10%	$\Delta\sigma/\sigma$=20 %, σ_x/σ_y=30%
Emittances mismatch, ± 10%	$\Delta\sigma/\sigma$=5 %, σ_x/σ_y=10%
Energy precision δE, ± 1MeV	Negligible on target $\Delta\sigma/\delta E$= 8 mm/MeV in Q15
Dipole field δB/B ±0.3 %	Negligible on target $\Delta\sigma/(\delta B/B)$= 2 mm/0.1%

The final spot size is also affected by optical errors arising from discrepancies between the assumed ideal and actual input Twiss parameters or emittance: the upstream matching section can be re-tuned to eliminate these mismatches, but it results that this might not be strictly necessary for emittance mismatching of ±10%.

The sensitivity of the beamline to an input beam energy error or to a dipole mispowering has been also studied: the largest effect on beam spot occours in the quadrupole Q15, where the dispersion function reaches its maximum. The effect at the first order is completely recovered at the exit of the FB section due to the double achromatism of the magnetic system.

Trajectory sensitivity and corrections

This study based on TRACEWIN code has been done to design and check the correction scheme (steerers and Beam Position Monitors). It concerns the effect of magnets misalignments (±0.5 mm) and quadrupoles tilt (XY rotation angle of ±0.5 deg) on the radius of the residual orbit defined as $r = \frac{1}{N}\sum_{1}^{N}\sqrt{x^2+y^2}$ with N=number of runs and x&y equal to the coordinates of the gravity position along the BTL In the calculations a BPM accuracy of 0.1 mm has been assumed. A correction set constituted by 6 XY steerers coupled to Beam Position Monitors measuring in both planes the centre is effective to correct element misalignments providing a centroid stability at target of ±0.3 mm (fig.5).

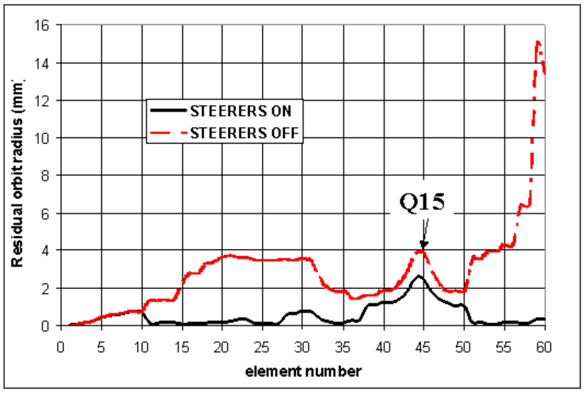

Fig. 5 Residual orbit plot with quadrupoles and dipoles random errors with corrections off and on

Checking the centroid position at target will be not an easy task. The last dipole and the following steering elements and diagnostics (the last BPM is placed at 2 m from the last dipole) are immersed in the TRIGA pool. This will need a specific design of the elements.

APERTURE ANALYSIS

The beam pipe radius needed to be at a safe value for minimizing losses is considered above 5σ. This requires in the emittance range 1-4 π mm mrad a beam pipe of 63 mm inner diameter for the quadrupole apertures as well as for the other items (steerers, BPMs, etc) and a useful gap respectively of 27 mm and 21 mm for the two dipoles.

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