IMPROVEMENT OF RELIABILITY OF THE TRASCO INTENSE PROTON SOURCE (TRIPS) AT INFN-LNS

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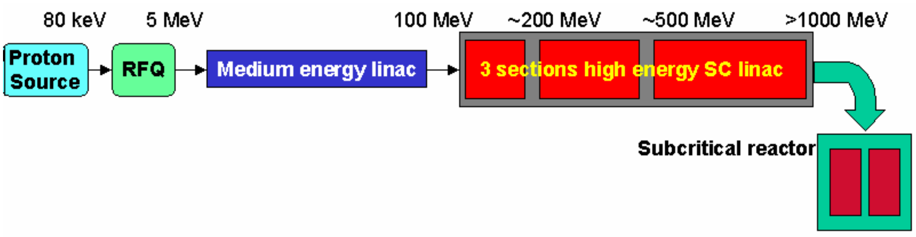
Abstract

Over the past two years, INFN-LNS has undertaken to improve the source reliability for high-power proton accelerators. A full set of magnetic field measurements has been carried out to define a different design of the TRIPS magnetic system, based on permanent magnets, in order to increase the reliability of the source devoted to the ADS. The OPERA-3D package was used to design the new magnetic system as a combination of three rings of NdFeB magnets and soft iron in between. The description of the magnetic measurements and the comparison with the simulations are presented, along with the design of a new version of the source, called PM-TRIPS. Finally the new low-energy beam transfer line (LEBT) will be described, with particular regard to the improvement of accelerator availability, which can be obtained with the installation of two PM-TRIPS sources or more on a switching magnet.

The TRIPS proton source

The *TRA*smutazione *SCO*rie (TRASCO) project is an R&D programme whose goal is the design of an accelerator-driven system (ADS) for nuclear waste transmutation. The high-current CW proton linear accelerator will drive a subcritical system devoted to the transmutation of nuclear wastes [1]. The scheme of the whole accelerator is shown in Figure 1; it consists of a high-intensity proton source that provides the beam to a high-energy linac made up of an RFQ [2], and medium and high accelerator sections. The final goal is the complete a conceptual design of the linac up to energies greater than 1 GeV for a nominal proton current of 30 mA [3]. The accelerator design is carried out by different INFN laboratories and the LNS is in charge of the source design and construction.

Figure 1. The TRASCO accelerator scheme



The *TR*asco *I*ntense *P*roton *S*ource (TRIPS) is a high-intensity microwave source whose goal is the injection of a maximum proton current of 35 mA in the following RFQ, with a RMS normalised emittance lower than 0.2 p mm mrad; the operating voltage is 80 kV.

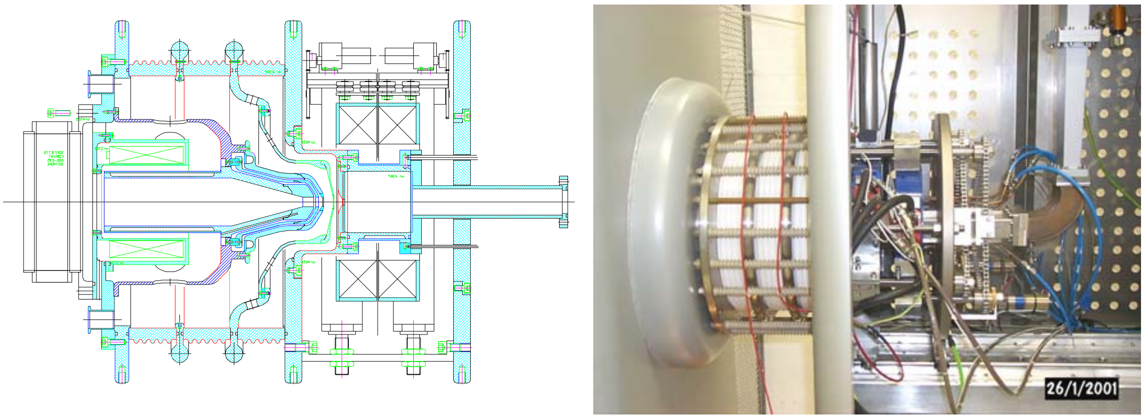
With respect to other sources for high-intensity applications, some new features have been added, according to the experience gained by the LNS Ion Source R&D Team with the high-intensity SILHI [4] source and with the high-efficiency MIDAS source [5]. The microwave matching system has been improved, an on-line movable coils system has been realised, and the extraction system has been optimised with the aim to increase the source availability and reliability in order to meet the requirements of the ADS driver.

The final design of TRIPS is shown in Figure 2, along with a photo of TRIPS on the 100-kV platform. The plasma is created by a 2.45-GHz, 2-kW magnetron coupled to the cylindrical water-cooled OFHC copper plasma chamber (100 mm long and 90 mm in diameter) through a circulator, a four-stub automatic tuning unit and a maximally flat matching transformer [6]. The transformer optimises the coupling between the microwave generator and the plasma chamber. It realises a progressive matching between the waveguide impedance and the plasma impedance, thus concentrating the electric field at the centre of the plasma chamber and increasing the proton fraction and the current density, which arrives up to 200 mA/cm^2, i.e. near the Child-Langmuir limit. A detailed description of TRIPS is given in Ref. [7]. The experimental set-up consisted at the beginning of a straight low-energy beam transfer line (LEBT) and only in 2003 did we installed a bending magnet in order to have a H$^+$ beam without contaminants.

Measurements of the beam emittance and space-charge compensation have been carried out with an emittance measuring unit (EMU) and a four-grid analyser (FGA) kindly provided by CEA, Saclay.

The measurements confirmed the computer code simulations, showing that the typical emittance of the source is between 0.07 p and 0.2 p mm mrad for currents between 30 and 50 mA (6-mm extraction hole). Our efforts were focused on the optimisation of the beam transport through the 30° dipole magnet, by changing some key parameters such as the puller voltage, the solenoid current and the RF power in order to minimise the beam aberrations and the space-charge effect.

Figure 2. The TRIPS ion source design and a photo of the source



Finally, we also checked the influence of beam line pressure on the space-charge compensation by using both the FGA and the EMU and injecting a controlled amount of nitrogen into the beam line, as had already been done with the SILHI source for different gases [8].

Figures 3 and 4 show the experimental set-up used in the measurements reported on here, with the EMU on the 0° branch and 30° branch, respectively. In the latter case we investigated both horizontal and vertical emittance (Figure 5). The section of the LEBT before the 30° dipole magnet consists of a direct-current current transformer (DCCT 1), a focusing solenoid, a four-sector ring to measure beam misalignments and a second current transformer (DCCT 2).

Figure 5 shows that the emittance does not change significantly in absolute values in the three situations, remaining around 0.14 p mm mrad for a 30-mA beam.

The normalised emittance decreases by putting the N_2 gas in the beam line, as shown in Figure 6; in fact we measured 0.148 p mm mrad with the N_2 and 0.185 mm mrad without N_2.

Figure 3. The low-energy beam transfer line with the emittance measurement unit on the 0° line

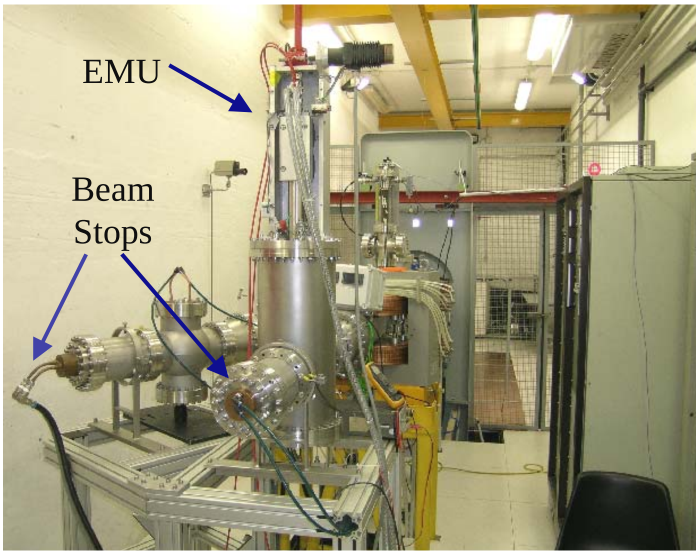


Figure 4. Emittance measurement unit on the 30 line (vertical and horizontal position)

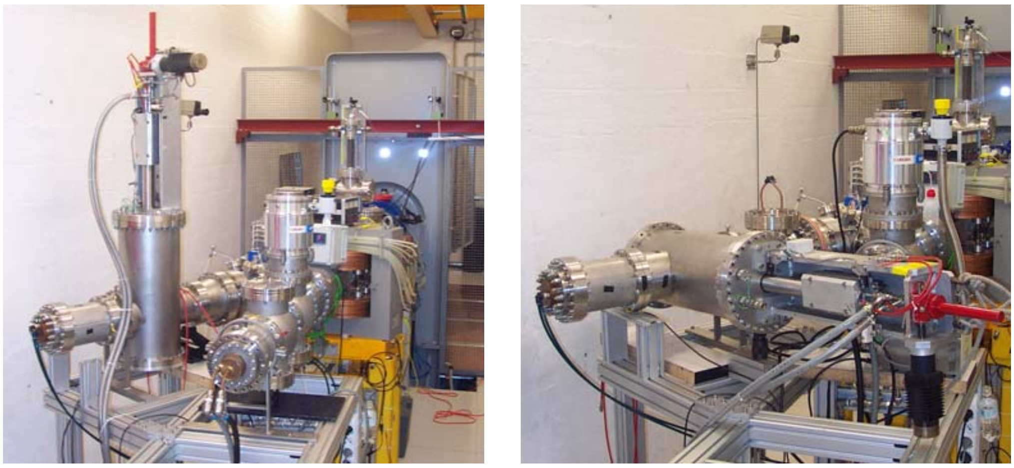
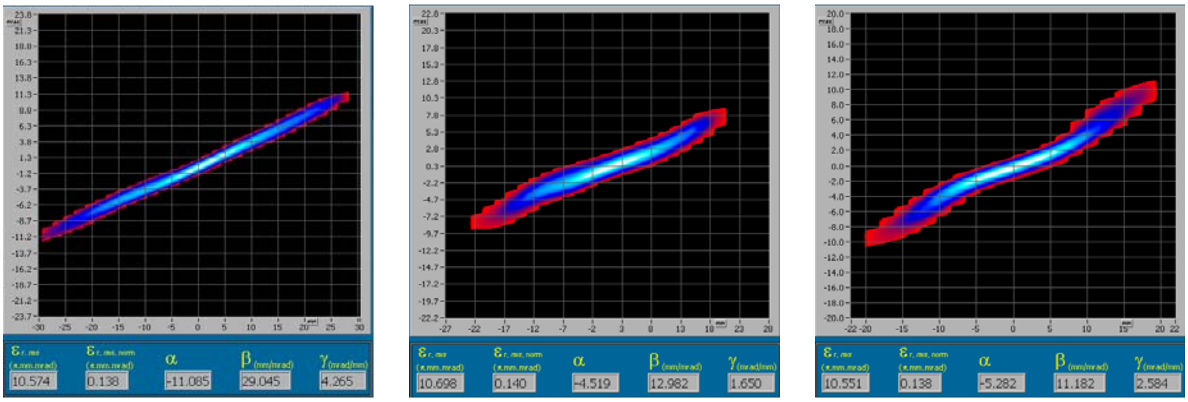
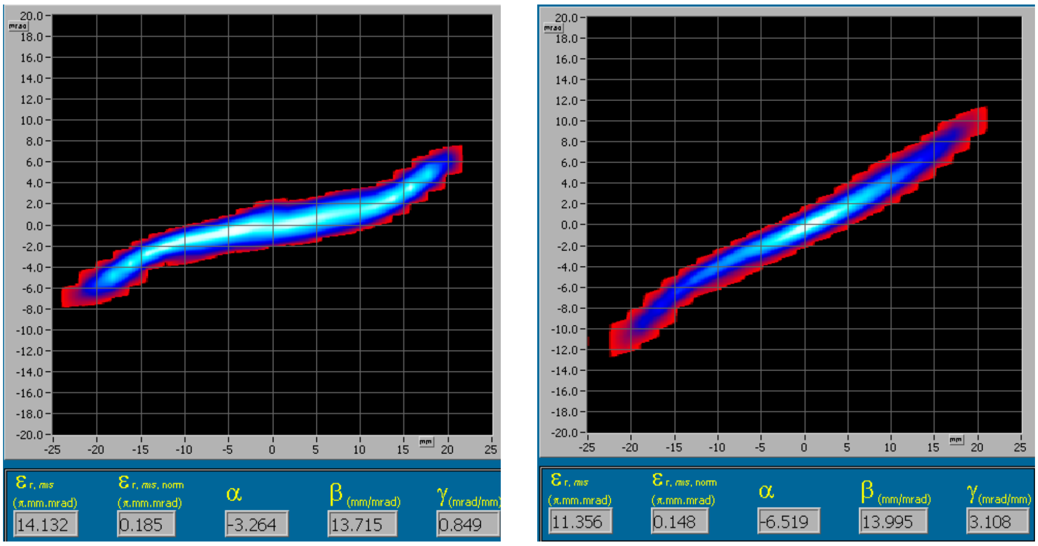


Figure 5. The proton beam emittance measured with: V_{extr} = 80 kV, I_{beam} = 30 mA respectively (from the left) on the 0° line, on the 30° line horizontally and vertically (e_{rms} » 0.14 p mm mrad)



$\varepsilon_{r,rms}$ (π.mm.mrad)	$\varepsilon_{r,rms,norm}$ (π.mm.mrad)	α	β (mm/mrad)	γ (mrad/mm)
10.574	0.138	-11.085	29.045	4.265
10.698	0.140	-4.519	12.982	1.650
10.551	0.138	-5.282	11.182	2.584

Figure 6. The RMS normalised emittance with and without N_2 in the 30° line with the EMU in horizontal position for beam current of 35 mA

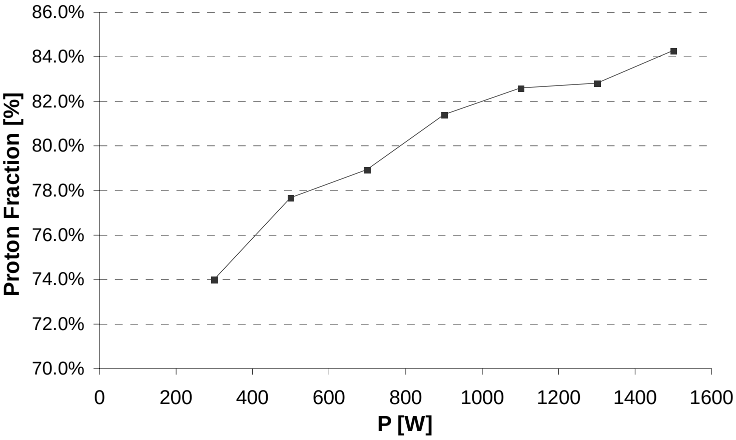


$\varepsilon_{r,rms}$ (π.mm.mrad)	$\varepsilon_{r,rms,norm}$ (π.mm.mrad)	α	β (mm/mrad)	γ (mrad/mm)
14.132	0.185	-3.264	13.715	0.849
11.356	0.148	-6.519	13.995	3.108

Comparing our measurements with those reported in [9], we also observed a little growth of the emittance because of the longer LEBT; in fact we passed from 0.138 p mm mrad to 0.156 p mm mrad with the RF power at 550 W and I_{sol} = 260 A.

The beam compensation was also measured, and it is always above 90% except for the case of a narrow beam close to the FGA, which was observed for a small range of solenoidal field between 240 and 260 A over 500 A. The measurements of proton fraction also provided satisfactory results, with values above 70% for beam power above 700 W (Figure 7).

Figure 7. The proton fraction vs. the RF power for a 80-keV, 35-mA proton beam



TRIPS reliability

The reliability is so crucial for the ADS driver that stringent requirements were demanded of the injector. In fact, beam availability close to 100% for long-term operations is mandatory for ADS purposes.

Such a value has not yet been achieved, but an encouraging value of 99.8% has been achieved on a long run test lasting over 142 h (see Figure 8). During the test two types of sparks were recorded:

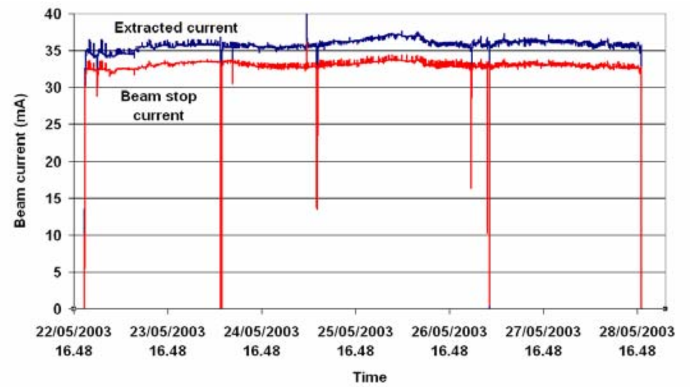
- Sparks that caused the interruption of source operations and required about two minutes to manually recover the beam at full intensity. Automatic recovery is under development.

- Sparks that are immediately recovered by the automatic procedures already implemented (the down-time is practically absent).

Two sparks of the first type and four sparks of the second type occurred, for a total of 99.8% reliability. The source did not require any particular tuning operations, except for slight variations of the hydrogen pressure in the plasma chamber. This parameter has a strong influence on the beam current stability, along with the discharge power. For this reason, feedback procedures have been implemented in the new control system and they are in the debugging phase.

Other than the high-voltage column and gas feedback, no other critical component was observed, with the exception of the microwave window, which may be changed once per 3 000 or 5 000 hours in order to prevent a vacuum breakdown which may stop the source for 24-48 hours.

Figure 8. The reliability test over 142 hours (reliability was 99.8%)



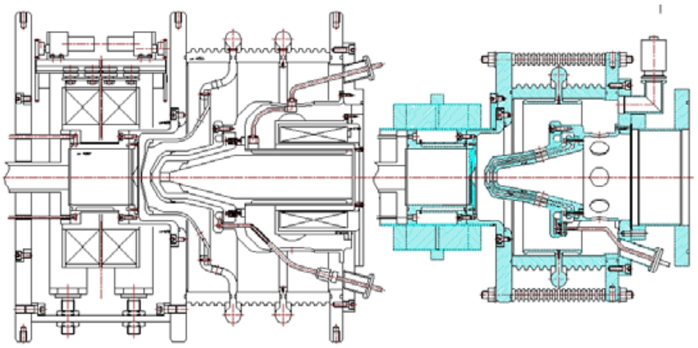
The optimum magnetic field and the PM-TRIPS design

In order to simplify the source and to increase the reliability of the injector, the construction of an optimised source called PM-TRIPS has been carried out.

The main modifications concern a simplification of the extraction geometry and of the extraction column, along with the replacement of the movable coils and power supplies with permanent magnets. This permits to avoid the use of a high voltage platform and of the insulation transformer, as the gas pipe and the microwave line will be insulated on their own. All the devices will be at ground potential except for the plasma chamber and the permanent magnets, which will make easier and more reliable the computer control of the source itself.

Figure 9 shows the design of PM-TRIPS compared with that of TRIPS. The plasma chamber and the microwave line are equal to the one used on TRIPS. The overall source dimensions are smaller due to a compact extraction system.

Figure 9. Comparison between TRIPS (left) and PM-TRIPS (right)

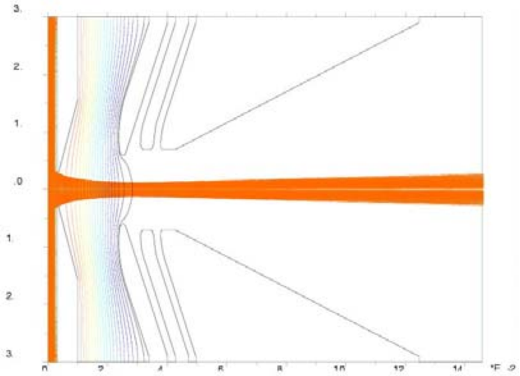


The extraction geometry was studied with the AXCEL code; with respect to the TRIPS source the extraction system was simplified by employing only four electrodes instead of five.

The five-electrode topology was chosen for TRIPS as it allows the on-line optimisation of the extracted beam and it is certainly important if the same source should work at a different current value. However, for a source designed to work continuously around a fixed current value, such flexibility can be sacrificed without a loss in terms of beam emittance.

The four-electrode system consists of a plasma electrode, made of molybdenum, two water-cooled grounded electrodes made of copper and a negatively-biased screening electrode, also made of copper, inserted between the two grounded electrodes, in order to avoid secondary electrons due to residual gas ionisation, going backwards. The shape, the extraction holes and the gap widths were recalculated with a special care to further reducing the extraction zone length, where the beam is not compensated. The RMS normalised emittance calculated 10 cm from the extraction electrode is 0.05 π mm mrad, which is almost the same as that calculated at the same position for the five-electrode configuration. Figure 10 shows a trajectory plot assuming a beam current of 40 mA (90% proton, 10% H^{2+}) with a space-charge compensation of 98% after the second grounded electrode.

Figure 10. Trajectory plot of the PM-TRIPS extraction system (units in cm)

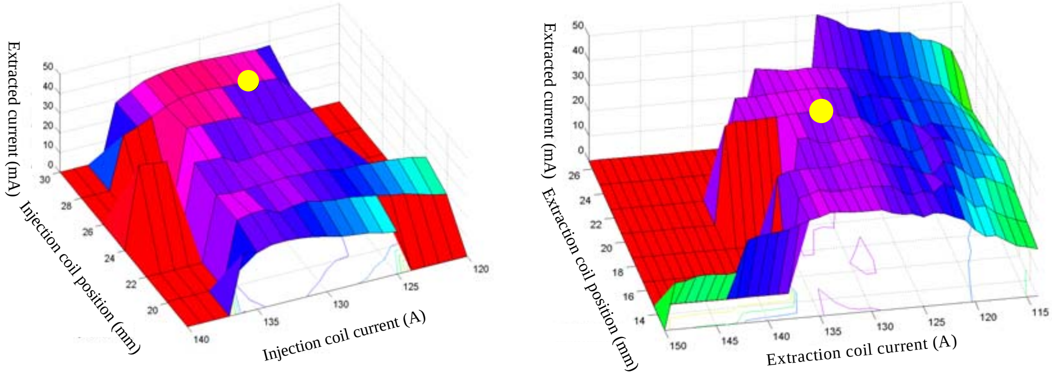


The other improvement consists of the optimisation of the permanent magnet system executing systematic measurements to obtain the best magnetic field profile for the TRIPS source by changing the coil positions and currents.

Figure 11 shows the beam current for different values of the coil current and position. From these measurements we concluded the following:

- The source is more sensible to variations of the extraction coil rather then to variations of the injection coil.
- The best performances are clearly obtained when the two ECR zones are located exactly on the BN disks, i.e. at the two ends of the plasma chamber.

Figure 11. The extracted current for different values of current and position of the two coils (the best operating point is represented by the dot)



We modelled the PM-TRIPS magnetic system with the aim to reproduce such an optimum field by using soft iron and permanent magnets. The magnetic system consists of a set of three VACODYM 745 HR permanent magnets, packaged together with two soft iron spacers and supported by a stainless steel tube. A good agreement has been found between the ideal TRIPS magnetic field and the expected magnetic profile produced by the permanent magnets, as shown in Ref. [9], where a full description of the magnetic measurements is available and the TOSCA modelling is reported.

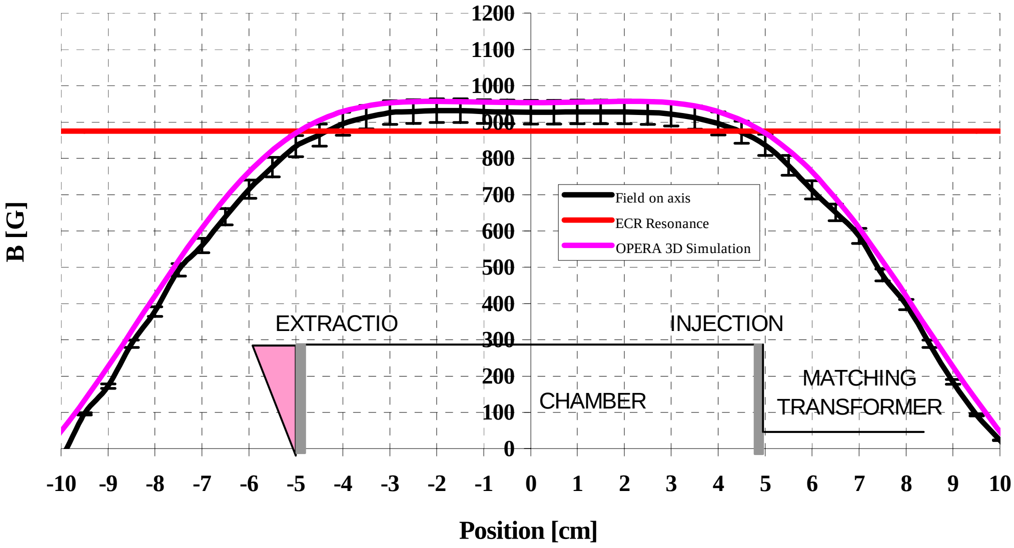
The PM-TRIPS and preliminary results

The magnets were delivered in April 2004 and were prepared for installation over the platform, in order to review the standard operation in the usual TRIPS environment before implementing a full HV insulation.

The magnetic field measurements were carried out with a special regard to the stray field over the extraction region which may generate a Penning discharge. The concern for the absolute values of the magnetic field inside the chamber was not so great; the plateau in Figure 11 shows that a change of few tens of Gauss may change the peak current only slightly.

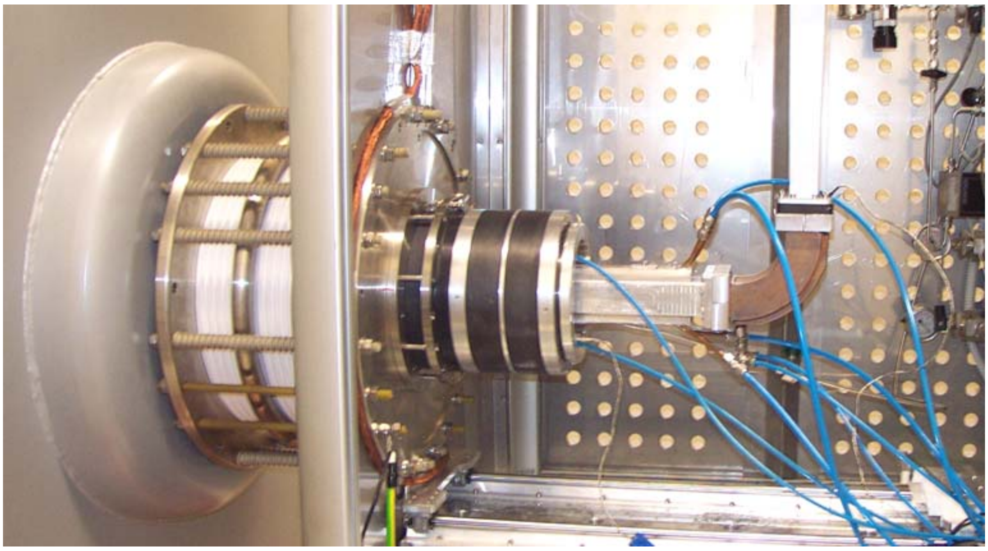
A good agreement has been found between the experimental PM-TRIPS magnetic field profile and the field calculated with the OPERA code (Figure 12).

Figure 12. Comparison of optimised PM-TRIPS measured field with that calculated using OPERA



The plasma was easily ignited without high voltage for the beam extraction, and the vacuum featured regular behaviour; but as soon as the high voltage was set on, a Penning discharge occurred in the extraction column. Because of this, we decided to stop the source tests until an effective shielding of the stray field in the extraction region is obtained. A study with the TOSCA code was begun and the preliminary calculations show that an existing spare VACODYM ring with an additional iron ring may dump the unwanted field down to acceptable values. Our goal is to decrease the stray field below the value that was obtained with the coil system (a few hundred Gauss). Figure 13 shows the PM-TRIPS temporary test bench.

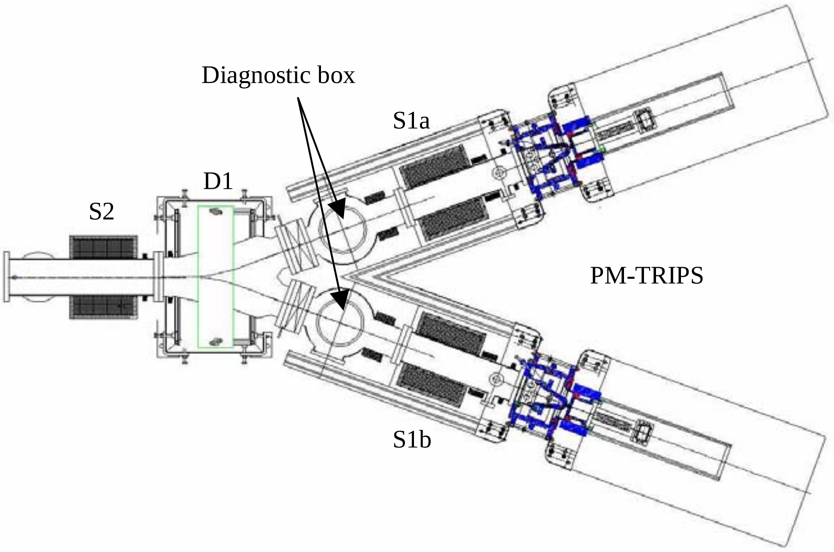
Figure 13. The PM-TRIPS source installed over the TRIPS platform



Low-energy beam transfer line (LEBT)

An important point for a further increase of the reliability in ADS plants is the redundancy of the sources. In fact, as the investment in the source is negligible with respect to the cost of the whole accelerator, the design of an injector with two sources working at the same time was considered, as shown in Figure 14. When a beam trip occurs the system would switch from one source to the other. This could be the solution to unexpected failures of the source in ADS plants. Such an operating mode could allow to schedule different periods of maintenance for each source while the other is working, thus permitting to provide the proton beam to the accelerator without interruption. Finally, the use of two sources in ADS plants is mandatory to maximise the mean time between failures (MTBF) and minimise the mean time to repair (MTTR).

Figure 14. The proposed injection scheme for ADS plants

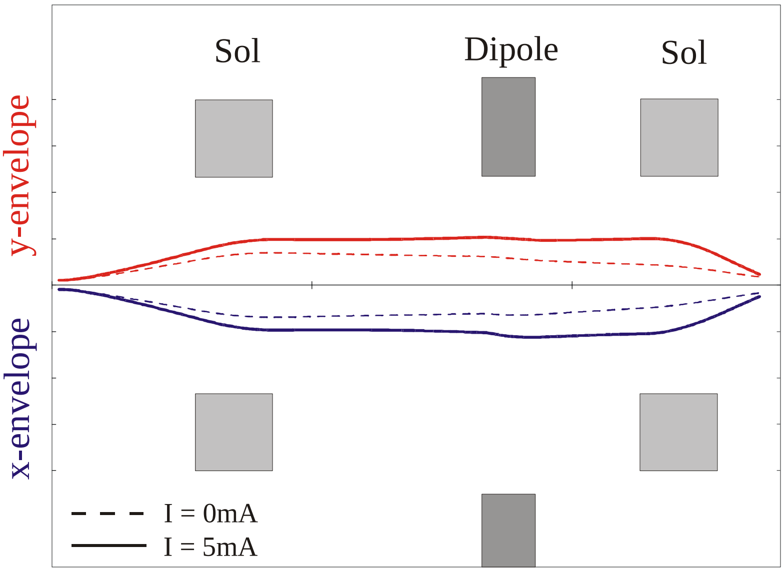


The system consists of two solenoids before and after a 20° dipole magnet. The length of the solenoids is 300 mm, but could be shortened, since in all calculations the magnetic field stayed well below 0.5 T. The dipole magnet was assumed to be rectangular; the beam enters the magnet under an angle of 20 , thus two sources can be coupled to the magnet. The overall length of the system is approximately 2.7 m.

Ion optical calculations were performed using the computer codes GICO and TRANSPORT. The initial phase space of the beam was assumed to be $x_0 = y_0 = -3$ mm and $a_0 = b_0 = -30$ mrad. Calculations were done for an H^+ beam, which is extracted with 80 kV voltage leading to a magnetic rigidity of approximately 0.041 Tm of the beam. Figure 15 shows the first-order beam envelopes in the x- and y-direction for a fully compensated beam (0-mA trace) and for a 35-mA proton beam with 85% of compensation (5-mA trace). It can be observed that an almost parallel transport is guaranteed for a relevant part of the LEBT and losses should be maintained low in such a manner. The separation between H^+ and H_2^+ is much larger than the dimensions of the two beams even in the presence of space-charge forces.

In both cases it is feasible to refocus the beam to a size of $x_{fin} \approx y_{fin} \approx -4$mm.

Figure 15. Layout of the PM-TRIPS beam transport line. First-order beam envelopes are drawn for an assumed uncompensated beam current of 0 mA (dashed lines) and 5 mA (solid lines), respectively.



Mid-term perspectives

The TRIPS source fulfilled all the requirements of the TRASCO/ADS project in terms of beam intensity, reproducibility, emittance and stability except for the high requested reliability at 80 kV.

The new configuration with a bending magnet permits easier operation of the facility and will improve the overall reliability. Higher-order calculations will soon be carried out to investigate the appealing possibility offered by two, simultaneously available compact sources.

We plan to solve the stray field problem of PM-TRIPS by June 2004, and then start to characterise the source over the HV platform. Afterwards, a full characterisation in the new environment (with insulated waveguide and gas pipe) will be performed.

Extensive reliability tests will be undertaken before the displacement of PM-TRIPS to the Laboratori Nazionali di Legnaro of INFN, where the source will be installed in 2005.

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TABLE OF CONTENTS

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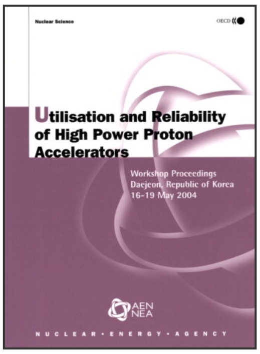

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