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1     Positron production using a 9 MeV electron linac for  
2                     the GBAR experiment

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49 **Abstract**

For the GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment at CERN's Antiproton Decelerator (AD) facility we have constructed a source of slow positrons, which uses a low-energy electron linear accelerator (linac). The driver linac produces electrons of 9 MeV kinetic energy that create positrons from bremsstrahlung-induced pair production. Staying below 10 MeV ensures no persistent radioactive activation in the target zone and that the radiation level outside the biological shield is safe for public access. An annealed tungsten-mesh assembly placed directly behind the target acts as a positron moderator. The system produces  $5 \times 10^7$  slow positrons per second, a performance demonstrating that a low-energy electron linac is a superior choice over positron-emitting radioactive sources for high positron flux.

50 *Keywords:* positron, linear accelerator, antimatter, antihydrogen,  
51 gravitation

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## 52 **1. Introduction**

53 An intense positron source is an indispensable constituent of all experi-  
54 mental setups which are used to study antihydrogen, the simplest anti-atom  
55 [1, 2, 3, 4]. Beyond their importance in antimatter research, positrons have  
56 been used for some time in materials science to study lattice defects and elec-  
57 tronic structure in metals, semiconductors and other solids [5, 6, 7, 8, 9] and  
58 as a sensitive probe in few-body atomic and molecular physics [10, 11, 12].  
59 Positronium has also found application in a variety of fundamental and ap-  
60 plied investigations [13, 14, 15]. Of particular relevance here is its use as  
61 a porosity diagnostic in polymers and porous oxides [13], via laser excita-  
62 tion in the elucidation of bound state leptonic physics and for applications  
63 in single-shot lifetime spectroscopy and the creation of Rydberg states [15].  
64 The advent of positron trapping and accumulation [16, 17] has facilitated the  
65 development of non-neutral positron plasma technology, which has provided  
66 new possibilities to manipulate and better control beam properties [18].

67 In the majority of these studies, and indeed for most modern experiments  
68 involving positrons, the ability to produce near-monoenergetic, low-energy  
69 beams in vacuum is the enabling technology. In this paper we present a slow  
70 positron beam based on a compact linac. The device provides positrons for  
71 the GBAR experiment at CERN, but similar systems could serve as the basis  
72 of versatile positron spectrometers for most of the areas of contemporary  
73 interest in the field, as outlined above.

74 In the following sections we introduce the GBAR project, then describe  
75 the experimental setup of the positron source: the linear electron accelerator,  
76 the electron target with the positron moderator and the positron beam line.  
77 In Section 7, 8 and 9 we discuss problems and solutions regarding radiation  
78 protection, beam diagnostics and electron background. Finally, we present  
79 the currently attained intensity of the positron source and characteristics of  
80 the beam in Section 10.

## 81 **2. Positron source for the GBAR experiment**

82 The GBAR collaboration aims at a precise measurement of the gravi-  
83 tational acceleration of antihydrogen in the gravitational field of the Earth  
84 [19, 20]. The GBAR scheme is based on the creation of a positive antihy-  
85 drogen ion (consisting of an antiproton and two positrons), which can be  
86 then sympathetically cooled to low temperature and neutralised by laser

87 photodetachment of one of the positrons. The resulting anti-atom is suf-  
 88 ficiently cold for the direct observation of the gravitational free fall. The  
 89 anti-ions are created in two consecutive reactions using a dense positron-  
 90 ium (Ps) cloud that serves as a target for antiprotons:  $\bar{p} + Ps \rightarrow \bar{H} + e^-$   
 91 followed by  $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$ . In the first step, an antiproton interacts  
 92 with a positronium to create an antihydrogen atom. Subsequently this newly  
 93 formed antiparticle reacts with a second positronium and produces a positive  
 94 antihydrogen ion. The anti-ion formation cross section is thus proportional  
 95 to the square of the positronium density, itself proportional to the positron  
 96 flux.

97 The experiment will receive antiprotons at 100 keV kinetic energy from  
 98 the new ELENA ring of the AD facility at CERN [21], which are then fur-  
 99 ther slowed down to a few keV energy by an electrostatic decelerator. The  
 100 expected intensity is  $4 \times 10^6$  antiprotons per pulse. In order to create one  
 101 anti-ion, this antiproton pulse must interact with a positronium target of  
 102 order  $10^{10} \text{ cm}^{-3}$  density. This high positronium density is obtained by im-  
 103 planting a pulse of the order of  $10^{10}$  positrons onto a converter consisting of  
 104 nanoporous silica. The positronium is formed in an  $1 \mu\text{m}$  thick porous silica  
 105 layer. The short lived (125 ps lifetime) spin singlets decay quickly while the  
 106 long lived (142 ns lifetime) spin triplets are released into the vacuum of a  
 107 cavity and form the positronium target cloud. As each antiproton must react  
 108 successively with two positronium atoms to form an anti-ion, the density of  
 109 the target cloud, hence the positron pulse intensity, is a crucial factor for the  
 110 success of the experiment. Positrons are first trapped in a buffer gas accu-  
 111 mulator [16, 22] and then collected in a high-field (5 T) Penning-Malmberg  
 112 trap [23] during the 110 s time lapse between two antiproton pulses, before  
 113 being ejected in an intense pulse onto the positron-positronium conversion  
 114 target. In order to be trapped the positron energy must be in the eV–keV  
 115 range (the so called slow positrons).

116 Low-energy positron generators most often use commercially available  
 117  $^{22}\text{Na}$  radioactive sources. Their activity is however limited in practice to  
 118 approximately 50 mCi (1.7 GBq), which in combination with a solid neon  
 119 moderator [24, 25, 26] can lead to a maximum of  $10^7$  low-energy positrons  
 120 per second. Furthermore, the half-life of  $^{22}\text{Na}$  is 2.6 years, thus the low-  
 121 energy beam intensity reduces over time and the source requires periodic  
 122 and complicated replacement. Devices using nuclear reactors [27, 28, 29, 30]  
 123 or large accelerator facilities [31, 32] can potentially provide a much higher  
 124 positron flux. However, for the GBAR experiment, where a high positron

125 intensity is crucial, a dedicated facility, with moderate size and cost, is the  
126 only feasible solution. We have thus chosen to construct a positron generator  
127 based on a low-energy linear electron accelerator because it has the potential  
128 to deliver a higher positron flux and at the same time it is compact enough  
129 to be placed in the available experimental area at CERN.

### 130 **3. Electron linear accelerator**

131 There have been a number of slow positron beam systems which used an  
132 electron linac as a positron source. The performance of a few of them is listed  
133 in Table 1. High-energy electrons hitting a dense metallic target abundantly  
134 generate positrons by pair production. However, these particles can only be  
135 used for beams after reduction of their energy by a positron moderator. The  
136 efficiency of the slow-positron production in the devices listed, defined as  
137 the number of slow positrons per electron impinging on the target, is in the  
138  $0.06 \times 10^{-7}$ – $15 \times 10^{-7}$  range. Potentially, higher efficiencies can be achieved  
139 by increasing the electron energy. However, the actual performance depends  
140 on the geometry of the target-moderator structure and efficiency is not the  
141 sole design criterion in many high-energy, high-power electron accelerators.  
142 Higher energy also requires a longer accelerator structure and a thicker bio-  
143 logical shield. In the case of the GBAR source in the AD hall, the radiation  
144 dose rate outside the biological shield must be compatible with public ac-  
145 cess. Even with electron kinetic energies as low as 9 MeV, the electron  
146 bremsstrahlung radiation produces neutrons by interacting with some nuclei  
147 present in the surrounding structural materials via the  $(\gamma, n)$  reaction. This  
148 process leads to the creation of short-lived radioisotopes in the vicinity of the  
149 electron target, but the total activation level is low and the target can be ap-  
150 proached immediately after switching off the linac. Above 10 MeV activation  
151 increases rapidly with energy. Dose-rate simulations showed that the size of  
152 the radiation shield at 18 MeV electron beam energy would be incompatible  
153 with the available volume and access to the target zone would be severely  
154 limited.

155 The GBAR electron accelerator (Fig. 1) is a water-cooled linac with a  
156 thermionic triode cathode, constructed by NCBJ (Poland). The microwave  
157 power is supplied by a 7.5 MW klystron (Thales 2157A), regulated by a  
158 solid-state modulator with pulse transformer from ScandiNova Systems. The  
159 accelerating section is composed of 18 cavities of 4.5 mm aperture radius  
160 with a total length of 900 mm. It is surrounded by a solenoid which provides

161 a 59 mT longitudinal magnetic field. The cavity is mounted in a vertical  
162 position. The accelerator produces electrons at 9 MeV kinetic energy (with  
163 0.5 MeV FWHM) in 2.85  $\mu$ s long pulses (FWHM). The repetition rate can  
164 be varied from 2 to 300 Hz. The peak electron current is 330 mA. The  
165 energy distribution has been verified by a magnetic dipole spectrometer. The  
166 size and position of the beam spot have been optimised by a removable  
167 YAG (yttrium aluminium garnet) screen, placed between the linac and the  
168 electron target and observed by a camera. The viewport and the camera  
169 of this diagnostic device have to be removed in normal operation, as they  
170 cannot withstand the very high radiation dose. Focusing and position of the  
171 electron beam can be controlled by a triplet magnetic lens system at the exit  
172 of the linac cavity. The beam can be focused to a spot as small as 3 mm in  
173 diameter. In the positron-production setting, we slightly defocus the beam  
174 spot, to approximately 5 mm diameter, in order to avoid local overheating  
175 of the target. The klystron and the accelerating section are both equipped  
176 with a closed-cycle water cooling system.

177 We constructed a test installation in CEA-Saclay [33] (in the following, we  
178 will refer to this system as the “Saclay source”) which is based on a 4.3 MeV  
179 linac with a magnetron as microwave source. It provides electron pulses with  
180 150 mA peak current, 2.5  $\mu$ s pulse length and 200 Hz repetition rate. The  
181 Saclay source produced  $2 \times 10^6$  slow positrons per second, a performance  
182 which is comparable with the yield of neon moderated isotope sources. The  
183 results proved that a source based on a low energy linac is a suitable device  
184 to supply positrons for the GBAR experiment. Some optimisation of the  
185 moderator and the target has been done with this facility.

#### 186 4. Linac target

187 In electron-linac-based sources, positrons are mostly created by the brems-  
188 strahlung radiation emitted by electrons impinging on a dense metallic tar-  
189 get with high atomic number. The energy spectrum of positrons generated  
190 by electrons at 9 MeV kinetic energy extends to approximately 7 MeV. It  
191 must be reduced in order to allow their subsequent transport and trapping.  
192 The “fast” antiparticles are slowed to an energy of a few electronvolts by a  
193 positron moderator [7, 8]. A high positron intensity requires a large power  
194 dissipated in the target, therefore both an efficient target cooling system  
195 and a sophisticated moderator configuration are important for high positron  
196 yield.

197 The linac target generates high energy positrons for subsequent modera-  
198 tion. It also produces a high flux of bremsstrahlung radiation which creates  
199 positrons in the moderator itself, this latter process being responsible for  
200 approximately 40 % of all slow positron output of the source. The tar-  
201 get is made of tungsten, as this metal was found to be the best choice for  
202 electro-production of positrons [34] because of its high atomic number and  
203 melting point. It has been designed to produce the highest number of slow  
204 positrons possible at 9 MeV electron energy while having sufficient cooling  
205 power to keep the target at moderate temperature. The thickness of the  
206 target has been optimized by simulating the stopping profile of positrons,  
207 created by electrons implanted into a thick tungsten plate (Fig. 2), using  
208 the GEANT4 simulation toolkit [35]. As we use tungsten for both the target  
209 and the moderator, the maximum of the stopping profile gives the depth  
210 where the highest number of slow positrons are produced in the moderator  
211 behind a target of a given thickness. Figure 2 shows that the maximum of  
212 slow-positron production efficiency is at approximately 1 mm depth. In the  
213 case of the GBAR linac the optimal thickness is used with a simple static  
214 construction, without rotating target or scanning of the beam, as the cooling  
215 system is able to absorb the power deposited in a 1 mm thick target. Al-  
216 though the Monte Carlo simulation is reliable only down to a few hundred  
217 electronvolt positron kinetic energy, the calculated profile is very close to the  
218 actual stopping profile because positrons in this energy range do not move  
219 more than 100 nm before thermalisation. Consequently, the calculated stop-  
220 ping profile is a good approximation for the depth dependency of positrons  
221 which are available for the final phase of moderation. The maximum yield  
222 is a broad function of the depth, with marginal changes only at the scale  
223 of the thickness of the moderator. The target is perpendicular to the beam  
224 axis. To improve heat conduction, it is machined in the form of a 5 mm  
225 diameter, 1 mm thick disc, milled out of a thicker tungsten block. It is in  
226 turn attached to a water-cooled copper structure. When the linac works at  
227 nominal power, the target assembly absorbs 1.5 kW. On the basis of a finite  
228 element calculation we estimate the temperature of the target as 1400 K.  
229 This high temperature is localized to the electron beam spot, the rest of the  
230 target structure is efficiently cooled by the water circuit.

## 231 5. Positron moderator

232 In the positron moderation process, high-energy positrons are implanted  
233 into a solid where they lose energy until they are close to thermal equilib-  
234 rium with the crystal lattice [8]. Some of the thermalized positrons reach  
235 the surface by diffusion. In the case of tungsten and some other materi-  
236 als, the work function of positrons is negative, i.e., the particles gain energy  
237 when they leave the metal. Only positrons that reached thermal energy  
238 in the vicinity of the surface, in a depth range in the order of 100 nm,  
239 have a chance to be emitted from the moderator. Positronium formation  
240 and positron-electron annihilation are other possible surface processes which  
241 limit the efficiency. Altogether, moderation is a near-surface process and its  
242 efficiency increases with the useful emitting area of the moderator structure.  
243 However, in complicated moderator structures most slow positrons can only  
244 leave the moderator after one or more collisions, with a significant proba-  
245 bility of loss at each interaction. Intense sources based on the  $^{22}\text{Na}$  isotope  
246 most often use solid neon kept at 7 K as moderator. The high power due  
247 to the scattered electron beam and high-energy gamma rays in the target  
248 zone makes application of a cryogenic moderator very difficult in the case of  
249 accelerator-based systems. In linac-based systems the moderator is usually a  
250 structure made of metallic plates or foils, annealed at high temperature. The  
251 material chosen is most often tungsten due to its high efficiency and relative  
252 stability [36, 37, 38, 39, 40, 41, 42]. The number of “fast” positrons created  
253 in the target increases quickly with electron energy. However, the mean en-  
254 ergy of the positrons increases as well, which entails a decrease in moderator  
255 efficiency. This effect attenuates the gain that arises from increasing the  
256 electron energy.

257 The simplest type of metallic moderator is a thin foil that must be an-  
258 nealed at high temperature in order to release slow positrons efficiently.  
259 High-temperature annealing removes defects and thereby increases the ef-  
260 fective diffusion length of low energy positrons in the metal. Furthermore,  
261 it cleans surface contamination and reduces the loss of positron emission  
262 through positron trapping at the surface or positronium creation. In order  
263 to increase the slow-positron yield, we have chosen a stack of tungsten mesh  
264 pieces as a moderator because this is a structure with a large surface per  
265 unit mass, readily available and easy to heat using electrical current. Similar  
266 structures have been found to have a higher moderator efficiency than a thin  
267 tungsten foil [43, 44, 45]. While positrons from a  $^{22}\text{Na}$  source with 180 keV

268 mean kinetic energy are quickly absorbed in a few layers of commercially  
269 available mesh, in the case of an electron-beam-based source, the number of  
270 moderated positrons emitted per unit area is independent of the depth in  
271 the stack of moderator layers, because of the broad stopping profile. Con-  
272 sequently, the advantage of a larger specific surface area is expected to be  
273 even more enhanced than in the case of isotope sources where the intensity of  
274 fast positrons emitted from the source is quickly attenuated in the moderator  
275 stack. Slow positrons emitted from a surface deep in the moderator stack can  
276 only escape if they undergo a few collisions with the wires of the mesh. The  
277 loss during the collisions limits the gain attained with an increased number of  
278 layers, leading to an optimal thickness. A further factor which influences the  
279 efficiency is the temperature of the moderator, which depends on the energy  
280 deposited in the moderator, which in turn also depends on the thickness.

281 The stack of thin tungsten mesh pieces is mounted 2 mm behind the elec-  
282 tron target (Fig. 3), parallel to the target. A woven wire mesh of 0.0008”  
283 (20.3  $\mu\text{m}$ ) thickness was used with 180 wires/inch density (141  $\mu\text{m}$  wire dis-  
284 tance). The mesh pieces were annealed in a vacuum chamber, with a pressure  
285 lower than  $10^{-7}$  mbar, using an electrical current giving a power density of  
286 about  $100 \text{ W/cm}^2$ . They were mounted on a stainless steel moderator holder  
287 in air and moved into the target chamber in typically less than 15 minutes.  
288 The moderator is biased at +50 V. The extraction electrode is a simple  
289 grounded plate with a 20 mm diameter hole located 27 mm downstream of  
290 the target. This simple design ensures that the electrode is not excessively  
291 heated by the electron beam. Simulations have shown that the extraction  
292 field does not have a significant negative effect on the beam quality. The  
293 slow positron yield was measured by a NaI scintillator coupled to a photo-  
294 multiplier at the exit point of the biological shield.

295 We performed measurements using the Saclay source to optimize the  
296 positron moderator. Its ideal thickness was obtained by measuring the slow-  
297 positron yield as a function of the number of mesh layers in the moderator  
298 stack (Fig. 4). The experimental uncertainty is dominated by the differ-  
299 ence in the properties of the electron beam between two measurements, as  
300 changing the moderator thickness is a time consuming procedure and each  
301 measurement was performed after a new start of the accelerator. We esti-  
302 mate this error to approximately 10 % of the signal. We found that the  
303 positron yield increases nearly linearly with the number of mesh layers up  
304 to about 9 layers, then the signal levels off. We concluded that the opti-  
305 mal thickness of the moderator is approximately 12 layers. In the figure,

306 results of a simple Monte Carlo simulation are also shown, using a probabil-  
307 ity of slow positron reflection from the surface of the wire of 0.56 [46]. The  
308 simulation was normalized to give the same efficiency value as the measure-  
309 ment at a thickness of 12 layers. As it is also visible in the simulation, we  
310 expect a small increase in positron yield between 12 and 15 layers. The ap-  
311 parent decrease in the measured values is compatible with the experimental  
312 uncertainty. Nevertheless, no significant improvement can be expected by  
313 increasing the number of mesh layers beyond 12 layers. As the change in the  
314 stopping profile of positrons within the thickness of the moderator is small,  
315 the density of positrons created per unit surface area is nearly independent  
316 of the depth within the moderator. Consequently, if the moderator efficiency  
317 per unit surface is unchanged we expect that the optimal thickness is the  
318 same at 4.3 MeV and 9 MeV electron energy, for the Saclay source and at  
319 CERN, respectively. This approximation does not take into account the loss  
320 of efficiency due to the increase in temperature with increasing moderator  
321 thickness, an effect which is significant in the case of the CERN beam (see  
322 below and 10.1).

323 We compared the efficiency of the optimized moderator stack with that  
324 of a simple flat moderator, placed in the same position. We used pieces of  
325  $25\ \mu\text{m}$  thick and 1 mm wide tungsten ribbon to construct a flat moderator.  
326 This geometry allows heating the metal by electrical current in the same  
327 chamber as done for the tungsten mesh. The difference between the geom-  
328 etry of the ribbon and that of the tungsten-mesh moderator was taken into  
329 account using a Monte Carlo simulation of the target-moderator structure.  
330 The simulation provides the density distribution of moderated positrons in  
331 the plane of the moderator. The efficiency of the flat moderator was ex-  
332 perimentally found to be only  $17 \pm 5\%$  of the efficiency of the optimized  
333 mesh configuration, which confirms the expectation that mesh moderators  
334 have significantly higher efficiency than thin foils, particularly, as here, for  
335 positrons incident with kinetic energies in the MeV range.

336 We also studied the effect of the temperature on the moderator efficiency  
337 at the Saclay source using *in-situ* heating of a single moderator mesh by  
338 electrical current (Fig. 5). The moderator was placed just behind the electron  
339 target, in a similar position as the standard moderator stack used in the  
340 setup. We estimated the temperature of the moderator on the basis of the  
341 heating power and radiative heat transfer, using an emissivity of 0.3 for  
342 the tungsten wire. As the exact value of the emissivity of the used wire is  
343 not known, the experimental error of the temperature is rather large. In

344 the figure, the error bar represents the range of temperature determined  
345 expecting an emissivity between 0.2 and 0.4. The uncertainty in the positron  
346 signal is limited to small fluctuations in the electron beam intensity during  
347 the measurement. We found that the moderator efficiency decreases by as  
348 much as 30 % between room temperature and 800 K, then continues to  
349 decrease more slowly dropping to about 15 % at 2800 K. The result is in  
350 qualitative agreement with the measurements of Al-Qaradawi et al [47]. The  
351 loss of efficiency can be attributed to the increasing positronium formation  
352 at the moderator surface at elevated temperature. As positronium formation  
353 competes with the emission of slow positrons from the surface of the tungsten  
354 mesh, this leads to a decrease in moderator efficiency.

355 We performed *in-situ* annealing of the moderator mesh using the same  
356 experimental setup. The intensity of the slow positron beam was measured  
357 after heating the mesh for 3 minutes at various heating power levels. Figure  
358 6 shows the positron flux as a function of the estimated annealing tempera-  
359 ture. The experimental uncertainties are the same as in the case of Figure  
360 5. The moderator efficiency is very low in the case of an unannealed mesh.  
361 The positron signal starts to increase above 1800 K annealing temperature  
362 and increased roughly linearly until 3000 degrees. This result illustrates the  
363 importance of annealing of the moderator at the highest temperature which  
364 is technically possible.

## 365 6. Positron transport

366 The target is surrounded by two coils in the Helmholtz configuration  
367 arranged co-axially with the same axis as that of the accelerating section.  
368 They produce a field that can be varied up to about 20 mT at the target  
369 location. Positrons are adiabatically guided by an 8 mT magnetic field which  
370 is generated by solenoids wound around the 100 mm diameter vacuum pipe  
371 (Fig. 1). At vacuum valves, bellows and other vacuum elements, larger coils  
372 are used to provide a smooth field. At each elbow, two pairs of racetrack coils  
373 introduce a variable dipole field that can be used for steering the positron  
374 beam. The total length of the beam transfer line between the electron target  
375 and the entry point of the positron trap is approximately 7.5 m. The “S”  
376 shaped part of the beam trajectory before the vacuum valve is in the zone  
377 where the beam line crosses the biological shield and a reinforcement of the  
378 radiation shield is necessary to avoid leakage of gamma radiation from the  
379 linac bunker.

## 380 7. Radiation protection

381 The intense electron pulses produce a very high radiation dose rate (up  
382 to 30 kGy/h) in the vicinity of the target chamber. Thus, the linac and the  
383 target chamber are placed in a bunker of approximately  $10 \times 11$  m footprint  
384 with 1.2 m thick walls, constructed from 67 % concrete and 33 % iron blocks.  
385 A stainless steel shielding box, with 40 mm thick walls, has been installed  
386 around the target, to protect the equipment in the linac bunker. This reduces  
387 the radiation dose by about a factor of 3 inside the bunker, and consequently  
388 outside. The radiation dose rate outside the bunker is sufficiently low for  
389 unlimited access. This means that it might be possible to contemplate the use  
390 of this relatively compact type of instrumentation in small laboratories. We  
391 observed a slight short-term activation of the mechanical structure around the  
392 linac target but it never exceeded a few  $\mu\text{Sv/h}$  equivalent dose rate at 400 mm  
393 distance from the target. Use of lead as shielding material is prohibited at  
394 this energy, as it would significantly increase the level of activation.

## 395 8. Positron diagnostics

396 In order to measure the positron flux at the end of the transport line [48],  
397 a 0.5 mm thick stainless steel plate is used as a beam diagnostic target. The  
398 target is mounted on a linear drive and can also be used as a scraper to  
399 estimate the beam size. A NaI(Tl) scintillator (50.8 mm diameter, 50.8 mm  
400 length) attached to a photomultiplier tube is used to detect 511 keV photons  
401 from positrons annihilating on the diagnostic target. The detector is placed  
402 at 800 mm distance from the target, so that the systematic error caused by  
403 uncertainties of the geometry can be neglected and calibration with single  
404 annihilation gamma photons can be used. To calibrate the detector efficiency,  
405 we first measured the mean electrical charge corresponding to the 511 keV  
406 photopeak at the anode of the photomultiplier ( $Q_{511\text{keV}}$ ). In a second step we  
407 determined the mean energy  $E_a$  that is deposited in the scintillator crystal  
408 after annihilation of one positron in the target. This was done by a Monte  
409 Carlo simulation of the detection using the GEANT4 package [35]. The simu-  
410 lation takes into account scattering in the environment of the positron target  
411 (vacuum pipe, target holder, vacuum flanges), the solid angle of the detector  
412 and Compton scattering in the scintillator. The charge corresponding to the  
413 photopeak is corrected by the factor determined in the simulation to obtain

414 the mean charge  $Q_m$

$$Q_m = Q_{511keV} \frac{E_a}{511 \text{ keV}} \quad (1)$$

415 from the annihilation of one positron in the target. At the detector distance  
416 used, each positron pulse produces on average only a few tens of 511 keV  
417 annihilation photons that reach the detector. This allows the determination  
418 of both the single-photon signal and measurement of the diagnostic signal  
419 with a moderate dynamic range.

420 In order to measure the momentum distribution of the positrons parallel  
421 to the beam axis, we used the first electrodes of the buffer-gas trap as a  
422 retarding field analyser. The relevant part of the trap consists of a series of  
423 tubular electrodes with an inner diameter of 16 mm and a total length of 149  
424 mm. In this case the positron flux was measured by detecting the annihilation  
425 gamma signal generated by positrons impinging on a target behind the last  
426 electrode by a plastic scintillator coupled to a photomultiplier. The trap is  
427 directly behind the positron diagnostic target and the magnetic field is 60 mT  
428 at the place of the measurement. The tubular electrodes are sufficiently long  
429 to ensure that the electric potential at the center is equal to that of the  
430 electron tube. The energy distribution can be deduced from the electrode  
431 voltage - positron annihilation signal curve. A fit of the measured values with  
432 a complementary error function shows a good agreement with  $\sigma_{\parallel t} = 4.2 \text{ eV}$   
433 fitting parameter, corresponding to a Gaussian energy distribution with  $\sigma_{\parallel t}$   
434 standard deviation (Fig. 7).

## 435 9. Electron background

436 Electrons are generated in the linac target chamber with a wide range of  
437 kinetic energies. Low-energy electrons are adiabatically guided together with  
438 the positron beam. Below  $\sim 100 \text{ eV}$  the electron background is several orders  
439 of magnitude stronger than the positron flux and we observe a significant  
440 number of electrons even above 2 keV kinetic energy. This background is  
441 not noticed in most applications (positron spectroscopy) but gas ionisation  
442 by electrons is potentially deleterious in buffer-gas traps. Only a potential  
443 barrier of about -5 kV can fully eliminate the electron background. A high-  
444 transparency (90 %) metallic grid at negative potential is used to block most  
445 electrons. Acceleration and subsequent deceleration of positrons by the grid  
446 leads to a deterioration of the beam quality, therefore the potential on the  
447 grid must be limited to the lowest possible level. We found that the best

448 trapping efficiency in the buffer gas trap is attained for a grid potential of  
449 -500 V.

## 450 10. Results

### 451 10.1. Positron flux

452 A steady-state positron flux of  $5.0 \pm 0.6 \times 10^7$  per second was detected  
453 at the diagnostic target at 300 Hz repetition frequency [48]. The number  
454 of positrons per linac pulse measured as a function of the repetition rate  
455 is shown in Figure 8. It decreases almost linearly by about 50 % between  
456 10 Hz and 300 Hz, most probably due to the increase of the moderator  
457 temperature with increasing linac frequency. The uncertainty of the positron  
458 intensity measurement is limited to the effect of small fluctuations in the  
459 beam intensity, estimated to 5 %. The moderator is heated directly by the  
460 electron beam (estimated as 150 W at full power by simulation) and indirectly  
461 by thermal radiation of the linac target. With no efficient cooling by heat  
462 conduction, its temperature is determined by radiative equilibrium.

463 The positron source has been running at full power for an extended pe-  
464 riod of time (more than 1000 hours). After installing a fresh moderator, the  
465 slow-positron yield stabilized after a short transition period (typically a few  
466 hours). On a longer time scale, there is a slow deterioration with accumu-  
467 lated electron dose. The long term deterioration of the positron yield can be  
468 attributed to both surface contamination and accumulation of lattice defects  
469 [49].

### 470 10.2. Energy distribution and beam shape

471 Tungsten mesh moderators are characterised by a rather broad angular  
472 distribution of the emitted positrons due to the microstructure of the moder-  
473 ator stack. This leads to a longitudinal momentum distribution  $p_{\parallel}$  that can  
474 be translated into an energy  $E_{\parallel} = \frac{p_{\parallel}^2}{2m}$  with a total width of approximately  
475 3 eV, the work function of tungsten. The broadening may be slightly in-  
476 creased by the electric field which penetrates into the mesh stack and may  
477 extract some positrons which are emitted backwards. The  $E_{\parallel}$  distribution  
478 measured by the energy analyzer depends on the magnetic field (B) at the  
479 location of the moderator and of the energy analyser.  $E_{\parallel}$  measured at 60 mT  
480 magnetic field (Fig. 7) can be fitted by a Gaussian with  $\sigma_{\parallel t} = 4.2$  eV. Assum-  
481 ing a fully adiabatic beam transport this width translates to  $\sigma_{\parallel m} = 0.7$  eV (1.6

482 eV FWHM) in the 9.7 mT magnetic field at the position of the moderator,  
483 using the fact that  $E_{\perp}/B_{\parallel}$  is an adiabatic invariant and the total kinetic en-  
484 ergy  $E = E_{\parallel} + E_{\perp}$  is constant. The latter assumption is only approximately  
485 fulfilled due to the non-zero width of the energy distribution of positrons  
486 emitted from the tungsten surface. The width of the energy distribution at  
487 the moderator is comparable with the 2.1 eV FWHM value found using a  
488  $^{22}\text{Na}$  positron source [50].

489 The beam diameter at the positron target can be estimated from measure-  
490 ments with the beam scraper (Fig. 9). We found that approximately 80 %  
491 of the positron intensity falls into a 13 mm broad vertical zone. In the case  
492 of adiabatic transport the beam diameter depends on the size of the positron  
493 emitting spot on the moderator and strength of the magnetic field at both  
494 the moderator and the beam scraper. The observed size is in agreement with  
495 the expected size of the positron emitting surface of the moderator stack.

## 496 11. Conclusions and outlook

497 We built and successfully commissioned a positron generator which is  
498 based on a compact, low-energy linear electron accelerator. The system  
499 provides  $5.0 \pm 0.6 \times 10^7$  e<sup>+</sup>/s positron flux, which is fed into a buffer-gas  
500 trap. The positron flux reached is comparable to or higher than most linac-  
501 based positron beams which use significantly higher electron energy. We  
502 have demonstrated that a low-energy linac, with no persistent activation of  
503 the environment, is a good alternative to radioactive sources when a high  
504 positron flux is needed, and as such may find wide uptake. Compared to  
505 other linac-based sources (Table 1) the GBAR source provides excellent flux  
506 for its input power and energy. The source will be the first of its kind to  
507 be used to fill a high-field Penning-Malmberg trap and it can also serve as a  
508 test bench for the application of positron traps at accelerator-based positron  
509 beams.

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Linac	e <sup>-</sup> energy MeV	e <sup>-</sup> beam power W	slow e <sup>+</sup> flux 10 <sup>7</sup> e <sup>+</sup> /s	efficiency 10 <sup>-7</sup> e <sup>+</sup> /e <sup>-</sup>
Oak Ridge [38]	180	55000	10	0.53
Livermore [37]	100	11000	1000	16
ETL, Japan [39]	75	300	1.0	6
KEK [41]	55	600	5	7.3
Ghent [40]	45	3800	2	0.4
Giessen [36]	35	3500	1.5	0.2
Mitsubishi, Japan [42]	18	16	0.077	1.35
GBAR, CERN	9	2500	5	0.28
Saclay, CEA [33]	4.3	300	0.2	0.05

Table 1: Performance of linac-based positron sources.

742 **13. Figures**

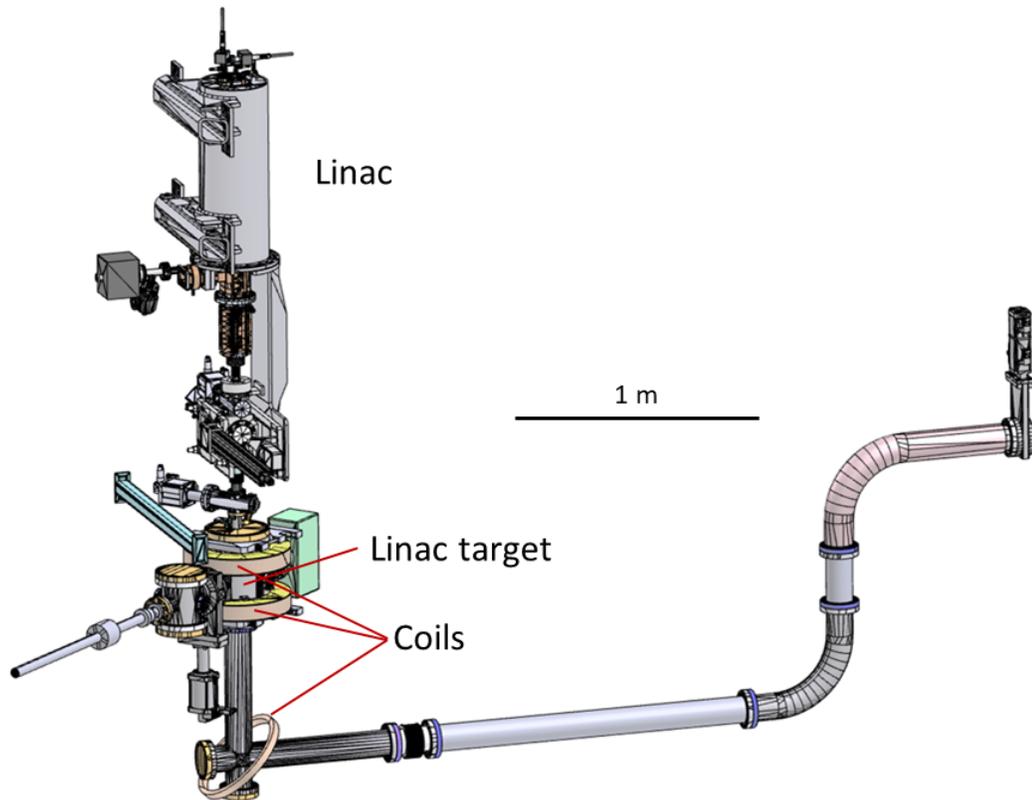


Figure 1: Schematic view of the linac (vertical structure on the left) and the positron transfer line. The transfer fields are generated by solenoids wound around the beam pipes and by the two larger coils placed around the linac target. The coil at 45 degrees position is used to fine-tune the magnetic field at the point where the positron beam turns sharply. The beam line crosses the biological shield at the “S” shaped section on the right.

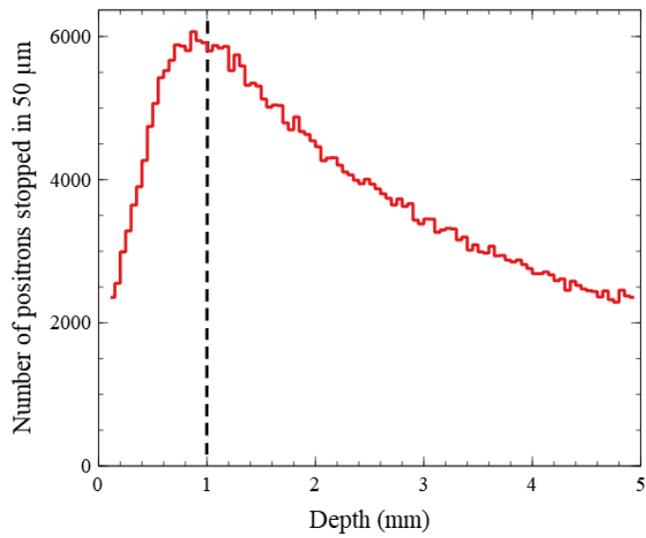


Figure 2: Positrons created by 9 MeV electrons and stopped in a tungsten plate (GEANT4 simulation with  $10^7$  electrons). The number of positrons annihilating in 0.05 mm thick layers is plotted as a function of the depth. The dashed line at 1 mm shows the thickness of the actually used electron target.

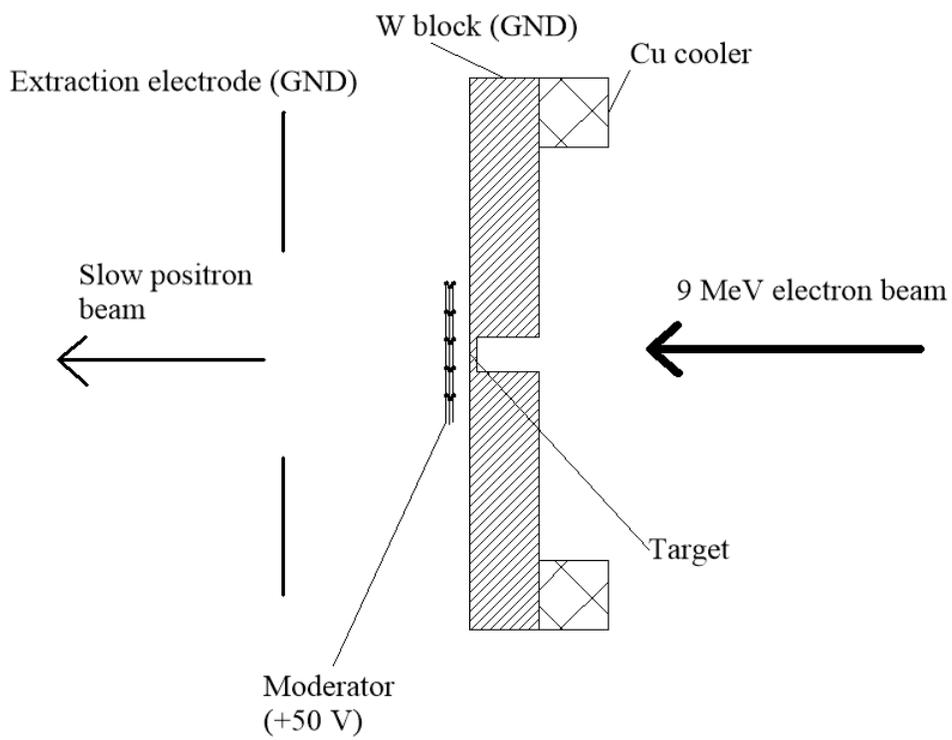


Figure 3: Cross section of the electron target. The potential of the moderator is +50 V, the rest of the structure is at ground (GND). The copper block (“Cu cooler”) is water cooled. The magnetic field of 9.7 mT is parallel with the electron and positron beams.

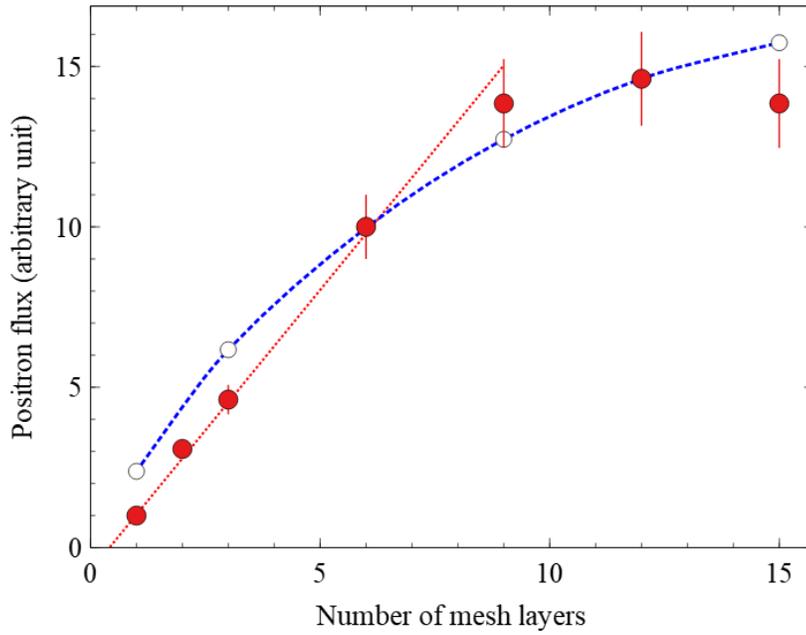


Figure 4: Slow positron flux as a function of the number of mesh layers (solid circles). Each layer is a 18x18 mm piece of tungsten mesh with 180 wires/inch density, annealed at higher than 2700 K temperature. The measurement was performed using the 4.3 MeV Saclay linac with a 1 mm thick tungsten target. A linear fit of the data points up to 9 layer thickness is shown with a dotted line. Results of a simple simulation (see text) are displayed with open circles. The dashed line is guide for the eye.

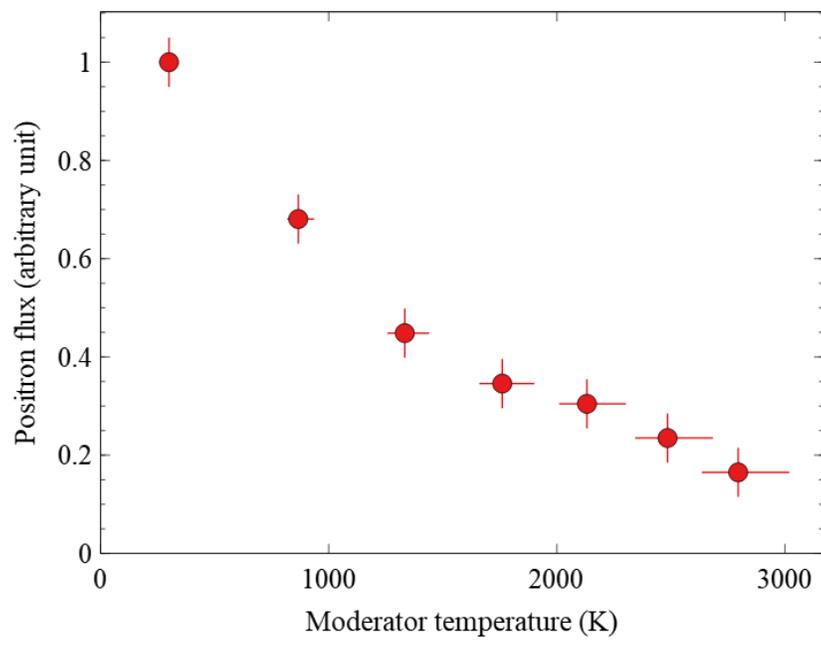


Figure 5: Slow positron flux as a function of the moderator temperature. The measurement was performed using the 4.3 MeV Saclay linac with 1 mm thick tungsten target. The temperature was estimated on the basis of the heating power and radiative heat exchange.

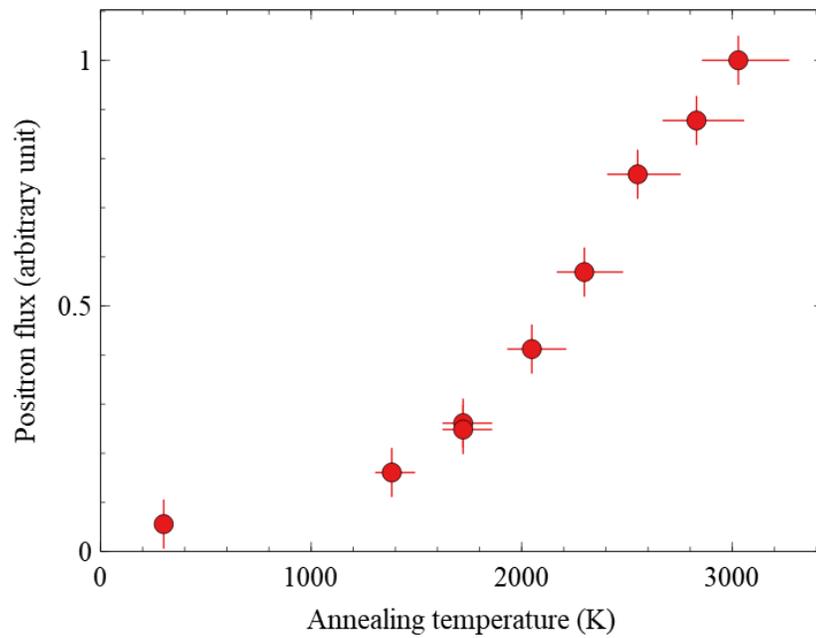


Figure 6: Slow positron flux as a function of the moderator annealing temperature. The measurement was performed using the 4.3 MeV Saclay linac with 1 mm thick tungsten target. The temperature was estimated on the basis of the heating power and radiative heat exchange.

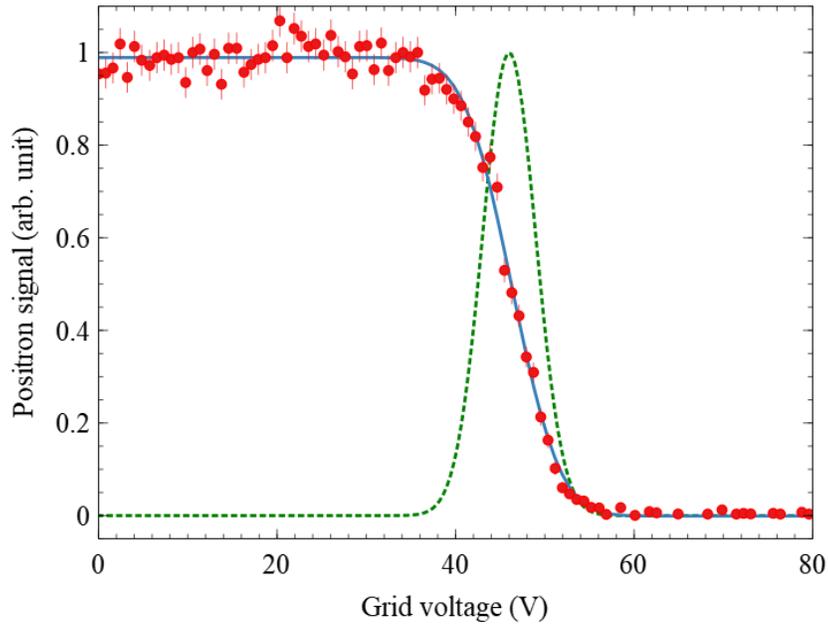


Figure 7: Positron annihilation signal as a function of the voltage of the grid of the retarding field analyzer at 50 V moderator voltage. At low grid potential all positrons are annihilated on the target while above approximately 60 V all particles are repelled by the grid and no positron signal is detected. The continuous line is a fit with a complementary error function, giving  $\sigma_{\parallel t} = 4.2$  eV. The dotted line shows the corresponding Gaussian energy distribution. The measurement was performed in a 60 mT longitudinal magnetic field.

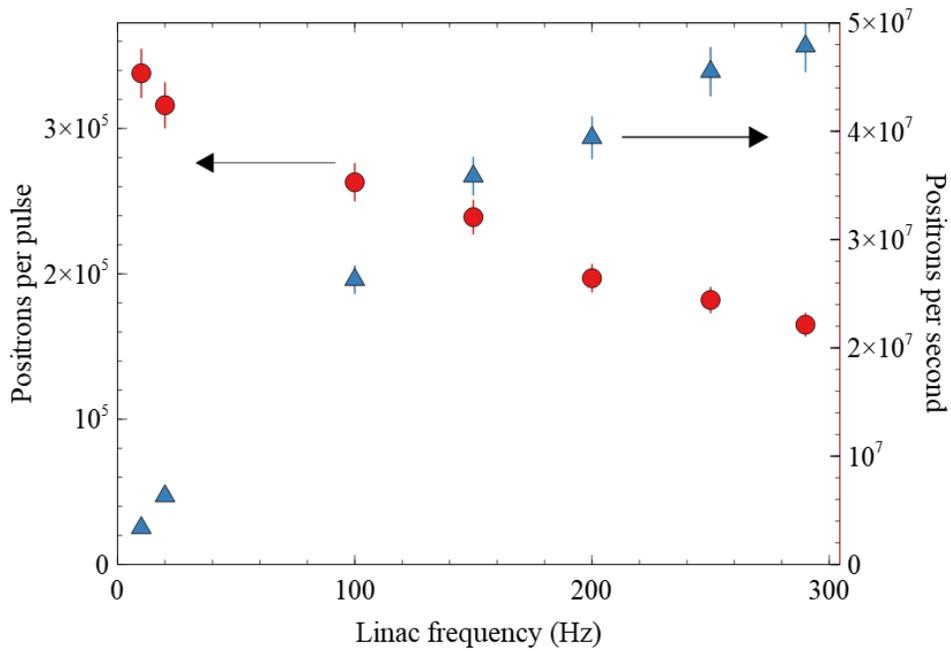


Figure 8: Slow positron yield of the GBAR positron source as a function of the linac frequency. Both the number of positrons per pulse (circles) and the number of positrons per second (positron flux) (triangles) are shown. The yield was measured after more than 30 minutes operation at a given frequency.

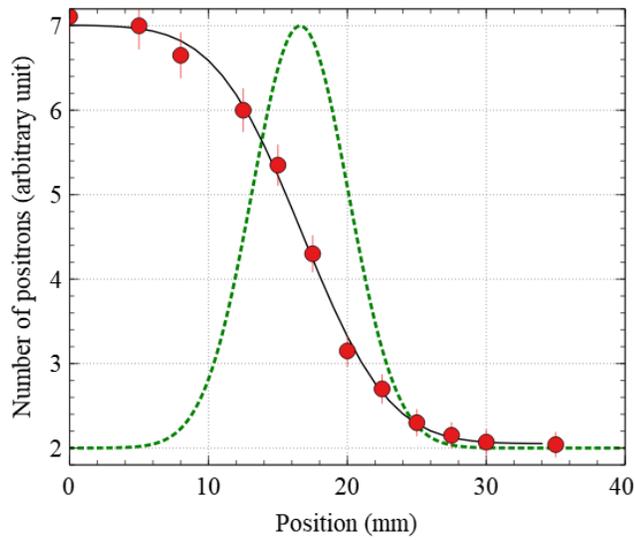


Figure 9: Positron annihilation signal as a function of the position of the scraper target. The continuous curve represents a complementary error function fit with  $\sigma = 4.9$  mm. The dotted line is the corresponding beam profile.