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HIGH INTENSITY, PULSED, SLOW POSITRON AND NEUTRON SOURCES AT INFN – FRASCATI

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Abstract

Considerable progress in RF Superconductivity in the last decade opened the possibility of building electron Linacs with high average intensity and high quality beams. This fact in turn has revitalized the use of Linacs for the production of secondary beams (like neutrons and slow positrons), which find many applications in Interdisciplinary Research.

An overview of such sources, to be developed at the INFN Frascati Laboratories and implemented in the future high-brilliance, X-FEL Facility, is presented in this paper.

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INTRODUCTION

The usefulness of low energy, high average intensity electron beams for production of secondary beams (like neutrons, slow positrons, high power FEL, etc.) is well known since many years, although in the past it has always suffered from the lack of power-effective accelerating structures. The rapid, impressive development of Superconducting RF cavities in the last few years has brought about a significant improvement in this field and the realization of a national facility for extensive applied physics studies, built around an electron Linac, seems now quite possible. Such an opportunity has been grasped by some developing countries, like South Korea (Pohang Laboratory), but also by some of the most advanced ones, like Germany (with the ELBE radiation source at the Forschungszentrum Rossendorf (FZR), near Dresden) and Russia (IREN Project at JINR), while others, like Japan and the United States, are still intensively using their already existing facilities. It is firmly established that neutron and slow positron beams deriving from primary electron beams constitute very useful investigation tools, complementary to the Synchrotron Light and Free Electron Laser (FEL) beams.

The former activity is present since more than 30 years at the Frascati National Laboratories (LNF) of INFN, the latter was recently revitalized by starting the X-FEL Project (SPARX), with an intensive R&D program on ultrabrilliant photoinjectors for a SASE UV FEL experiment. The interaction between such big programme and the development of new tools for research in applied physics will be certainly positive.

In this paper, the scientific cases for neutron and slow positron beams in the LNF area are outlined.

NEUTRON SOURCE

The most efficient physical process leading to production of intense pulses of fast neutrons is obviously nuclear spallation. Unfortunately, the world's largest project, the European Spallation Source (ESS), is still waiting for a preliminary approuval by the European Community that would not come, if any, before 2003, so as to start operation by 2012.

The Italian project TRASCO, a joint ENEA-INFN effort, is similarly aiming at constructing a SC proton Linac for neutron production with application in nuclear waste burning and in studies on an energy amplifier but it is still at the level of the feasibility study and component prototyping and testing for the High Energy Linac, while first beam tests have been done with the proton source.

Historically, high-power, low-energy electron linacs have been used to produce relatively high fluxes of neutrons via the (γ,n) reaction. It is also worth mentioning that this technique has recently been revitalized as an interesting alternative for the production of radioactive beams through photofission (γ,f), due to the relatively low cost of high intensity electron accelerators and the less amount of R&D required, compared to other primary beam accelerators [1].

Since several years, INFN ha started the Project SPES at Legnaro Nat. Labs for the production of exotic beams (RNB). The production of a neutron beam, based on a 100 MeV proton (deuteron) beam impinging on a Be target, is part of the Project. An estimated max. intensity of $1.4 \bullet 10^{10}$ neutrons/(sec•beamW) is expected. This Project is still in a study phase, the Conceptual Design Report was published in March 2002, a construction plus commissioning time of 5 –7 years is foreseen for the facility.

Hence, owing to this quite long time schedule, the quick realization of a simple low-cost neutron source, to be built around an existing, working accelerator (the DAΦNE Linac) appears quite an interesting opportunity, in view of the future, very promising development of a real

high intensity neutron facility, to be implemented on the SPARX SC Linac. Such concept should be especially attractive for Synchrotron Light Community, which is well established in the LNF Area since some 30 years and is involved in the project of the high brilliance X-FEL.

The main applications of a fairly intense, pulsed neutron source are:

- establishing a nuclear data system (see e.g.. the US Nuclear Data Program (USNDP), a DOE-funded project, and the HINDAS European Project[2])
- developing instrumentation for future spallation neutron sources
- testing and improving models in experimental neutron nuclear astrophysics[3]
- material science (like studies of neutron induced processes, in connection with nuclear fusion programmes) and medical applications (like Boron Neutron Capture Therapy (BNCT), a promising technique for the treatment of brain and other tumours at the cellular level)

The neutron yield per kW of beam power has been estimated by Swanson [4] for electron energies above 40 MeV as $1.21 \bullet 10^{11}$ x $Z^{0.66}$ for high-Z material target. The yield of photoneutron is proportional to the convolution of the (γ,n) cross section and the bremsstrahlung spectrum, which decreases rapidly with photon energy. The result is a yield curve which increases rapidly with primary electron energy for constant current up to approximately 25 MeV and more slowly thereafter. For constant beam power, the neutron yield is changing very little with electron energy above 35 MeV (Fig. 1).

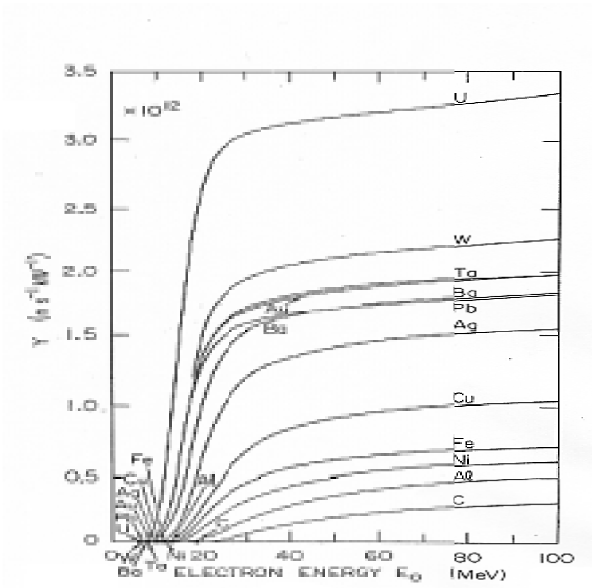

Fig. 1. The neutron yield as function of electron energy for various target materials (from ref. 4)

So a low-energy, high current SC Linac, like the ELBE machine [5], seems best suited to neutron production, also for economical and safety reasons. Another reason for a SC choice is the possibility of obtaining high duty cycle. High fluxes have been obtained also at normal conducting, conventional electron Linac, like Pohang, Oak Ridge, Geel, Dubna, working at higher energies (at 140, 150 and 200 MeV, respectively).

SLOW POSITRON SOURCE

Slow positron beams are deemed to be an useful tool in various studies of condensed matter. This technique can be regarded as complementary to the well-known investigations by means of neutrons, X-rays and electrons. Due to their propensity to trap into vacancy related crystalline defects, positrons can be used to probe defects in metals, to study Fermi surfaces and material surfaces and interfaces, and to obtain detailed information about the electronic structure of materials at the atomic level (Fig 2).In particular, there is a steadily growing demand in the semiconductor market for lower impurity materials, both established and relatively new, to fulfil the requirements of electronic and opto-electronic devices. In the last few years, there has been progress in the theoretical understanding and experimental techniques of Positron Annihilation Spectroscopy, to provide information about defects in semiconductors, superconductors and metals, what is important for the industrial research and development of new technologies and materials.

The main difficulty with such techniques is the limited counting rate in laboratory experiments and the complicated analysis and interpretation of results, which restricted the investigation mostly to "scientific" samples, and prevented systematic studies of formation, behaviour and annealing of lattice defects in "industrial" samples.

So, intense positron sources are required, with corresponding high quality beam features, like tunability in a wide low (1 ÷ 200 eV) and high (100 eV ÷ 40 keV) energy range, high time resolution (in the ns or ps range), reduced spotsize (≤ 1μ).

The experiments, to be done at a Linac based positron source, are broadly divided in two classes:

1. lifetime experiments, requiring very short (~100 ps) pulses and a bunch spacing > 100 ns
1. surface physics studies and atomic/molecular scattering experiments, requiring high duty cycle, quasi-continuous beams, not too short bunches

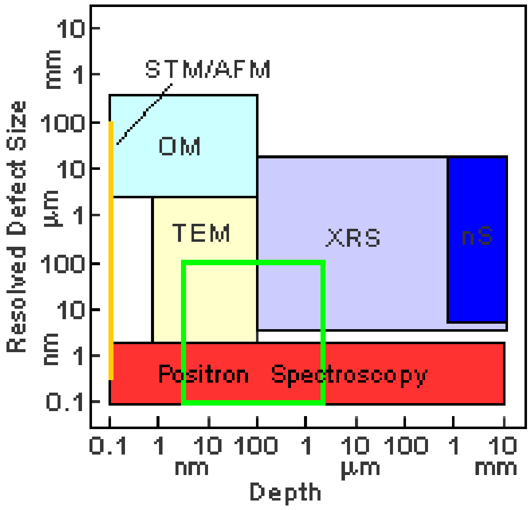

Fig. 2. Positron annihilation spectroscopy compared to various standard techniques in general vacancy defect analysis [6]. Shown are regions accessible: optical microscopy (OM), neutron scattering (nS), transmission electron microscopy (TEM), scanning tunneling microscopy (STM), atomic force microscopy (AFM), and x-ray scattering (XRS). The solid green line outlines the range of interest for studies of fine lines used as electronic interconnects on semiconductor chips .

Also, it is worth mentioning that Positronium Physics is a fundamental test of bound state QED-predictions, because of the absence of QCD and Weak Interactions contributions at the present level of accuracy.

A positron beam system consists of three main components: a source of positrons at high energy, a moderating system that thermalizes the positrons and emits a mono-energetic eV energy flux and a transport system that accelerates and transports the positron beam.

Very efficient transport system are readily available and there is little to be done to increase e^+ beam current through improvement of the transport system.

Positron moderators have been extensively studied for over two decades and relatively efficient moderating systems have been developed. The limitation in moderator efficiency are based on the physics of the e^+ interaction in the moderating medium.

The only component of e^+ beams that has no physical, but only practical, limits is the initial source strength.

The processes that produce positrons are basically two: they can be emitted via weak interaction (β^+ decay) by radioisotope sources or reactor beams, or they can be produced electromagnetically via bremsstrahlung and pair production by electron beams hitting high-Z targets at accelerators. The latter is the dominant method, being limited only by photon energy deposition and heating of the pair production target. Also it seems more promising, for slow positron manipulation, because of the higher trapping efficiency in a Penning–like trap, being a pulsed source.

A typical 100mCi, Na-22 source, can deliver $2{\bullet}10^6$ e^+/s, while the world's intensity record is held by the positron beam of Lawrence Livermore National Laboratory (LLNL), with its $1{\bullet}10^{10}$ e^+/s pulsed beam, for a power of 45 kW of the primary electron beam [6]. This makes the LLNL complex the only dedicated intense e^+ beam facility in the world. All the other accelerator-based positron facilities have been developed at existing linacs, whose characteristics are set by the needs defined by the original facility function. A recent example is the KEK LINAC [7], where from 2 kW, 2 GeV electron beam a total yield of 10^8 *slow* (≡ energy between 50 eV and 40 keV) e^+/s was obtained and further improvement (using the KEKB injector) is foreseen.

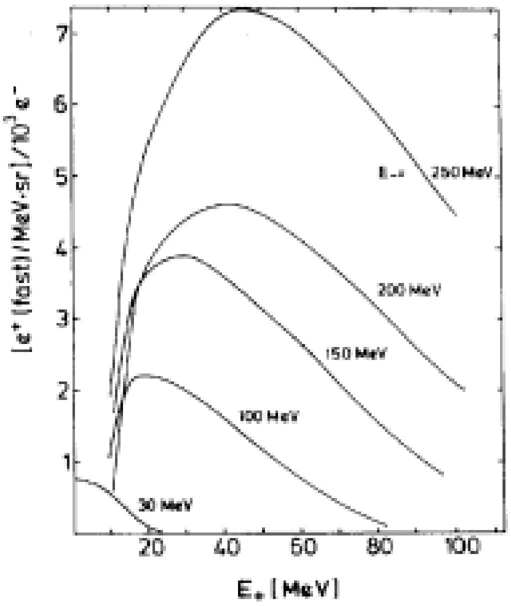

Fig. 3. Positron spectra for a fixed target thickness equivalent to 4 mm W at various electron energies (from ref. 8)

A low energy primary beam is certainly less efficient in the positron production as compared with a higher energy beam, for the same power loss. In a thick target, the number of emitted positrons and their energy spectrum depends basically on the target thickness and the primary electron energy (E_-) in an almost linear way. For a target thickness small compared with the median range of the primary electron (after 95% of the incident energy has been converted to other forms, including e^+), the positron spectrum has a maximum around 20% of E_-, then it decreases slowly towards higher energy (fig.3). When the target thickness becomes comparable with the median range, the maximum in the energy spectrum of the e^+ shifts towards low energies and simultaneously the yield reaches a maximum, so there is an optimum thickness for a conversion target which delivers the highest number of e^+ with the lowest possible energies, as shown in fig. 4 for a Tantalum target.

When positrons are created by β^+ decay or pair production, they have a broad energy distribution around a mean value of 100 keV or higher. After implantation into a metal a positron is slowed down to nearly thermal energies within a very short time interval of the order of 1 ps. A thermal e^+ inside bulk matter has a typical lifetime of 100 ps before annihilation. During its lifetime, the e^+ diffuses in a random walk motion over a volume with a radius of ~ 1000 A, called the diffusion length. When a thermal e^+ encounters the surface of a metal, several processes are possible, among which there is the emission into the vacuum within a narrow angle to the surface normal, so that nearly monochromatic slow positron beams are formed. The devices which convert high energy positrons with a broad energy spectrum into nearly monoenergetic low energy positrons are called moderators. Though not the most efficient, the most commonly used moderator downstream the conversion target of an accelerator is poly-crystalline vane tungsten, mainly because

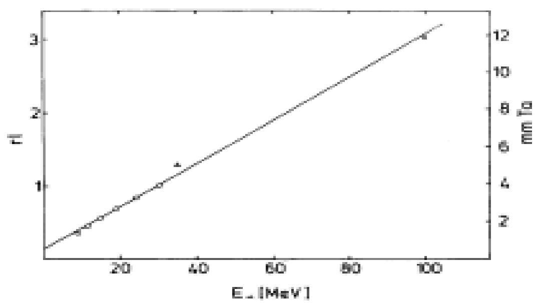

Fig. 4. The optimum thickness of a Ta conversion target vs. electron energy for max. slow positron production rate (from ref. 8)

of practical reasons. Since it is impossible to measure the absolute number of moderated e^+ near the converter-moderator assembly, the conversion efficiency is defined as the ratio of the number of slow positrons to the number of primary electrons impinging on the target, as measured at the end of the transport/focusing beamline in the destination experimental area. Upon these conditions the conversion efficiency shows a more or less linear behaviour, for all the target thicknesses, from a threshold up to 100 MeV. Thereafter some flattening is predicted by theory. Typical values are around $0.5 \div 1.5$ e^+ (slow)/10^6 e^-.

BASIC ACCELERATOR PARAMETERS

Most existing electron facilities, which are presently used for the production of both neutron and slow positron beams, were originally designed for other purposes.

Among the most recent facilities, still in a commissioning phase or already operating, the FZR German ELBE, although mainly devoted to the development of a FEL for High Power Infrared Radiation, looks also well suited to host such exotic beam sources.

Again in Germany, the DESY TTF facility was recently proposed as a candidate site for hosting a possible European Slow Positron Source.

The main features are summarized in the following table:

Accelerator	TTF	ELBE	SPARX	DAΦNE LINAC
Electron energy(MeV)	390 1000	40	150 (‘warm Photoinjector’)	$50 \div 750$ 250(conv. en.)
Beam power (kW)	Max. 72	Max. 40		0.5@250 MeV
Bunch charge (pC)	~ 1000	77	~ 1000	$4\bullet10^4$ (macrobunch)
Bunches/pulse	7200	$1176 \div 471000$		1
Bunch length (ps)	0.6	$2 \div 10$		
Bunch distance (ns)	100	77		
Repetition rate (Hz)	10	$25 \div 100$		50
Mean current (μA)	72	1000	72 ??	2
Pulse length (ms)	~ 0.72	~ $0.09 \div 36.3$		$1\bullet10^{-5}$
Pulse distance (ms)	~ 2.8	~ $3.7 \div 39.9$		
Duty cycle*	~ $7\bullet10^{-3}$	~ $2.3\bullet10^{-3}$ $\div0.91$		
Emittance(mm•mrad)	1 (@ 1GeV, @1 nC)	$3 \div 20$		10
Max. # of slow e^+/s	$4.4\bullet10^9$	$1.3\bullet10^8$ **	$9\bullet10^8$ ***	$5\bullet10^7$ ***
Neutron yield n/s		$6\bullet10^{13}$		~ $0.8\bullet10^{12}$

* number of bunches ☒ bunch distance ☒ rep. rate

** at I=0.28 mA, limited by target heating

*** for estimated conversion efficiencies of $2\bullet10^{-6}$ e^+/e^- @150 MeV and $4\bullet10^{-6}$ e^+/e^- @250MeV [8]

Many features of the above Accelerators are related to the FEL activities, where the main goal is to maximize the bunch charge density (maximum bunch charge, minimum transverse and longitudinal emittance), thereby strongly constraining the machine parameters. For the production of secondary beams, like neutrons and slow positrons, high intensity and high duty cycle are the basic requirements, with a clear preference for a higher Energy Accelerator in the positron case, a lower Energy one in the neutron case.

In a Linac based slow positron beam, the original short pulselength (of the order of ps) of the electron beam cannot be preserved after the thermalisation in a multifoil moderator and in the corresponding transport system. Therefore, one has to use in lifetime experiments a buncher and/or a stretcher (Penning Trap), followed by a pulsing system.

However for some experiments a high duty-cycle slow positron beam is required. In this respect Superconducting Linacs (as ELBE and TTF) may be operated in a 'quasi' cw-mode, i.e. with an 'infinite' long train of bunches, with high average currents (~ 1 mA). It seems possible now to obtain a quasi-continuous beam with high intensity (at ELBE $2 \bullet 10^8$ e^+/s at the energy of 40 MeV and average current ~ 1 mA) and without complicated Penning Traps. In this way the problems caused by pile-up in the electronic systems are greatly reduced, resulting in big advantages for spectroscopy, and especially for working with coincidence arrangements.

For the SPARX Project the above parameters are only indicative and, if the Superconducting option will be chosen, both neutron and slow positron yield figures will be obviously much higher.

CONCLUSIONS

The importance of powerful SC electron Linacs for the the production of secondary beams was outlined. It is quite clear that a significant improvement over the existing sources can be obtained with a relatively modest effort in terms of time and money. The usefulness of slow positrons and neutrons in the domain of material research is quite well recognized since several decades, and their importance as an investigation tool complementary, and in some cases superior, to Synchrotron Radiation is also very well known.

Thanks to the presence of the DAΦNE Linac with its Beam Test Facility, the development and optimization work can start soon. Such facility can find their natural integration within a future, desirable Laboratory of Applied Physics and Interdisciplinary Research, to be built in the Rome Research Area around the already approuved High Brilliance X-ray FEL Source.

APPENDIX I

A neutron target for an electron Linac

The giant photonuclear resonance is the main phenomenon in the absorption of electromagnetic radiation of energy greater than the nucleon emission threshold, which is tipically around 8 MeV for medium and high-Z nuclei. For these the resonance peak lies between 14 and 18 MeV and it is characterized by a rapid rise to the peak and a more gradual decrease at high energy. The giant resonance may be interpreted as a collective excitation of the target nucleus, with subsequent decay into various channels which are independent from each other, so their cross sections are computed on a pure statistical basis. In this approach the spectrum of the emitted neutrons is given by the Weisskopf's "evaporation" formula and the angular distribution is isotropic with respect to the momentum of the photon, having the correlations of the emitted particle to the incident particle been lost..

Another mechanism contributing to the photoneutron spectrum is the direct emission, which tends to prevail at higher energy and may not be isotropic, since it occurs on a time scale comparable with the transit time across the nucleus. The Quasi-Deuteron (which owns an electric dipole moment) model has been used to explain the data up to a γ-energy of 150 MeV, with some success.

In general, the spectrum of the emitted neutron will be continuous, ranging from eV up to the electron beam energy reduced by the neutron bind energy.

Following the approach of other Laboratories [Pohang, ELBE, ORELA], the bremsstrahlung target and the photoneutron target coincide. The design of such devices is nowadays greatly facilitated by powerful computer codes, like EGS4, to study photoneutron spectra, and MCNP and FLUKA (where also photonuclear interactions have been recently implemented), to study neutron production and transport inside the target and the moderator.

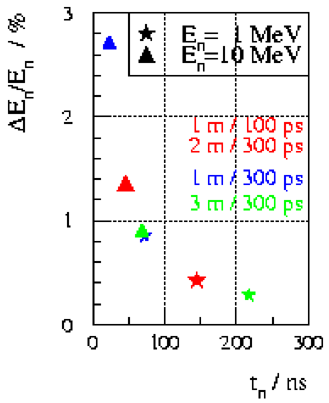

Fig. 5. Energy resolution-time dependence for 100 and 300 ps detector resolution

Tantalum (Z=73) seems the best choice as the high-Z material, since it has high density, high melting point and high resistance against corrosion by cooling water. Its neutron production rate seems also sufficient for short (sub-ns) pulse generation, which is needed for time-of-flight studies. An example of the FLUKA calculation of neutron production for the ELBE accelerator is shown in fig. 5, where the possibility of obtaining a neutron flux of $4 \bullet 10^5$ n/sec/cm^2 with an energy resolution of 1% at 1 MeV for a flight path of just 1 m is clearly demonstrated.

By the way, the expected energy resolution of the CERN n_TOF experiment (PS213) is of the order of 10^{-4} on a 200 m long flight path.

To reduce background from other particles, the neutron observation should be done perpendicular to the electron beam direction.

APPENDIX II

A slow positron production system

Although a conversion target for positron production exists already on the DAΦNE Linac, the production and collection of slow positrons required a special, dedicated system, because the moderator must be located very close to the converter, to intercept as much as possible of strongly diverging positrons. A typical converter – moderator assembly is shown in fig. 6. According to a broad experience, Tantalum is deemed to be a good material also for a positron converter, although Tungsten is preferred for its higher melting point. Other parameters, like the specific heat capacity and the thermal conductivity have to be considered, depending on the beam parameters and the mechanical design of the target (ex. rotating targets). A general comparison of various materials is given in ref. 8.

The moderator vanes are arranged in the "venetian blind" geometry, with a thickness of the order of 25 ÷ 250 μm and are chemically cleaned and annealed at high temperature and under high vacuum. The produced low energy e^+ are confined by an axial magnetic field (~ 10^{-2} T), accelerated downstream parallel to the magnetic field by a potential V (≤ 40 kV) and then transported over a distance between 10 and 40 m to an experimental area which is well screened from the high radiation background at the conversion target. The positron beamline should not be in the line of sight of the primary electron beam. One or more re-moderation and re-bunching stages can be implemented to enhance the beam brightness (by overcoming Liouville's limitations) and shorten the pulselength.

As we said, the still critical point in a slow e^+ beam generation is the target – moderator system, which requires a careful simulation work (with codes like EGS4) being the production rate strongly geometry-dependent, and a certain amount of R&D about the degradation of the moderation efficiency due to irradiation, which is perhaps the main problem in the existing sources.

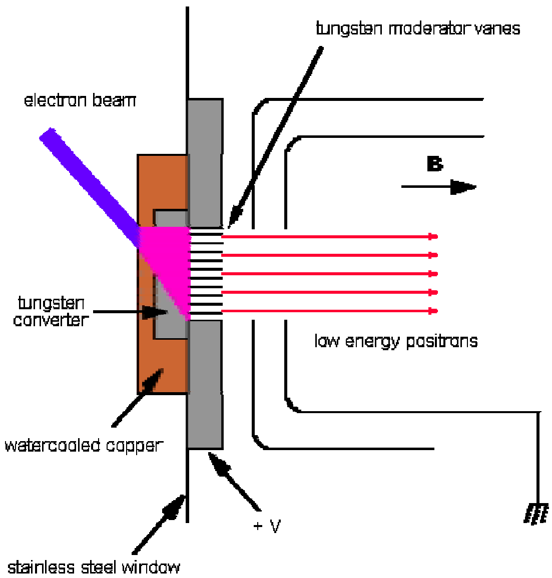

Fig. 6. Sketch of the target assembly in the LLNL positron beam system

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