

Chapter 11

Potential Applications

The construction of the TTFL is itself a project of considerable magnitude, offering unique beam physics features, quite aside from its possible linear collider prospects. Thus, it is natural to identify applications in experimental physics for the TTFL. Two examples are presented below; the use of the TTFL as an electron source for a SASE FEL and as a facility for investigations with slow positrons.

11.1 A Self-Amplified-Spontaneous-Emission Free-Electron Laser at 200 eV

The workshop on Fourth Generation Light Sources held at SLAC in 1992 focussed on X-ray lasers¹, and with the recent development of low emittance electron guns the construction of X-ray lasers at 1 Å wavelength at high energy linacs comes in reach. The scientific applications of such coherent X-rays have been discussed at SLAC in February 1994.²

The Brookhaven National Laboratory suggested a Free-Electron Laser in the deep UV region, called DUV.³ The DUV-FEL operates as a combination of a harmonic generator and single pass amplifier. The concept involves coupling of the coherent radiation provided by a “conventional” pulsed laser with a high current electron bunch inside a magnetic wiggler designed to be

¹SSRL Report 92/02

²SLAC-Report-437

³BNL-Report-49713

resonant at the seed laser wavelength. This scheme imparts the coherence and relative bandwidth of the seed laser on the radiation produced by the FEL. The DUV-FEL will provide intense pulses of coherent ultraviolet radiation with wavelengths ranging from 300 to 75 nm. The pulse width will be variable from about 7 ps to under 200 fs. The DUV-FEL concept cannot be extended to realize a FEL in the X-ray regime.

11.1.1 The TESLA Option

At DESY the construction of a Self-Amplified-Spontaneous-Emission(SASE) FEL at the TESLA Test Facility (TTF) is under discussion. Due to its exceptional capability to maintain high electron beam quality during acceleration, a superconducting linac is the optimum choice to drive a SASE FEL at high energies. The goal is to produce coherent radiation tunable in the photon energy range up to 200 eV (6 nm).

In atomic, molecular and solid state physics the intensity, collimation, polarization, coherence, flexibility, and time structure of the VUV laser radiation allow novel studies of structure and dynamics. Exiting new research opportunities in imaging by coherent radiation, in time resolved pump and probe experiments and in nonlinear laser-matter interaction are expected.

Applications in biology comprise investigations of radiation damage, time resolved phosphorescence and fluorescence studies and Raman spectroscopy providing structural information on biologically important macromolecules in solution. In addition, attempts could be made to directly image the topology of large molecular assemblies.

Possible applications of such a laser in many different fields of sciences have been discussed in some detail within the scientific case of the Brookhaven DUV-FEL proposal proposal.⁴ Examples are given for

- photofragmentation spectroscopy
- photoelectron spectroscopy of radicals, complexes, and clusters
- photoionization of vibrationally excited states
- state selective detection of dilute species

⁴*op cit*

- photodesorption and photodissociation from surfaces
- crossed beam radical-molecule reactions
- excited state spectroscopy
- microprobe experiments

Construction of this 200 eV laser might pave the way towards an even more challenging FEL in the Ångström range.

With the goal of a 1 Å X-ray laser in mind, experiments with X-ray beams of a degree of coherence typical for 3rd generation synchrotron radiation sources will be carried out at DESY. To this end, the undulator beam under construction at the PETRA storage ring will be used. PETRA will be operated at 12 GeV with a possible emittance of 15 nm at that electron energy. These experiments will supply experience indispensable to handle the enormous X-ray brilliance of a future X-ray FEL.

Besides direct applications of FEL radiation, FEL radiation sources will be needed for the $\gamma - \gamma$ collider option of linear colliders. This represents another link between linear collider R&D and FEL development.

The technical concept

a) basics

The radiated power P of a relativistic charge q in a transverse magnetic field B is given by⁵

$$P = \frac{q^2}{6\pi\epsilon_0 m_0^2 c} q^2 B^2 \gamma^2$$

Thus, for a point-like electron bunch, P depends *quadratically* on the number of electrons. This is, however, only true as long as the bunch length is shorter than the radiated wavelength. Otherwise, the radiation contributions add up incoherently, yielding a linear dependence only. The generation of (say) nanometer long, intense bunches from an electron gun is impossible, but it can be accomplished by self-bunching of a longer bunch in its own radiation field generated in an undulator. After the self-bunching has been

⁵see e.g. Jackson: Classical Electrodynamics

developed within a characteristic distance called gain length L_g , the radiation exponentially increases up to saturation due to nonlinear effects.⁶

The gain in power, compared to spontaneous radiation without microbunching, might be as high as six orders of magnitude. Although stimulated emission is also involved, the essential effect is increasing the spontaneous emission, similar to the optical klystron.⁷ This explains the name *Self-Amplified Spontaneous Emission* = SASE. Since SASE is a single pass effect, it is especially interesting in the VUV and X-ray region, where optical resonators are not available due to lack of mirrors.

The basic concept of SASE was first demonstrated experimentally in the microwave region at LLNL.⁸

b) RF gun

Both small emittance values and high phase space densities in all three dimensions are mandatory for achieving microbunching and saturation within reasonable undulator length. To achieve a photon wavelength λ , the transverse beam emittance ε (or the normalized emittance ε_n , respectively) must not exceed a critical value given by

$$\varepsilon = \frac{\varepsilon_n}{\beta\gamma} \leq \frac{\lambda}{4\pi}$$

Thermionic guns are not able to supply the required phase-space densities. The essential break-through was the development of the RF gun by Fraser and Sheffield⁹ and the emittance compensation scheme devised by Carlsten¹⁰. Meanwhile a number of RF guns have been built and operated yielding 1 nC charge at 3π mm mrad normalized emittance and an rms bunch length σ_s in the few mm range.¹¹

We aim at a normalized emittance of 1π mm mrad at 1 nC and $\sigma_s = 1$ mm. A key component will be the laser system which has to deliver ultrashort pulses at 1 MHz repetition rate. This is currently under investigation at the Max-Born-Institut in Berlin.

⁶R. Bonifacio, C. Pellegrini, L. M. Narducci, Opt. Commun. 50 (1984) 373

⁷N. A. Vinokurov, A. N. Skrinsky, INP/Novosibirsk Preprint 1977

⁸T. J. Orzechowski et al., Phys. Rev. Lett. 54 (1985) 889

⁹J. Fraser and R. Sheffield, Nucl. Instr. Meth. A250(1986) 71

¹⁰B. Carlsten (Nucl. Instr. Meth. A285(1989) 313

¹¹see e.g. C. Travier: Review of Electron Guns, Proc. EPAC, 1994

11.1. A SELF-AMPLIFIED-SPONTANEOUS-EMISSION FREE-ELECTRON LASER AT 200 EV

It should be noted that a low emittance electron gun serving the TESLA pulse train pattern would be extremely useful for the TESLA Linear Collider, because eventually the electron damping ring could be saved. The phase space density required for TESLA500 is very close to what is needed for the SASE FEL.

c) bunch compression and acceleration

The peak electron beam current needed to achieve a reasonably short gain length is in the few thousand Ampere range. Even when starting at 1 mm rms bunch length, further bunch compression is required to reach that value. It cannot be done at very low energy because Coulomb forces would increase the beam size and energy width. On the other hand, it should not be done at too high energy for two reasons:

1. The cosine-like time dependence of the accelerating voltage introduces some correlated energy spread which scales quadratically with the bunch length. To avoid phase space filamentation during bunch compression, the nonlinear part of this energy spread should not get much larger than the initial, uncorrelated energy spread of the beam.
2. At each bunch compression by a factor C , the uncorrelated energy spread increases by at least the same factor C (Liouville Theoreme). The longitudinal wakefield, however, only scales with $\sqrt{\text{bunchlength}}$. Thus, to make optimum use of adiabatic damping, one should compress before the wakefield dominates the energy width. It is an essential advantage of the low RF frequency of TESLA, that wakefield effects are very small. Consequently, extremely small bunch length and small energy width do not exclude each other.

As indicated in Fig. 11.1, a first compression stage of a factor 4 is foreseen after the first superconducting RF module, i.e. at about 130 MeV beam energy. It still has to be checked if it could be done right after the RF gun preaccelerator, which would be favourable for technical reasons. The second stage brings the bunch length down to 50 mm. This is done after the 4th module at some 500 MeV.

To reach the final energy of 1 GeV required for the FEL, four more RF modules will be necessary.

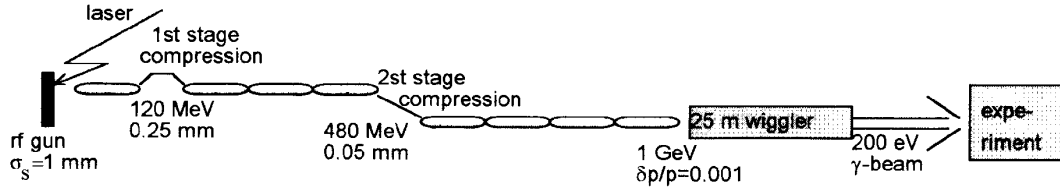


Figure 11.1: Schematic layout of a 1 GeV SASE FEL facility based on the TESLA Test Facility. The bunch length is reduced from 1mm to $50\mu\text{m}$ within two steps of bunch compression, the first of which is after the first superconducting RF module. Whether the first stage of bunch compression can, alternatively, be placed just after the RF gun, is not yet clear. The over-all length is some 160 meters.

We assume the RF gun to deliver a beam of 20 keV rms energy width at 10 MeV beam energy. This means, at $\sigma_s = 1$ mm, a longitudinal emittance of 20 keV mm. As we need a relative energy width of 0.001 at 1 GeV, Liouville Theoreme would allow a bunch compression down to $20\mu\text{m}$. Thus, we allow for a factor of 2.5 of phase space dilution due to wakefield effects and phase jitter. A more detailed analysis will show if less than $50\mu\text{m}$ bunch length can be achieved.

d) undulator

After having prepared an electron beam of high brilliance, the key component of the FEL will be the undulator. The peak field of 0.5 T at period length of 27.3 mm and a gap of 12 mm (maybe even 8 mm gap would be tolerable) does not seem to be the problem. However, the considerable length of about 25 m requires careful investigation of field tolerances, means of periodic focussing and cost minimization.

A tentative layout of the TTF SASE FEL is sketched in Fig. 11.1. Table 11.1 shows a preliminary parameter list.

¹²K. J. Kim and M. Xie (Nucl. Instr. Meth. A, 331 (1993), 359)

Table 11.1: Preliminary parameter list of a TESLA SASE FEL. The insertion device is assumed to be a planar hybrid undulator. The values¹² quoted should be considered a guideline only since neither optimization is finished yet nor any experimental experience is available in this wavelength regime. Therefore, a first test is envisaged at a wavelength larger by some factor of ten.

VARIABLE	UNITS	VALUE
beam energy	GeV	1.000
λ (radiation wavelength)	nm	6.4 (200 eV)
λ_W (wiggler period)	mm	27.3
wiggler gap	mm	12
B (wiggler peak field)	T	0.497
β (beam optics beta function)	m	5
rms beam size	mm	0.05
ε^n (normalized emittance)	π mrad mm	1.0
peak electron beam current	A	2490
electrons per Gaussian bunch		6.24×10^9
photons per Gaussian bunch		6.2×10^{13}
peak electron beam power	GW	2490
energy spread σ_ν/γ	10^{-3}	1.00
bunch length	μm	48.
L_g (power gain length)	m	1.00
L_s (saturation length)	m	18.2
P_{sat} (saturated power)	MW	2780
peak brilliance	photons/s/mm ² /mr ² /0.1%	8.73×10^{27}

11.2 A Source of Slow-Positrons for Applied Physics

Slow-positrons, i.e. monoenergetic positrons with an energy of a few eV up to some keV, provide a unique probe for solid state physics¹³, but are also widely used for observations of quantum chemistry associated with light-mass particles¹⁴, atomic physics¹⁵, astrophysical applications¹⁶ and tests of the quantum electrodynamics.

The experimental study of the interaction of positrons with matter is a relatively young field which has received a big boost in the late seventies on developments of highly efficient moderator materials¹⁷ with a negative work function for positrons. Positrons which penetrate into these materials are thermalized and reemitted into the vacuum, normal to the moderator surface with an energy of a few eV and an energy width of less than 0.1 eV. This is the basic process for the production of slow-positrons.

The same physical principle – reemission due to a negative work function - can be used to decrease the emittance of the beam by orders of magnitude by means of a re-moderation of the beam.^{18 19}

The improved performance of slow positron sources and experimental possibilities is reflected in a rapidly growing number of publications and increasing interest in workshops and conferences relating slow-positron beam applications.¹³

¹³P. J. Schultz, K. G. Lyn, *Interaction of positron beams with surfaces, thin films, and interface*, Rev. Mod. Phys. 60, p. 701 (1988).

¹⁴H. Arche, Proceedings of the 5th Intern. Conf. on Positron Annihilation, Lake Yamanaka, Japan, p. 31 (1979).

¹⁵A. Dupasquier, A. Zecca, Riv. Nuovo Cimento 8, p. 3 (1985).

¹⁶*Positron Scattering in Gases*, Proceeding of the 2nd NATO Advanced Research Workshop 1983, Ed.: J. W. Humberston, M. R. C. McDowell, Plenum New York.

¹⁷M. Leventhal, C. J. MacCallum, Proceedings of the 7th International Conference on Positron Annihilation, p. 1003, New Dehli (1985)

¹⁸K. F. Canter, P. G. Coleman, T. C. Giffith, G. R. Heyland, J. Phys. B5, L167 (1972). S. Pendyala, P. W. Zitzewitz, J. W. McGowan, P. H. R. Orth, Phys Lett. A43, p. 293 (1973).

S. Pendyala, D. Bartell, F. E. Giouard, J. W. McGowan, *Energy Distribution of Slow Positrons Diffusing from Incomplete d-Shell Transition Metals*, Phys. Rev. Let. 33, 17, p. 1031 (1974).

¹⁹A. P. Mills Jr., Appl. Phys. 23, p. 189 (1980).

New kinds of experiments like positron microscopy and studies of exotic antimatter systems like a two-component Fermigas require further developments of the sources with respect to

- emittance,
- intensity and
- time structure.

While sources with modest intensity ($\sim 10^6 e^+/s$) based on the moderation of positrons from radioactive materials can be realized with acceptable expenditure in small-scale laboratories, high-intensity sources require the operation in proximity of a high flux reactor or a particle accelerator and, in addition, the organization of a ‘service facility’ with a large, open user community.

In order to characterize the relevance of the different source parameters, we will consider experiments with slow positrons in a most general form, concentrating on applications in solid state physics and hereby following closely the presentation in the review article of P. J. Schultz and K. G. Lynn.¹³

After a brief discussion of the layout of a slow positron source, we will estimate the performance of a source based on the TESLA Test Facility (TTF) and compare it with existing and planned sources.

11.2.1 Experiments with slow positrons

While the positron is stable in vacuum, it annihilates under the emission of two 511 keV photons in ordinary matter. If the electron-positron-system is at rest, the photons are emitted in exactly opposite directions. Deviations in the collinearity as well as fluctuations of the photon energy (doppler-broadening) are hence direct measurements of the momentum of the electron-positron-system (see Fig. 11.2). When a positron enters a solid, it rapidly loses its kinetic energy until it is thermalized. Since, on the average, only one positron is in the solid at one time, it resides near the bottom of its own energy-band. Hence, when the positron annihilates, it does not contribute to the momentum of the system and the deviation of the collinearity of the two photons is a direct measurement of the electron momentum in the solid. The measurement of the Angular Correlation of the Annihilation Radiation

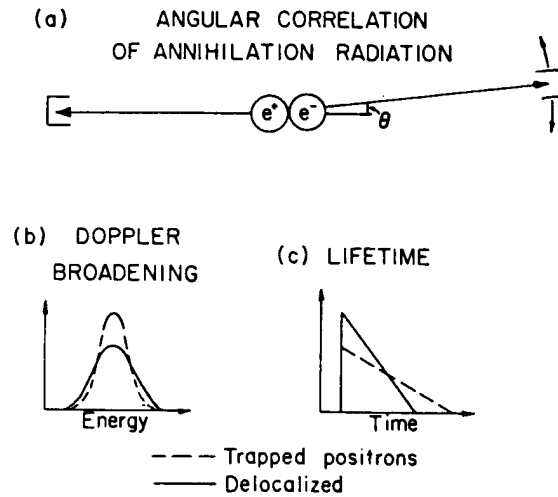


Figure 11.2: Electron momentum reflected in the deviation of γ -ray collinearity in ACRA measurements (a), or in the width of the γ -ray annihilation line shape (b). When positrons trap in defects there is a reduced overlap with energetic core electrons, leading to narrow momentum (or γ -ray energy) spectra, and there is a general decrease in the electron concentration, leading to longer positron lifetimes (c).¹³

(ACAR) is therefore a sensitive and widely used technique to measure the Fermi surfaces of metals and alloys. However, positrons can also be trapped in lattice defects like vacancies, voids and dislocations. A trapped positron has a reduced overlap with energetic core electrons which leads to a smaller doppler-broadening and the general decrease in electron concentration near traps is reflected in an increased positron lifetime (Fig. 11.2).

Vacancy concentrations of $\sim 10^{-7}$ show a significant effect on the positron annihilation characteristics and by means of variation of the positron energy from some eV up to some keV even depths profiles can be measured.²⁰ The formation of a positronium atom (Ps), the lightest hydrogenic system, was predicted in 1934 by Mohorovicic and observed 1951 by Deutsch. While the formation of positronium in the bulk of defect free metals or semiconductors is

²⁰W. Triftshaeuser, G. Koegel, Phys. Rev. Lett. 48, p. 1741 (1982).

forbidden for energetic reasons, a high probability for positronium formation on the surface of a solid is found, due to the opposite signed work functions of positrons and electrons.²¹

These positronium atoms can be thermally desorbed, leading to the formation of a positronium beam.²²

On the other hand positrons can also be trapped on the surface or be re-emitted as free, slow positrons depending on the (local) surface characteristics. Hence they provide a sensitive probe for surface effects, useful for investigations of thin surface layers, surface defects and contaminations.²³ Since positrons have the same mass as electrons, they will exhibit similar diffraction effects when scattering from a crystal surface. Thus positron diffraction may become a useful surface analysis technique, complementing methods of Low Energy Electron Diffraction (LEED). The absence of exchange forces for positrons allows a more simpler interpretation of LEED patterns²³ it requires, however, sources with high intensity and small emittance for LEED to become a practicable technique. Thus brightness enhancement techniques are used to increase the brightness of the beam for LEED and other applications.²¹

Time structured beams

The time scale for positrons shown in Table 11.2 indicates the relevance of the observable time for slow positron experiments. Hence, bunched slow positron beams seem to have a promising future, even though they require more sophisticated detectors to handle the high intensity in the pulse.

Efforts to bunch a continuous slow positron beam^{24 25} have led to time resolutions of $8 \times 10^{-9} - 2 \times 10^{-10} s$. (The disadvantage of these technique is the necessarily increased energy width which, however, can be offset by a re-moderation stage.)

²¹A. P. Mills Jr., Phys. Rev. Lett. 41, p. 1828 (1978).

²²A. P. Mills Jr., W. S. Crane, Phys. Rev. A31, p. 593 (1985).

²³A. P. Mills Jr., *Surface Analysis and Atomic Physics with Slow Positron Beams*, Science 218, p. 335 (1982).

²⁴A. P. Mills Jr., L. Pfeifer, P. M. Platzman, Phys. Rev. Lett. 51, p. 1085 (1983).

²⁵D. Schoedlbauer, G. Koegel, W. Triftshaeuser, Phys. Status Solidi A102, p. 549 (1987).
D. Schoedlbauer, P. Speer, G. Koegel, W. Triftshaeuser, in Proceedings of the 7th International Conference on Positron Annihilation, p. 957, New Dehli (1985)

Table 11.2: Time scales for Positrons.

	Time
Lifetime in vacuum	$\sim 2 \times 10^{22}$ yr
Scattering or diffraction	$\sim 10^{-15}$ sec
Thermalization (to \sim Fermi energy)	$\sim 10^{-13}$ sec
Thermalization (to $\sim \frac{3}{2}kT$)	$\sim 10^{-12}$ sec
Trapping (after thermalization)	$\sim 10^{-15}$ sec
e^+ lifetime	
Freely diffusing	$\sim 1 \times 10^{-10}$ sec
Monovacancy trapped	$\sim 2 \times 10^{-10}$ sec
Multivacancy/void trapped	$\sim 4 \times 10^{-10}$ sec
Surface state	$\sim 4 - 6 \times 10^{-10}$ sec
Annihilation time	$\sim 10^{-21}$ sec
Ps lifetime	
Singlet, vacuum	$\sim 1.25 \times 10^{-10}$ sec
Triplet, vacuum	$\sim 1.42 \times 10^{-7}$ sec
Triplet, in solids (molecular crystals and insulators)	$\leq 10^{-9}$ sec

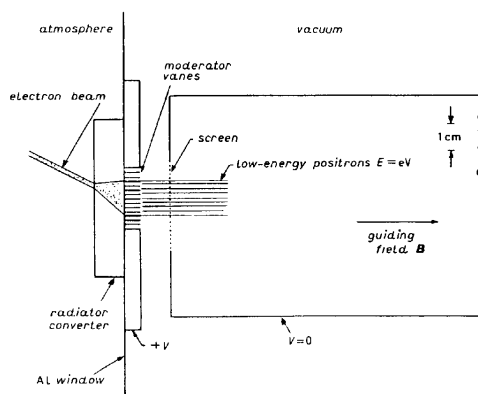


Figure 11.3: The front-end of the LLNL high intensity slow-positron beam.¹⁵

The pulsed structure of linac based slow positron beams seems to be an obvious advantage, compared to sources based on radioactive materials, if time tagged experiments are considered.

On the other hand, also devices to stretch a pulsed positron beam to a more or less continuous beam have been developed (penning trap²⁶) which are useful for studies like gas scattering experiments and the formation of anti-hydrogen.

11.2.2 Layout of a slow positron source

Figure 11.3 shows the front-end of the LLNL high intensity slow-positron beam. The positrons generated in the conversion target by the high energy primary electron beam are moderated in a vane moderator of vacuum annealed tungsten vanes.

Here the positrons lose their kinetic energy and are re-emitted into the vacuum, preferentially normal to the surface, due to the negative work function of the moderator material. Typically 10^{-6} positrons are re-emitted in this way to form a positron beam with an energy width of only $< 0.1\text{eV}$ at $\sim 1\text{eV}$. (The moderator efficiency of low energy positrons ($\sim \text{keV}$) from

²⁶L. D. Hulet Jr., T. A. Lewis, R. G. Alsmiller Jr., R. Peele, S. Pendyala, J. M. Dale, T. M. Rosseel, Oake Ridge National Laboratory, CONF-861114-21 (1987).

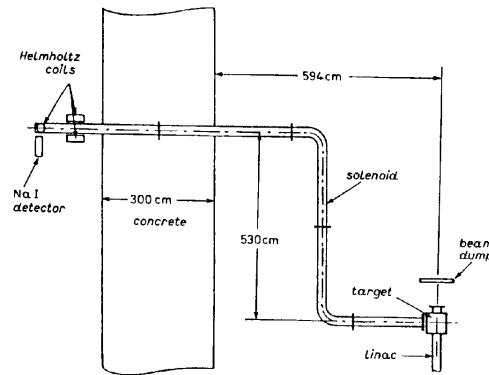


Figure 11.4: Scheme of the slow-positron facility at University Mainz.¹⁵

radioactive sources is typically 10^{-3}). The positrons are accelerated with an extraction field to some keV and guided, electrostatically or magnetically focused (solenoid $\sim 10^{-3}T$) to the experiment.

The beam transport line of Fig. 11.4 indicates shielding requirements and bends, necessary to separate the positrons from gammas, neutrons and electrons. Note that the target assembly can easily be combined with the beam dump.

Brightness enhancement

In order to reduce the emittance of the positron beam a re-moderation can be performed: The beam is focused onto a moderator with the spot size as small as possible. The moderator takes the divergence out of the beam and hence re-emits a positron beam with reduced emittance. In a single step the emittance reduction is limited by the minimum attainable spot size, given by aberrations of the lens system.

However, the procedure can be repeated and is then limited by the unavoidable losses of the order of 30% - 50% occurring in each moderation stage.

With respect to brightness B , defined as:

$$B = \frac{I}{\theta^2 \times d^2 \times E}$$

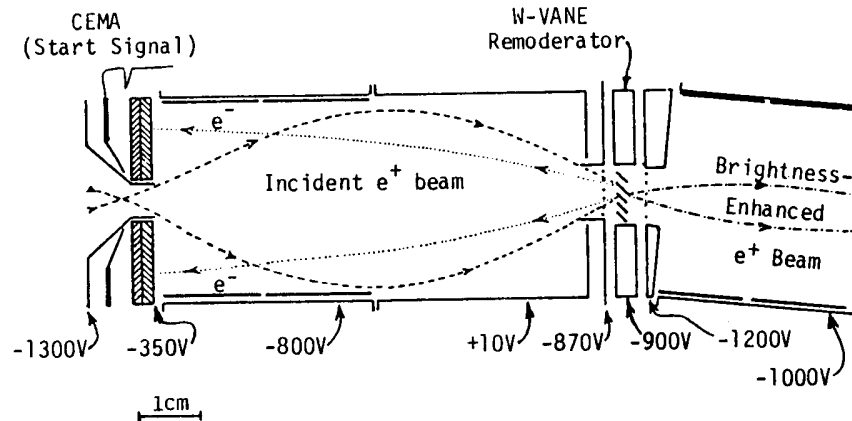


Figure 11.5: Brightness enhancement set up in transmission geometry.²⁷

d = beam diameter

θ = angular divergence

I = positron intensity (particles per second)

E = kinetic energy of the beam

an improvement of a factor of ~ 500 has been achieved²⁸ Fig. 11.5 shows a brightness enhancement stage in transmission geometry. Instead of a vane moderator also a thin single-crystal foil can be used.²⁹

The transmission geometry is advantageous from the beam optics point of view, but the moderator efficiency obtained so far is smaller than in a back-scattering geometry.

11.2.3 A slow-positron source at the TTF

The conversion efficiency of a linac based slow-positron source, defined as the number of slow-positrons divided by the number of incoming electrons,

²⁷Van House, *A Brightness Enhanced, Timed, Slow-Positron Beam* in: International Workshop on Positron (Electron) Gas Scattering, Detroit (1985)

²⁸K. F. Canter, in: *Positron Studies of Solids, Surfaces and Atoms*, World Scientific, Singapore 1986, Ed.: A. P. Mills Jr., W. S. Crane, K. F. Canter, p. 102.

²⁹D. M. Chen, K. G. Lynn, R. Pareja, B. Nielsen, *Phys. Rev. B* 31, p. 4123 (1985).

Table 11.3: Parameters of a slow-positron source at the TTF.

Primary Electron Beam	
Energy MeV	400
Power kW	26.1
Slow-positron Beam	
Intensity $\frac{e^+_{slow}}{s}$	$(3.3 \pm 3) \times 10^9$
Pulse Width ps	~ 6
min. pulse distance ns	1000
Number of pulses $\frac{1}{s}$	8000

depends strongly on details of the source geometry and the moderator efficiency (surface roughness, surface contaminations etc.). In addition some uncertainty arises from the extrapolation to higher electron beam energies. A reasonably scaling for facilities above ~ 70 MeV is a simple scaling with the total beam power.³⁰ Table 11.4 summarizes the performance of five facilities. The average yield is $(1.22 \pm 1) \times 10^8 \frac{e^+}{s \cdot kW}$. Taken this number an intensity of $3.3 * 10^9 \frac{e^+}{s}$ and peak intensities as high as $7.0 \times 10^{16} \frac{e^+}{s}$ can be reached at the TTF. Further source parameters are collected in Table 11.3. A comparison with existing and planned sources (Tables 11.4 and 11.5) indicates that a source driven by the TTF linac can compete with the sources of the next generation and may, for the near future, even become the source with the highest intensity in Europe. In addition the time structure matches very well the requirements of the positron time scale of Table 11.2. The bunch length of $\sim 6ps$ is much shorter than the positron or positronium lifetime in solids ($> 10^{-10}s$), respectively. The bunch spacing of $1\mu s$ on the other hand is much longer than all relevant lifetimes ($\leq 10^{-9}s$) and allows a full observation of all processes.

³⁰C. Coceva, P. Giacobbe, ENEA report, Bologna (1984).

Table 11.4: Existing linac based slow-positron sources.

FACILITY	Beam Energy MeV	Intensity $\frac{e^+_{slow}}{s}$	Pulse Width ns	Efficiency $\frac{e^+_{slow}}{s \times kW}$
LLNL	100	3.0×10^9	< 20	0.9×10^8
Mainz	160	5.0×10^7	1 - 3000	3.1×10^8
ETL Tsukuba	75	1.4×10^7	?	0.5×10^8
ETL Tsukuba	75	1.0×10^7	?	1.3×10^8
JAERI Tokai	100	3.0×10^7	?	0.3×10^8

Table 11.5: Planned and existing slow-positron sources. As primary sources electron beams (\diamond), bremsstrahlung photon beams (\clubsuit) and radioactive isotopes are used. The planned high intensity sources based on isotopes are located at high flux fission reactors.

FACILITY	Status	Intensity $\frac{e^+_{slow}}{s}$	Pulse Width
Univ. of Michigan	existing	$4.0 \times 10^7 - 4.0 * 10^8$	continuous
BNL	planned	10^9	continuous
HFIR/ANS*	planned	$10^{10}/10^{12}$	continuous
Munich/Grenoble	planned ?	$10^{11} - 10^{12}$	continuous
ORNL \clubsuit	existing	10^8	2-30 ns
KEK-PF \diamond	planned	4×10^8	$1\mu s$
KEK-PF \diamond	planned	2×10^9	$1\mu s$
Positron Factory (IAERI)	planned	10^{10}	$2\mu s$
CEBAF \diamond	planned	2.5×10^{10}	$\sim 1ps$

*High Flux Isotope Reactor/Advanced Neutron Source at ORNL

