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THE INTENSE SLOW POSITRON SOURCE CONCEPT: A
THEORETICAL PERSPECTIVE ON A PROPOSED
INEL FACILITY^{†*}

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ABSTRACT

An analysis has been performed of the INEL Intense Slow Positron Source (ISPS) concept. The results of the theoretical study are encouraging. A full-scale device with a monoenergetic 5 KeV positron beam of $\geq 10^{12}$ e⁺/s on a ≤ 0.03 -cm-diameter target appears feasible and can be obtained within the existing infrastructure of INEL reactor facilities. A 30.0-cm-diameter, large area source dish, moderated at first with thin crystalline W films and later by solid Ne, is proposed as the initial device in order to explore problems with a facility scale system. A demonstration scale beam at $\geq 10^{10}$ slow e⁺/s is proposed using a ⁵⁸Co source plated on a 6-cm-diameter source dish insert, placed in a 30-cm adaptor.

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In this paper we discuss the theoretical basis for the ISPS in the context of both computer calculations for a point design and general scaling relationships developed from parametric simulation studies. We present the ISPS concept in the context of a 20-year program, which has the goal of achieving a positron plasma (hot or cold) at $10^{14} \text{ e}^+/\text{cm}^3$.

INTRODUCTION

This paper is intended as both a historical summary of certain recent research directions in the general area of intense positron beam production at the INEL, as well as a starting point for explaining present directions. In the first part of this paper we discuss the evolution of the NEAR (Nuclear E-Plus Accelerator Reactor) concept.^(1,2,3) We then discuss the "Umbrella" concept and how it has evolved to the INEL ISPS (Intense Slow Positron Source).^(4,5) Finally we discuss in detail "Concept A" for the INEL ISPS.⁽⁴⁾

SECTION A—THE NEAR CONCEPT

The NEAR Concept^(1,2,3) was conceived as a method of producing fast positron beams by direct extraction. The basic ideas for the NEAR are illustrated in Figure 1. Early analysis^(2,3) indicated that the NEAR could produce $\sim 10^{17}$ fast e^+/s for a five to ten assembly system. Neutron Monte Carlo studies for a High Temperature Gas Reactor (HTGR) NEAR were performed based on the model shown in Figures 2 and 3 and the system obtained criticality (i.e., $k_{\text{eff}} \sim 1.0$) for a central neutron thermal flux of $\leq 10^{15} \text{ n/cm}^2/\text{s}$. We believe that a beryllium/water/enriched uranium system of similar design could be configured for a central neutron thermal flux of $\leq 5 \times 10^{16} \text{ n/cm}^2/\text{s}$. However this is only a speculation at this time. Positron beam extraction technology was investigated and appears to be feasible.⁽¹⁾ The main technological issues associated with the NEAR are the high voltage breakdown characteristics of accelerator components in a high neutron flux environment. It was believed at the time these studies were concluded that the initial INEL program (yet to be formulated) should not have as its focus research on high voltage materials breakdown because of high flux neutron damage. It was also believed that since the ultimate NEAR reactor would cost $\sim \$5$ billion, pursuing such a program would be premature. Even a single NEAR assembly capable of producing $\leq 10^{16}$ fast e^+/s utilizing the INEL Advanced Test Reactor (ATR) seemed to be too expensive a first step (in the range of \$10 to \$20 million).

Idealized fast positron electromagnetic extraction computer code calculations were performed, based on INEL developed software, for various NEAR geometries. Both cylinders and disks were studied. We summarized these studies below.

Positive beta particle trajectories were calculated numerically using a fourth order Runge-Kutta method to integrate the relativistic equations of motion in static **E** and **B** fields.

Fig. 1. NEAR assemblies—conceptual.

The geometry consists of a cylinder of radius, b , and length, d . The cylinder axis is oriented along the z -axis beginning at $z = 0$ and extending to $z = -d$. A current loop of radius a lies in the x - y plane at $z = 0$.

The magnetic field components produced by the current loop are evaluated via elliptic integrals except near the z -axis where they are supplemented by an expression for B_z holding along the z -axis. The B -field is scaled to its value at the center of the loop, B_0 . A uniform electric field was applied along the z -direction.

The positrons were assumed to be emitted isotropically from the interior cylinder walls at $\rho = b$ and along the base disk at $z = -d$. The computed trajectories

Fig. 2. Cross-sectional description of NEAR concept model.

Fig. 3. Axial description of NEAR concept model.

were assigned weights based on the positron emission energy spectrum of Cu^{64} . Particles were followed in time until one of the following conditions were met:

1. The particle escaped the cylinder through the exit aperture at the top of the cylinder.
2. The particle was lost by making a collision with the cylinder wall.
3. The particle was lost by making a collision with the base-disk of the cylinder.
4. The particle survived the maximum time allowed for a trajectory without encountering the cylinder wall.

The particles were launched from discrete bins in velocity and configuration space. Cylindrical symmetry was assumed so that all particles could be launched from the x-axis.

Cylinder Walls—The cylinder walls were binned into 0.15 m segments with trajectories launched from the center of each segment. The initial launching angles were binned in the polar angle ϕ from 90.0 to 270 degrees in steps of 10 degrees referred to the x-axis and in the polar angle θ from zero to 180 degrees in steps of 10 degrees referred to the z-axis. The actual angle used for the launching was the center of each bin.

Base Disk—The base disk was binned radially into five segments and particles launched from the midpoint of each segment. The azimuthal angle was binned from $\phi = 0$ to 360 degrees in steps of 20 degrees. The polar angle was binned from $\theta = 0$ to 90 degrees in increments of five degrees.

Contour plots were drawn showing the phase space distribution of the particles reaching the exit aperture. Since a 20 by 20 contour grid was specified, some of the plots are rather coarse. Because of the coarse binning used in this preliminary study, a more detailed investigation involving either finer binning or Monte Carlo analysis is probably warranted.

The contour plot axes are specified in units of the perpendicular and parallel components of the dimensionless vector $\gamma\beta$ where $\gamma = (1 - \beta^2)^{-1/2}$ and $\beta = v/c$ with c the speed of light. The particle kinetic energy at any point in phase space is given by $E = m_0c^2(\gamma - 1)$ where $m_0c^2 = 0.511$ MeV. The quantity $\gamma\beta = p/(m_0c)$ is a dimensionless relativistic momentum and is related to the total particle energy by $E_T = m_0c^2(\gamma^2\beta^2 + 1)^{1/2}$.

Plots of relative number of escaping particles versus radius were made at the exit aperture. These are also binned in radius.

The energy range expected for the emitted particles was discretized into seven bins with energies 0.025, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 MeV, respectively. Each computed trajectory was weighted according to the phase space volume corresponding to its discrete bin.

Each trajectory reaching the exit aperture is written to a file and subsequently weighted via Liouville's theorem to the phase space volume it initially occupied. Table 1 shows the fraction of particles escaping through the exit aperture per unit time. Each case corresponds to $B_0 = 10$ kG and a current loop with $a = 0.5$ m. The fraction of the total binned, weighted positron trajectories exiting the top of the cylinder was computed based on the total number of binned, weighted trajectories that were launched.

Phase space studies illustrated in Figures 4 and 5 indicated that ~ 10 to 15% total extraction efficiency for usable phase space exists for the NEAR geometries investigated, when fast positrons are the desired outcome. Obviously one could also utilize conventional slow positron moderation techniques for such a NEAR produced beam in an appropriate geometry.

We have also investigated cryogenic moderated discs in NEAR extraction geometry (Ar, Kr, Ne, etc.) and found 100% transport efficiency. These calculations are summarized below.

Low energy positrons were launched from a disk $a = 0.5$ m in radius and 1.5 m axially from the center of a wire loop producing a B-field of 10 kG at its center. The initial energies of the positrons ranged from zero to 5.5 eV in 11 discrete steps. Uniform E-fields of 1 and 5 MV/m were applied parallel to the disk axis.

Since the initial energies are very small compared to energy each particle gained in the E-field, all particles originating at a given radius on the disk exited the loop with practically the same energy. The gyro-radii of the launched particles were small enough to ensure that all trajectories reached the exit aperture without intersecting the cylinder wall at $r = 0.5$ m.

A table of trajectory results as a function of launching radius r_i follows for $E_0 = 1$ and 5 MV/m (Table 2). The radius at which the positron intercepts the exit aperture is r_f .

SECTION B—THE "UMBRELLA" CONCEPT

Our analysis of optimum NEAR positron extraction geometries lead us to the conclusion that a simple disc geometry would be very effective. Additionally, our

Table 1a. Disk emissions.

E_0 (MV/m)	Hole radius (m)	Depth (m)	Area (m ²)	Fraction exciting (%)	Area × % product
0	0.5	-1.5	0.785	1.3	0.010
1	0.5	-1.5	0.785	26	0.2
5	0.5	-1.5	0.785	97	0.76
1	0.5	-3.0	0.785	7.6	0.060
5	0.5	-3.0	0.785	34	0.27
0	0.08	-1.5	0.020	1.5	0.00030
1	0.08	-1.5	0.020	21	0.0042
5	0.08	-1.5	0.020	35	0.007
1	0.08	-3.0	0.020	1.6	0.00032
5	0.08	-3.0	0.020	34	0.0068

Table 1b. Cylinder emissions.

E_0 (MV/m)	Hole radius (m)	Depth (m)	Area (m ²)	Fraction exciting (%)	Area × % product
1	0.5	-1.5	4.71	38	1.8
5	0.5	-1.5	4.71	70	3.3
1	0.08	-1.5	0.754	13	0.098
5	0.08	-1.5	0.754	22	0.17
1	0.5	-3.0	9.42	27	2.5
5	0.5	-3.0	9.42	67	6.3
1	0.08	-3.0	1.51	10	0.15
5	0.08	-3.0	1.51	21	0.32
0	0.5	-3.0	9.42	5.3	0.50
0	0.08	-3.0	1.51	3.2	0.048

economics analysis indicated that an $\leq \$5$ million cost was associated with an ex-situ disc [as compared to an in-situ NEAR assembly ($\sim \$10$ to $\$20$ million)]. Initial INEL interest was in using ^{64}Cu as the positron emitter. A one meter squared surface area disc was envisioned emitting $\sim 10^{15}$ fast positrons/s. A proof-of-principle 30-cm-diameter device was studied. The source, rather than being a disc, was envisioned to be a spherical segment of 30-cm chord (25-cm radius). The source would fold up like an umbrella, and hence the name, and would be placed inside the INEL ATR for irradiation (inside a capsule). After irradiation the source would be

Fig. 4. Relative distribution for disk emission.

transferred via an interim cask (after removal from the irradiation capsule) and placed into a source insertion machine. The source insertion machine would transfer the hot source into position for beam generation in the ISPS prototype.⁽⁴⁾

Both a thin crystal moderator array and cryogenic moderation was analyzed (refer to Figures, 6, 7, and 8 for details of the "Umbrella" Concept).

The INEL also analyzed ^{58}Co , ^{22}Na , ^{18}F , and ^{79}Kr as isotope options. After much debate ^{58}Co was selected, utilizing the INEL EBR-II Reactor. Again, cost considerations were the deciding factors. Although chemical processing and isotope deposition are required for ^{58}Co , it was perceived by INEL personnel as a viable approach for a prototype ISPS device given INEL expertise in hot materials handling,

Fig. 5. Relative distribution for cylinder emission.

Table 2a. $E_0 = 1$ MV/m.

$r_i(m)$	$\gamma\beta_{\perp}$	$\gamma\beta_{\parallel}$	r_f/a
0.05	0.026258	3.8075	0.017840
0.15	0.080155	3.8069	0.053222
0.25	0.13857	3.8047	0.097713
0.35	0.20418	3.8020	0.12082
0.45	0.28004	3.7987	0.15214

Table 2b. $E_0 = 5 \text{ MV/m}$

$r_i(\text{m})$	$\gamma\beta_{\perp}$	$\gamma\beta_{\parallel}$	r_f/a
0.05	0.13264	15.962	0.017986
0.15	0.42635	15.654	0.05352
0.25	0.78354	15.635	0.088241
0.35	1.2565	15.598	0.12166
0.45	1.8728	15.575	0.15465

Fig. 6. ISPS source concept.

Fig. 7 Interim cask to source insertion machine transfer sequence.

Fig. 8. ISPS cross section.

chemistry, and extensive hot cell facilities. An $\sim 10^{15}$ fast e^+ /s, 30-cm chord (25-cm radius) ^{58}Co ISPS device was envisioned.

A twenty-year program was proposed with the ultimate goal of achieving a $10^{14} e^+/\text{cm}^3$ plasma. Positron microscope applications were stressed for the early phases of the program (refer to Figure 9 for details).

Our attention then focused on the startup phase of our program. Two conceptual devices were investigated: "Concept A," a gridded design, and "Concept B," a gridless design. In this paper we will only discuss "Concept A" in detail.

SECTION C—BEAM OPTICS—"CONCEPT A" SYSTEM DESIGN

Our Concept A design has a spherical section onto which a neutron activated positron source is deposited (Co, Cu, F, Kr, etc.). Such a source produces a broad spectrum of positron energies ranging from a few to thousands of electron volts. An energy moderating material placed over the source slows down (thermalizes) the positrons and reemits a small fraction ($\sim 10^{-2}$ to 10^{-4}) with a nearly monoenergetic distribution near a few eV. These "slow" positrons are then reaccelerated and focused

Fig. 9. INEL 20-year view of positron application.

to a smaller diameter using an electric field of several keV. This process of acceleration, focusing, and remoderation (known as brightness enhancement) is repeated until the beam diameter is reduced to the desired size. Brightness enhancement through remoderators circumvents Liouville's theorem as long as the theorem is obeyed within each stage segment [i.e., between the moderator (or remoderator) and the next remoderator]. Within stages

$$\theta_1^2 d_1^2 E_1 = \theta_2^2 d_2^2 E_2 \quad (1)$$

where E_1 and E_2 are the particle energies exiting the first moderator (remoderator) and entering the second remoderator, respectively; d_1 and d_2 are the beam diameters at the first surface and second surface, and θ is the angle of beam divergence at the corresponding surface. The prototype instrument design (Concept A) consists of the source and one stage of remoderation (see Figure 10). The design brings the 30-cm source diameter down to a 0.3-mm beam diameter in two stages.

The beam physics of the INEL intense slow positron source is relatively straightforward. To examine the optics design features in detail, positron trajectory codes have been run for a wide variety of configurations. The beam analysis followed the positron trajectory from a spherical segment through an initial moderator,

acceleration and beam size reduction (Stage One), to a first remoderator, and then acceleration and refocusing to a second remoderator (Stage Two). Some preliminary calculations have also been done for the final beam extraction after the second remoderator. The bulk of the analysis has used two computer codes, SIMION and EGUN. SIMION, which was developed at the INEL and is well-known and used internationally, treats the positrons as independent particles and calculates their trajectories for a given set of boundary conditions over a specified geometry. EGUN, developed at the Stanford Linear Accelerator Center, is capable of more detailed calculations than SIMION because it can take into account collective effects and the effects of curved surfaces without introducing unspecified field errors. Space charge issues, which are important at high current densities, have been analyzed with a Particle In-Cell (PIC) technique. The details of the INEL Concept A design for a positron generator are described in the next few sections.

STAGE ONE ANALYSIS

From a detailed fine-mesh positron beam optics analysis with EGUN, we have obtained a set of empirical scaling relationships for the various physical effects.

Thermal Effect

The angle of positron emission from a surface, Θ_* , is determined by the properties and temperature of the moderator. To a good approximation, in tungsten (a well-studied moderator) the transverse beam energy is proportional to $k_B T$ (where k_B is the Boltzmann constant). Defining the angle of emission from a remoderator surface with

$$\tan \Theta_* = \left(\frac{E_\perp}{E_\parallel} \right)^{1/2} = \left| \frac{v_\perp}{v_\parallel} \right| \quad (2)$$

if $E_\perp = 4 k_B T$ (HWHM^a), then

<u>T (K)</u>	<u>$k_B T$ (mV)</u>
300 (water cooling)	100
80 (liquid nitrogen)	30
5 (liquid helium)	2

This is a good approximation for tungsten between 300 and 77 K, although it breaks down below ~60 K remaining somewhere near 30 mV (HWHM) or 60 mV

a. HWHM = half width at half maximum.

Fig. 10. Features of the Concept A design.

(FWHM^b). The 5 K, 2 mV analysis serves as a theoretical lower bound for moderator and remoderator materials other than tungsten in this study.

Based on these observations and EGUN calculations, we obtain the relationship

$$\frac{\text{Thermal Error at Focus (mm)}}{\text{Radius (mm)}} = \pm 0.56 \times 10^{-2} \left[\frac{\text{Surface Ejection Energy (eV)}}{\text{Extraction Energy (eV)}} \times T_{\text{FWHM}} \text{ (K)} \right]^{1/2} \quad (3)$$

This relationship has been used to predict the "smear" in focus for a number of cases. For tungsten (2.5 eV ejection energy), using an extraction energy of 5 keV and a temperature of 300 K, the thermal error at the focus is ± 0.54 mm for a 250-mm-radius device.

b. FWHA = full width at half maximum.

Effect of "Flat" Moderator Crystal Plates and Placement

A design issue that needs to be addressed is the focus effect of flat moderator plates placed on or near a hemisphere (i.e., a spherical segment). Using a second scaling relationship developed from EGUN calculations, we have

$$\frac{\text{Error at Focus caused by Flat (mm)}}{\text{Radius (mm)}} = \pm 0.112 \left[\frac{\text{Length of Flat (mm)}}{\text{Radius (mm)}} \right] \left[\frac{\text{Length of Flat (mm)}}{\text{Extraction Gap Length (mm)}} \right]^{1/2} \quad (4)$$

For a typical case of 1 cm × 1 cm crystal of tungsten and an accelerator grid 5 cm away, the focus error is ±0.5 mm because of the flatness of the crystal plates for a 250-mm-radius device.

For the single crystal moderator flats, the misalignment error relative to the center of a crystal flat that acts as the pivot on a spherical surface results in the scaling relationship

$$\frac{\text{Alignment Error at Focus (mm)}}{\text{Radius (mm)}} = \pm 0.93 \frac{\text{Edge Displacement (mm)}}{\text{Length of Flat (mm)}} \left[\frac{\text{Length of Flat (mm)}}{\text{Extraction Gap Length (mm)}} \right]^{1/2} \times \text{Form Factor} \quad (5)$$

The form factor is ≤2.0 for parameters of interest to us. Considering the same tungsten flat as before (with the accelerating grid), a 0.1-mm edge displacement results in a focus misalignment of ±2.0 mm.

SIMION calculations, where applicable, were found to be in agreement within the accuracy of the code, for this set of empirical scaling relationships.

Effect of Grid and End Effects

As mentioned elsewhere,⁽⁵⁾ detailed EGUN calculations were made to study the effect of the accelerating grid. Trajectories for a concentric grid have been calculated for several placements of such a grid, as well as for the case with no grid (i.e., biasing the first remoderator sufficiently to bring the majority of positrons to it). For such a concentric grid, the effects of the finite grid mesh size have also been examined. We calculated the defocusing effect, which was first analyzed by Davisson and Calbick,^(6,7) and found smearing on the order of 1 mm² for a grid size of 1 mm. For our Concept A Stage One design, the error caused by the finite grid mesh size is given by

Fig. 11. End effect EGUN calculation for Stage One.

$$\frac{\text{Total Error caused by Grid Mesh at the Focus (mm)}}{\text{Mesh Spacing (mm)}} = \frac{\text{Radius (mm)}}{4 \times \text{Extraction Gap Length (mm)}} \quad (6)$$

Other effects that can cause defocusing occur at the edges of the moderator and/or grid. These "end" effects arise because of the electric field gradients at these terminations. An example is shown in Figure 11. For a 5.0-cm gap between the grid and moderator array, the end-effect defocusing is ± 0.50 mm when the concentric field region is extended by two gap lengths beyond the active positron transport region.

Summary

The final remaining issue for Concept A, other than space charge which will be discussed later, is global misalignment of the moderator array and the electrostatic grid. If these two elements are not exactly concentric (i.e., their radial vectors do not have the same focus), the entire beam spot will shift by an amount approximately equal to the displacement from the original focus of the radial vectors. The Intense Slow Positron Source (ISPS) Concept A device is designed so that if bench alignment of these two elements does not produce the same focal radial vectors and, hence, the beam spot is not on the optical axis of Stage Two, the entire Stage Two Einzel lens assembly can be displaced in the x-y plane (assuming $\hat{z}$ to be the positron beam axis) by a set of linear actuators. An electrostatic, x-y beam focusing field device can be incorporated into the exit aperture of Stage Two to compensate for this mechanical displacement.

Table 3 gives the maximum set of errors for a "well-constructed" Concept A device.

Examination of our Stage One, Concept A device physics suggests that a gridless design should have certain advantages. Equations (4) and (5) indicate that a factor of $\sim 2x$ benefit exists for placing the grid at the origin, and hence reducing the effect of local field errors from the moderator surface. This could result in a factor of $4x$ brightness enhancement, relative to Concept A, if the end effects can be overcome. An additional factor of $2x$ in positron beam brightness can be obtained from elimination of beam loss to the grid and its support structure, and an overall reduction of complexity of the total design can be achieved. These ideas are presently under investigation both computationally and experimentally, in the context of the Concept B^(8,9) optics design.

STAGE TWO ANALYSIS

The purpose of the second stage of positron acceleration is to reduce the positron beam delivered by Stage One from millimeter to submillimeter radius. Most of the calculations for the Stage Two design were performed with the SIMION code.

The size of the beam spot delivered by Stage One will be affected by various "parasitic" aberrations of mechanical (alignment) origin. Starting with a concave spherical emitter of 250-mm radius and 300-mm chord, there is good reason to expect (on the basis of preliminary beam trajectory calculations) that the converging positron

Table 3. Maximum set of errors.

<u>Cause of Error</u>	<u>Error (mm)</u>
Moderator tile positioning error of 0.1 mm	± 2.0
Flat tiles 1 cm $\times$ 1 cm	± 0.5
Thermal spreading (reemitted positrons)	± 0.6
Grid wire mesh defocusing	± 0.6
End effect (5-cm separation with 2x gap extension)	± 0.5
Rms	2.3

beam will be smaller than 10 mm in diameter. If the structure is well-built, the focal spot will reduce to about 3 mm FWHM. This corresponds to a radial size reduction of 10^{-2} and an area reduction of 10^{-4} . Stage Two should be designed to provide comparable performance, i.e., to reduce an initial 3-mm-diameter spot to 0.3 mm or less. Preliminary calculations of a simple electrostatic focusing system suggest that this is indeed possible and, therefore, a realistic goal to pursue.

To avoid unnecessary geometric aberrations, the particle source for Stage Two (a remoderator) should have either a spherical (preferably concave for natural focusing) or flat emitting surface. Since the remoderator will most likely be a flat film or foil, a flat surface was assumed for model calculations. An applied electric field at the emitting surface accelerates a beam of particles away from the emitter.

An electrode having negative voltage must be placed near the emitting surface to generate the extraction field. [Although this field does not extract positrons from within the surface—positrons are energetically expelled in the absence of an external field—the term "extraction" will be used in the following discussion of the surface field and the electrode(s) which produce it to demarcate this region.] As a tentative (and simplistic) first design, this electrode was shaped as a moderately thick disk, placed parallel to the source plane with an extraction aperture (having rounded edges) surrounding the extraction region (see Figure 12). This combination of open electrodes (without grids) produces a longitudinal accelerating field that diverges away from the opening; consequently, it contributes radial forces that cause divergence or defocusing of the accelerated particles.

To focus this diverging beam back to the axis, an additional convergent lens is required. This second lens could be magnetic (solenoidal or "round" type used in electron microscopes) or electrostatic (Einzel lens). Einzel lenses can be accel/decel (meaning particles accelerate when entering and decelerate when exiting) or decel/accel. In very broad terms, decel/accel Einzel lenses require less operating voltage (and are much preferred for this reason) but produce greater focal aberrations. In either case, the focal length scales linearly with the lens diameter (i.e., a magnified image of lens and rays at fixed potentials does not change proportions) and the focal

length is a nonlinear function of voltage. After examining a large set of cases, our analysis indicates that a decel/accel design gives the optimum result with an $\sim 36\times$ beam diameter reduction, including 300 K HWHM noise.

Calculations by EGUN for a Stage Two accel/decel type of lens indicate that space charge interactions for a beam focused down from 3-mm radius to 0.06-mm radius are not significant for currents less than 1 mA. At about 10 mA the spot size begins to enlarge and refocusing would be required. At about 100 mA it will not be possible to keep the spot below about 0.5-mm radius using lens adjustment.

Calculations for a similar beam envelope in a decel/accel lens were not performed. Although the decel/accel case can be anticipated to be less favorable, since the beam remains large except near the final "point" focus, the two results should not be too different for low currents (< 1 mA). Based on the EGUN calculations, there should be no problem with space charge for any positron current that is likely to be produced in Stage Two. Space charge issues are discussed further in the next section.

Space Charge Analysis

Based on this analysis, experience, and recent simulations, it is generally possible to say, qualitatively, that if $\lambda_{De} > \ell$ (where λ_{De} is the Debye length and ℓ is the

Fig. 12. Extraction region of Stage Two.

characteristic length), space charge effects can be neglected. On the other hand, if $\lambda_{De} \leq \ell$, space charge effects begin to occur. We will present, here, an order of magnitude analysis of the positron beam parameters expected for the ISPS device during various phases of the proposed experimental program (Table 4). Phase I is assumed to occur during the first three years of the experimental program.

The longitudinal space charge effect is severest at the surface of the final target. Therefore, we estimated the space charge effect at that point. As can be seen from Table 5, the most severe number for Phase II for the longitudinal Debye length is ~ 10 cm, while the transport length is of this order (or longer), and hence, the space charge effects are minimal. Thus, precise effects need to be looked at numerically. In Phase I it is safe to say that little to no longitudinal space charge effect exists. Note that numbers in Table 5 are based on the instantaneous electron density on the target, which is higher than the in-flight effective density. Table 5 results were obtained from the following calculation.

The longitudinal Debye length at the dynamical energy of 5 keV is given by

$$\lambda_{De}^l = \frac{2 \times 10^9 \text{ cm/s}}{6 \times 10^4 \sqrt{n_e}} \quad (7a)$$

The positron density on the target (where A is the area) for Phase I (very early) is given by

$$n_e = \frac{1.6 \times 10^7}{2 \times 10^9 \text{ A}} \approx \frac{10^{-2}}{\text{A}} \text{ cm}^{-3} \quad (7b)$$

Table 4. ISPS physics parameters^a used in space charge analysis.

	$\phi_e + (5 \text{ keV})$ on exit remoderator of Stage Two Einzel lens with 0.03-cm-diameter unit area (e^+/s)
Phase I (very early)	1.6×10^7
Phase I (early)	8.2×10^9
Phase I (late)	1.6×10^{10}
Phase II (early)	2.0×10^{11}
Phase II (facility scale)	2.9×10^{12}

a. Stages One and Two as per previous analysis; one moderator (Stage One) surface and one remoderator (Stage Two) surface.

Table 5. Longitudinal space charge analysis.

	λ_{De}^l (cm)	
	$A = 10^{-1} \text{ cm}^2$	$A = 10^{-3} \text{ cm}^2$
Phase I (very early)	$\lambda_{De}^l \approx 10^5$	$\lambda_{De}^l \approx 10^4$
Phase I (early)	$\lambda_{De}^l \approx 5 \times 10^3$	$\lambda_{De}^l \approx 5 \times 10^2$
Phase I (late)	$\lambda_{De}^l \sim 3 \times 10^3$	$\lambda_{De}^l \sim 3 \times 10^2$
Phase II (early)	$\lambda_{De}^l \sim 5 \times 10^2$	$\lambda_{De}^l \sim 50$
Phase II (facility scale)	$\lambda_{De}^l \sim 10^2$	$\lambda_{De}^l \sim 10$

A = Area of target spot size.

The transverse space charge effect is most severe for the ISPS on the surface of the first remoderator, where the transverse temperature is expected to be at its lowest value. The precise temperature rise of the beam during flight from the surface of the remoderator to the target will be evaluated in later work. As can be seen in Table 6, the most severe numbers are again for Phase II, where the transverse Debye length is of the order of the focal size. Thus, a dynamical estimate becomes necessary for this case.

The initial transverse temperature of the positron beam emanating from the surface of the remoderator can, conservatively, be assumed to be as low as the temperature of the metal surface. If the remoderator is at room temperature, the beam transverse temperature is ≥ 300 K. If the remoderator is at a lower temperature, so is the positron beam transverse temperature. Therefore, the Debye length of the beam in the transverse direction is much smaller than that in the longitudinal direction. The transverse Debye length can be estimated (at 300 K) as

Table 6. Transverse space charge analysis.

	$\lambda_{De}^\perp$ (cm) at three values of T_e		
	300 K	70 K	4 K
Phase I (very early)	$\sim 10^2$	~ 50	~ 10
Phase I (early)	~ 5	~ 3	~ 0.5
Phase I (late)	~ 3	~ 1.5	~ 0.3
Phase II (early)	~ 0.4	~ 0.2	~ 0.04
Phase II (facility scale)	~ 0.1	~ 0.05	~ 0.01

$$\lambda_{De}^{\perp} = \frac{4 \times 10^7 T_e^{1/2}}{6 \times 10^4 n_e^{1/2}} \approx \frac{10^2}{\sqrt{n_e}} \text{ cm} , \quad (8a)$$

where T_e is in eV and n_e is in $(\text{cm})^{-3}$. The positron density on the target for Phase I (very early) is estimated as

$$n_e \sim \frac{1.6 \times 10^7}{6 \times 10^7 A} \sim \frac{0.3}{A} \text{ cm}^{-3} , \quad (8b)$$

If A is $\sim 0.3 \text{ cm}^2$, $n_e = 1 \text{ cm}^{-3}$.

The dynamical effect of the transverse space charge is estimated next. Since space charge effects become important only in Phase II at the first remoderator surface, that case is considered. The simplest way is to estimate the space charge acceleration time by evaluating the plasma time. For Phase II, the inverse plasma frequency is given by

$$\omega_{pe}^{-1} \sim \frac{1}{6 \times 10^4 \sqrt{n_e}} \text{ s} = \frac{\sqrt{2}}{6} \times 10^{-7} \sim \frac{1}{4} \times 10^{-7} \text{ s} . \quad (9a)$$

On the other hand, the acceleration time for the beam to reach from $\sim 2 \text{ eV}$ to 5 keV over the length ℓ is

$$t = \frac{v}{a}, \text{ where } 2 a \ell = v^2 . \quad (9b)$$

Therefore, $t = 6 \times 10^{-8} \text{ s}$ if we set $\ell = 10^2 \text{ cm}$ (estimated maximum distance between the first remoderator and the target). Note that this time is comparable to or slightly longer than the plasma time. This means that space charge can eventually affect the dynamical orbits over the flight from the surface of the first remoderator to the target in the Phase II scenario. However, we believe at this time that this will be a small effect.

Examination of Table 6 indicates that for a certain range of parameters the transverse Debye length tends to be equal to, or smaller than, the beam transverse size. When the beam transverse size is greater than the transverse Debye length, we expect that the beam will begin to spread because of space charge effects. When it spreads, we expect that the beam will acquire an increased transverse temperature. On the other hand, the dynamical Debye length in the longitudinal direction is greater than, or at its worst about equal to, the longitudinal dimension, so that the space charge effect in the longitudinal direction is not serious.

When the transverse space charge effect increases the transverse temperature, the beam expansion (because of space charge) ceases when the heated beam acquires a transverse Debye length roughly equal to the beam transverse size. On the other hand, the time for growth of the space charge expansion is comparable with the beam drift time. Thus the e-folding of the instability is not large. This results in a dynamical situation for Phase II for $T_e = 0.03$ eV, where the transverse temperature begins to increase while the beam is longitudinally boosted. An accurate assessment of these cases thus requires dynamical (time-dependent) analysis and/or computer simulation (perhaps 2D). We estimate that the saturated temperature will be the original longitudinal temperature of ~ 2 eV. However, confirming this requires further theoretical and computational work.

A one-dimensional PIC simulation code developed at the Physics Department of the University of Texas was adapted for simulation of some aspects of the proposed experiments. Preliminary one-dimensional PIC simulations assumed a beam longitudinal energy of 5 keV (instantaneous boost from 2.5 eV to 5 keV) with a beam transverse temperature of 300 K and a 5-mm initial beam diameter. For Phase II (early) we have observed an $\sim 40\%$ increase in transverse velocity over the thermal velocity (because of space charge) over a time of $20 \omega_{pe}^{-1}$ (this corresponds to a length of ~ 10 m). For Phase II (facility scale), we have observed an $\sim 300\%$ increase in transverse velocity over a time of $20 \omega_{pe}^{-1}$. Based on the results presented earlier and these simulations, we conclude that space charge effects will be negligible in Stages One and Two of the ISPS for Phase I of the program. Further work needs to be done to investigate the ISPS Phase II device, and the brightness enhanced beams beyond Stage Two, for Phases I and II. This work will be performed during the INEL ISPS demonstration program.

Beam Extraction

At this point in the ISPS device development, the INEL has not devoted as much effort to the design of a beam extraction system for the ISPS. It is our intent to design a beam extraction system during Phase I. We present some preliminary ideas below.

Further brightness enhancement steps with remoderators for Phases I and II require a careful analysis. Hence, the use of reflection or transmission remoderation steps over distances of several meters or more is not advisable unless additional brightness enhancement is not attempted. It is desirable to design a beam extraction system with at least two 90-degree bends so that the positron microscope's first remoderator is not in a direct line of sight from the ISPS source disk (because of the strong γ radiation field). The simplest approach is to (a) boost the beam rapidly to 5 keV off the second Stage Two remoderator; (b) use two 90-degree electrostatic (or magnetic) bending elements and allow the beam to thermally expand (because of the $\sim 1/40$ eV transverse beam energy) at 5 keV longitudinal beam drift energy between these elements; and then (c) repeat the Stage Two Einzel lens to reduce the beam

back to submillimeter size. A more desirable approach is to compensate for the thermal beam expansion by placing focusing elements between the 90-degree bending sections. A third approach is to separate the Stage One and Stage Two ISPS elements. This approach has several operational advantages for a facility-scale ISPS device. We discuss several aspects of such a preliminary design below.

The main feature of the proof-of-principle ISPS Phase I design is two blockhouses, with a 90-degree bend for source shielding. A third blockhouse may also be desirable for safely loading the source. The optics includes a modified electrostatic lens just after the first remoderator. This is followed by an asymmetric Einzel lens, an electrostatic 90-degree turn, a second asymmetric Einzel lens, and then either a transmission remoderator or a reflection remoderator in Blockhouse 2. Placing the modified electrostatic lens just after the first remoderator has some advantages.

Engineering Design Considerations

Engineering studies have investigated both Cu and Co as positron sources for the ISPS device. Most of our detailed (early) studies were done for Cu.

Moderator Array

A cryogenic rare gas moderator structure and a W moderator array have been investigated. Our Concept A engineering analysis has emphasized the W moderator array. This array would be constructed of W foils 1,500 to 20,000 Å thick. Two design concepts have been identified for the array. The first, a tile design, requires a large number of foil "tiles" that would be attached to a hemispherical structure (Figure 13). The second concept, called the integral design, involves fabricating a hemispherical segment, applying a substrate, and coating it with W by sputtering or chemical vapor deposition, and then removing the substrate. It is anticipated that the structure will be fabricated from a readily machinable, nonmagnetic material. Ideally, the material should have a coefficient of thermal expansion similar to that of W. Matching the thermal expansion coefficients would eliminate concerns that the differential thermal growth would cause the foil to go slack (possibly wrinkling and losing focusing accuracy) or to be pulled too tightly (possibly damaging the foil).

In the tile design a number of W-foil devices, each consisting of a 1,500 to 20,000 Å W single crystal (or polycrystal) foil attached to a W frame (Figure 14), are assembled into a structure. The 0.5-mm-(0.020-in.) thick frames have an outside diameter of 1.0 cm (0.39 in.) and an inside diameter of 0.7 cm (0.28 in.). The hemispherical structure supports the frames and focuses them on the first remoderator target. This structure will have a number^c of 0.7-cm-(0.28-in.-) diameter holes and

c. Over 600 in the Cu option and 10 to 20 for the Co option for Phase I.

Fig. 13. Moderator array isometric view.

1.0-cm-(0.39-in.-) diameter by 0.5-mm-(0.020-in.-) deep spotfaces on the inner (concave) surface on a 1.07-cm-(0.42-in.-) triangular pitch. The spotfaces are used to align the foil devices. The desired alignment tolerance for each frame is $\pm 50 \mu\text{m}$ (0.002 in.-) on the target; early prototype tolerances of $\pm 1 \text{ mm}$ are acceptable. Evaluation of foil preparation and mounting methods will be performed early in the design phase. The advantage of this tile concept is that it is proven—as stated in various articles in the positron literature. The major disadvantage is that a large number of foil devices are required and the assembly will be very labor intensive. However, the Co option significantly reduces the number of the W foils required (10 to 20) for the array for Phase I of the project.

The integral design starts with a spherical segment structure similar to that of the tile design but there are no spotfaces. The size of the holes depends on the structural properties of the W foil, so the optimum hole size will be determined based on the strength of the foil and the optical performance of the assembly. A substrate will be applied to the back of the structure, filling the holes. The front of the substrate/structure assembly will then be machined to obtain a smooth, spherical

Fig. 14. Tungsten foil tile.

surface (Figure 15). A W film will be applied to this surface using a sputtering or chemical vapor deposition technique. Finally, the substrate will be dissolved, leaving a foil/structure assembly. This concept is very attractive. However, the technique has not been demonstrated, and the properties of the resulting foil are unknown, as are the properties of positrons moderated by such foils. Thus, some development is needed early in the design phase before the final moderator array concept can be selected. Presently, the tile design is the baseline concept. The "integral" design is a promising advanced concept.

The INEL has in-house capabilities to develop and fabricate both the tile and integral moderator array designs. Our Enerjet Model UCV-18/6 magnetron sputtering system with a CHA SR15-2 electron beam evaporator provides the capability to apply coatings of metals, ceramics, polymers, etc., ranging from nanometer to millimeter thicknesses. The magnetron sputtering system consists of a 10 kW dc power supply, 600 W RF power supply, and 6-, 3-, and 2-in. guns. The e-beam attachment consists of a 15 kW power supply and two e-beam guns, capable of simultaneous deposition. A LN_2 cryotrapped 8-in. diffusion pump is used to pump the vacuum chamber to the 10^{-7} torr range. Thin-film deposition rates and thicknesses are monitored by quartz crystal oscillators that are calibrated using standard atomic absorption techniques. Substrates (static or rotated) can be cooled to LN_2 temperatures or heated to 1200°C . Reactive gases, such as O_2 , N_2 , and C_2H_2 , can be introduced into the chamber to deposit thin films of oxides, nitrides, and carbides, respectively. An experienced research and development staff of five people is available to aid in the moderator array development effort.

For the Phase II design, the maximum allowable moderator array temperature is on the order of 300 K, with a maximum allowable variation in temperature over the array surface of less than 30 K. Calculations indicate that this can be accomplished for the Cu concept with two water-cooling coils, one at a radius of one-half the outside radius and another at the outer radius. The temperature variation over the

Fig. 15. Integral moderator array fabrication.

structure itself (i.e., the 3-mm thickness) will be less than 15 K. It is believed that a similar design will work for the Co concept, however, additional calculations need to be performed because of the higher specific activity of Co.

The temperatures of the foils attached to the moderator structure were also investigated for the Cu concept. In these calculations, the maximum calculated temperature difference between the center and edge of the foil was 25 K. Thus, the maximum temperature variation between the coolest part of the moderator array structure and the hottest point on the foil is 40 K (15 + 25). Although this is larger than the desired value of 30 K, given the conservative nature of the analysis and the early stage of the design the concept is certainly feasible.

Electrostatic Grid

The electrostatic grid accelerates the positrons emitted by the moderator array. The grid is a hemispherical segment with a radius of 20 cm (7.87 in.) and chord of 34 cm (13.5 in.) located concentric with the moderator array. In this design, it is maintained at -5.0 keV relative to the moderator array.

The precision of the focus of the positron beam is strongly affected by the dimensional alignment of the electrostatic grid. The current plan is to make the grid from 1-mm-square Cu mesh using a spherical form; a structural support will be attached to the mesh before it is removed from the form. Dimensional tolerances for the grid are a factor of two to three less severe than those of the moderator array.

Remoderators

The Stage Two remoderators focus and transmit the positron beam. Both remoderators are of single-crystal W foil and frame construction. The first remoderator is expected to be 1 cm in diameter. The second remoderator is expected to be 0.2 cm in diameter, although the beam diameter at the second remoderator could be as small as 0.03 cm.

Calculations were performed to determine the temperature distribution in the remoderator foils. In this analysis, the heat sources considered were thermalization of the positron beam and thermal radiation from the surroundings. Various beam impact diameters and remoderator operating temperatures were considered. The results indicate that the practical lower limit for the remoderator operating temperature is on the order of 20 to 30 K with He cooling.

Electrostatic Lens (Stage 2)

An electrostatic (Einzel) lens will be used to focus the positron beam emitted by the first remoderator onto the second remoderator. The lens, shown in Figure 16, consists of six coaxial electrodes. These electrodes will be separated by insulating

sections; precise spacing between the electrodes will be achieved by machining the insulators. The electrodes and insulating spacers will be aligned prior to assembly of the lens in the moderator/grid/lens mounting structure. The penetrations through the vacuum vessel for the electrical connections will be made using standard high vacuum, high voltage, insulated feedthroughs.

Mounting Structure

The various components of the Concept A ISPS must be precisely aligned to each other to ensure optimum beam collection and focusing. The moderator array, electrostatic grid, remoderators, and electrostatic lens are all mounted on a common base. Where necessary, electrical insulation is provided between components with different electrical potentials. These devices will be assembled and aligned "on the bench" prior to installation in the vacuum vessel. After the source has been positioned next to the moderator array, the remoderators can be remotely aligned in the horizontal directions to optimize the beam brightness.

SECTION D—SUMMARY AND CONCLUSIONS

Various positron production concepts have been investigated at the INEL. We believe that NEAR technology can produce $\sim 10^{17}$ fast e^+ /s for an ultimate device and $\leq 10^{16}$ fast e^+ /s for a single assembly in the INEL ATR. ISPS technology can produce $\leq 10^{15}$ fast e^+ /s. We have discussed the "Concept A" ISPS device in this paper. It has

Fig. 16. Remoderator/lens assembly.

the highest theoretical confidence level at this time (utilizing thin crystal moderation or cryogenic Neon). Two other papers in these proceedings discuss our "Concept B" gridless cryogenic device.^(8,9) The principle theoretical uncertainty with "Concept B" is the macroscopic physics of the device versus the microscopic physics of Concept A (i.e., gridless versus gridded). A proof-of-principle three-quarter-scale, gridless design experiment utilizing electrons has achieved ~100x beam diameter compression in one stage (large area source to first remoderator surface). Beam transport efficiency is currently under study for this Concept B device.⁽⁸⁾

The INEL believes that the ⁵⁸Co ISPS is the best first step it can take at the lowest cost to the positron research community. We also believe that the ISPS will have numerous application opportunities in both basic and applied physics (refer to Table 7 for a list of possible applications).

Table 7. Applications of the ISPS.

	National impact
Positron Microscope Facility	Reduce material defects
• U. of Michigan and INTEL Corporation collaboration	
Microelectronics Fabrication Technology	Reduce integrated circuit size
• X-rays	
• Positrons	
• INTEL Corporation collaboration	
Tunable channeling x-ray sources	Higher x-ray beam intensity
• Lithography	Unique
• 10 keV for DOE-DP	
Thin film NDE/NDT solid state R&D with positrons	Density and reliability improvement
• U. of Michigan and INTEL Corporation collaboration	
e ⁺ Accelerator and storage ring	Unique
e ⁺ Pure plasma and (e ⁺ e ⁻) equal mass plasma research	Basic research
Positronium QED measurements, Bose condensation of Ps, etc.	Basic research
Spin-off technologies	N/A
• Material science for naval reactors	
• Aging work for NRC	
• In-service inspection for ATR	

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