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by

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Abstract

A research and development effort is underway at the Advanced Photon Source (APS) to use an rf gun as a low-emittance electron source for injection into the 100- to 650-MeV linac subsystem and subsequent transport to an undulator test area. This configuration would combine the acceleration capability of the 200-MeV S-band electron linac and the in-line 450-MeV positron linac that normally provide positrons to the positron accumulator ring (PAR). A transport line that bypasses the PAR will bring the electrons to the undulator test area. Characterization techniques will be discussed for the electron beam with a normalized, rms emittance of <10 π mm mrad (1σ) at micropulse charges of up to 350 pC and micropulse durations of ~5 ps (FWHM). Tests proposed include measurement of particle beam transport effects (at one-tenth the storage ring beam rigidity) caused by small undulator field errors as well as operations intended to produce diffraction-limited and possibly even coherent, short wavelength radiation (<200 nm).

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1. Introduction

At the Advanced Photon Source (APS) [1], a research and development effort is underway using an rf gun [2] as a low-emittance electron source for injection into the 100- to 650-MeV linac subsystem and subsequent transport to an undulator test area. This configuration would combine the acceleration capability of the 200-MeV S-band electron linac and the in-line 450-MeV positron linac that normally provide positrons to the positron accumulator ring (PAR). A transport line that bypasses the PAR will bring the electrons to the undulator test area. Characterization and preservation of the low-emittance beam will be critical to the undulator tests. At the high energy end, emittance measurements will be done using a three-screen technique over a 10-m drift space as the baseline method with optical transition radiation interferometry (OTRI) [3,4] and variable quadrupole field, single-screen techniques as complementary measurements. To measure the anticipated sub-100-μm spot sizes, OTR conversion screens will be used as well as gated, intensified camera technology [5]. At the low-energy end, due to beamline space limitations, probably the variable quadrupole techniques will be used.

The primary purpose of the undulator test line is to achieve full characterization of the undulators before their insertion into the storage ring. This will be done by passing a beam of sufficient quality (very low emittance) through the field of the undulator magnet under test. The beam will thus be used to measure directly the effect that the magnetic field errors within an undulator have on the beam, and the undulator's capability of forcing the beam to generate high quality light. Characterization will be performed in two ways. First, the influence the undulator has on the beam will be measured as a function of beam input position and angle as well as undulator gap size (at one-tenth the rigidity of the 7-GeV storage ring beam [6]). With sufficiently low emittance, these measurements can be used to generate the transfer map of the device [7]. The second method will be to measure the properties of the resulting generated radiation. A very low emittance beam allows the possibility of generating diffraction-limited radiation. Measurement of the properties of the generated light are thus a direct measure of the undulator quality and not that of the beam.

There are two other secondary uses of the line. Production of useful quantities of diffraction-limited short wavelength radiation (<200 nm), and possibly even coherent radiation, for use by experimenters will be possible. A further use will be as a test bed to characterize present diagnostics as well as new concepts before installation into the storage ring.

These objectives require preservation of the emittance during acceleration and transport. Simulations predict that a beam of normalized, rms emittance $<2\ \pi$ mm mrad (1σ) at micropulse charges of up to 350 pC can be produced at the gun exit. Compression of bunches to durations of ~5 ps (FWHM) is also predicted, and the emittance objective at the undulator test area is $<10\ \pi$ mm mrad.

2. System Background

The APS will be a third-generation synchrotron radiation user facility based on a 7-GeV positron beam in an 1104-m circumference ring. The source of these positrons is a thermionic electron gun, two in-line S-band linear accelerators (the 200-MeV electron linac and the 450-MeV positron linac), and the converter target between them. For the low-emittance mode, it is planned to install an rf thermionic gun with an alpha-magnet and inject into the electron linac just after the first accelerator tank. The converter target is retracted and the positron accelerator is merely rephased to accelerate electrons. A schematic of this is shown in Fig. 1. As described below, the immediate acceleration of the electrons by the high gradient field makes this a low-emittance source.

The rf gun is a modification of the one operating on the injector at SSRL and was described in detail by Borland in Ref. 2. It is a side-coupled $\pi/2$-mode, standing-wave structure, and resonant at 2856 MHz. Several changes were made in the APS design to improve beam emittance by a factor of three to four over that of the SSRL gun. The projected normalized emittances of $<10\ \pi$ mm mrad at micropulse charges up to 350 pC at 650 MeV are indicated in Table I. The macropulse bunch length is limited by the rf system. Results of simulations of the gun performance are given in Fig. 2. The emittance expected up to 350 pC per bunch as a function of gun cell field gradient is shown. The highest gradients are advantageous, and at the gun exit emittances less than $2\ \pi$ mm mrad are simulated.

3. Characterization Techniques and Simulations

A more complete summary of the beam parameters and the diagnostics techniques proposed for characterizing the beam is given in Table II. The nominal value, the span, diagnostic technique system resolution, and measurement bandwidth/timescale are shown. The discussion below will emphasize the characterization of transverse and longitudinal aspects.

A. Transverse Characterizations

Although beam position monitors are planned using the stripline pickup technology, the transverse emittance of the beam is a more critical parameter. At the high energy end of the linac system, the transverse emittance measurements will be done using a three-screen technique over a 10-m drift space (the PAR bypass line of Fig. 1) as the baseline method with optical transition radiation interferometry (OTRI) and variable quadrupole field, single-screen techniques as complementary measurements. To assess the spatial profiles with rms sizes $\sigma_{x,y}$ ~100 μm, OTR single conversion foils/screens will be used at the three axial locations. Since single micropulse charges are of the order of 350 pC, gated, intensified camera technology will be employed as a complement to standard cameras. The surface-emission character of OTR would avoid the spatial-resolution-limiting effects of phosphor grain size, phosphor thickness, or Cherenkov radiation converter thickness. The OTRI technique is schematically shown in Fig. 3. The forward radiation generated by the beam at the first foil interferes with the backward radiation of the second foil. The angular distribution pattern observed at the backsurface of the second foil exhibits an interference pattern which can be analyzed for beam divergence and energy effects.

Two quadrupoles upstream of the 10-m drift space will allow some adjustment of the partition between beam size and beam divergence when the waist is at the center screen. By matching the spot sizes at the first and third screens with a beam minimum at the center screen, the three-screen formalism to calculate emittance is simplified. Emittance determination with 15 to 20% accuracy with an imaging system resolution of 25 μm (FWHM) is expected. It is noted that one is observing the projections on the x and y axes, but with 3-location data, one could employ some tomographical techniques for reconstruction of transverse phase space.

For the OTRI, one of the critical aspects is keeping the beam scattering produced by the first foil less than the actual rms divergence of the beam. Preliminary estimates of the scattering for a 650-MeV electron by a 1-μm-thick Al foil are encouraging. Particle beam rms divergences of 20 to 100 μrad should be measurable. A closer look at this for energies between 200 and 650 MeV is planned. Assuming an interfoil spacing of about 125 cm (desired spacing scales roughly as $\gamma^2\lambda$), radiation at 630-670 nm, and an energy of 650 MeV, Fig. 4 shows calculations of interference patterns for 80- and 100-μrad rms divergence. The difference in fringe visibility would be used to determine beam divergence with 10 to 15% accuracy. The calculations were done on a Sun workstation using D. W. Rule's code GINTRF1 [8]. Energy centroid effects were also discernable in the calculations, but these will be described elesewhere. The possibility of using OTR spectroscopy to measure these low emittance beams is under consideration. A simulation of a similar transverse phase space at E = 185 MeV was previously addressed for the NIST microtron by Rule and Fiorito [9].

B. Longitudinal Characterizations

Both energy spread and micropulse bunch length are of interest, but the primary emphasis is on bunch length and assessment of peak current. APS will employ an alpha-magnet-based magnetic bunching system. Space-charge effects on a drifting beam can cause temporal elongation at low γ. The momentum spread out of the gun is essentially 100%. The momentum spread admitted into the linac will be limited to ± 5% by slits in the alpha magnet.

At 350 pC per bunch, the nominal bunch length would be 5 ps (FWHM). This peak current can be increased by bunching, but emittance degradation is possible. Thus, tracking the emittance with peak current is an objective. In particular, producing useful quantities of diffraction-limited radiation is strongly dependent on low emittance, and if one hopes to obtain any coherent radiation, then peak charge density is also critical. In the 10-m drift space area, the micropulse bunch length can be determined via the prompt OTR radiation. Although a fast, single-sweep streak camera measurement is possible, the signal-to-noise ratio in the measurement can be improved using synchroscan techniques at 119 MHz (a subharmonic of 2856 MHz). Resolution of about 2 ps (FWHM) should be possible. This system also could be used to minimize the transverse wakefield effects due to beam center offsets in the accelerator tanks as demonstrated previously.

4. Summary

In summary, the projected performance of the APS linac operating in the low-emittance mode would extend the demonstrated diagnostic measurement envelope and provide useful data to the community interested in bright sources of radiation. Both the projected generation of diffraction-limited (and possibly coherent radiation at λ <200 nm) and the effects of magnetic field errors on the beams and radiation properties are accessible. This information is particularly relevant to designs of the next generation of light sources [10].

Acknowledgement

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Table I
APS linac beam properties in low-emittance mode (rf-gun)

RF frequency (MHz)	2856
Beam energy (MeV)	100 to 650
Micropulse charge (pC)	350
Micropulse duration (ps)	5 (FWHM)
Macropulse length (μs)	1 or 5
Macropulse repetition rate (Hz)	1 to 20
Normalized emittance (π mm mrad)	<10 (1σ)

UNDULATOR TEST LINE

TABLE II. PARTICLE BEAM PARAMETERS AND DIAGNOSTICS PERFORMANCE

Parameter	Nominal Value	Span	Technique	Resolution	Error	Bandwidth/ Timescale
Position	Reference line	± 2 cm	BPM, log-ratio OTR foil	100 μm 25 μm	250 μm 25 μm	2 Hz 30 Hz image
Transverse Profile	$\sigma = 100\ \mu m$	0.05 to 2 mm	OTR foil	~25 μm(FWHM)	25 μm	30 Hz image
Divergence	$\sigma \sim 20\ \mu rad$	10 to 100 μrad	OTR, OTRI	~10 μrad	20%	TBD
Emittance	$\sigma_N = 2\ \pi$mm-mrad	2 to 40 π	Three-screen, OTR, OTRI	~1/2 πmm-mrad	30%	TBD
Charge Peak Current	350 pC/bunch	50 to 350 pC 1.7 to 12 mA	FCT FCT	2 pC 60 μA	1% 1%	30 ns (macropulse)
Energy	650 MeV	100 to 650	Bending magnet + detector	0.3%	0.3%	5 Hz
Spread Jitter Slew	0.1% TBD TBD					
Micropulse Duration	5 ps	0.8 to 15 ps	Streak camera, OTR, SR	2 ps	10%	30 Hz image 2 Hz calc.
Photon Beam Jitter Slew	5 ps	0.8 to 15 ps	Streak camera, OTR, SR Synchroscan	2 ps	10%	30 Hz image
Beam Loss	Relative loss rate and location	Ampl.: 0 to 100% Position: 60 m	Gas-filled coaxial cable Pulse timing	Ampl.:2×10^{-10} C/s Position: 60 m Ampl.: 0.5 nC Position: <3 m	N/A 60 m N/A <3 m	100 ms 100 ms 100 ms 100 ms

Figure Captions

Fig. 1 Schematic of the undulator test line showing the rf gun, in-line linacs, transport line, and undulator test area. In the low emittance mode, the second linac is rephased to accelerate electrons.

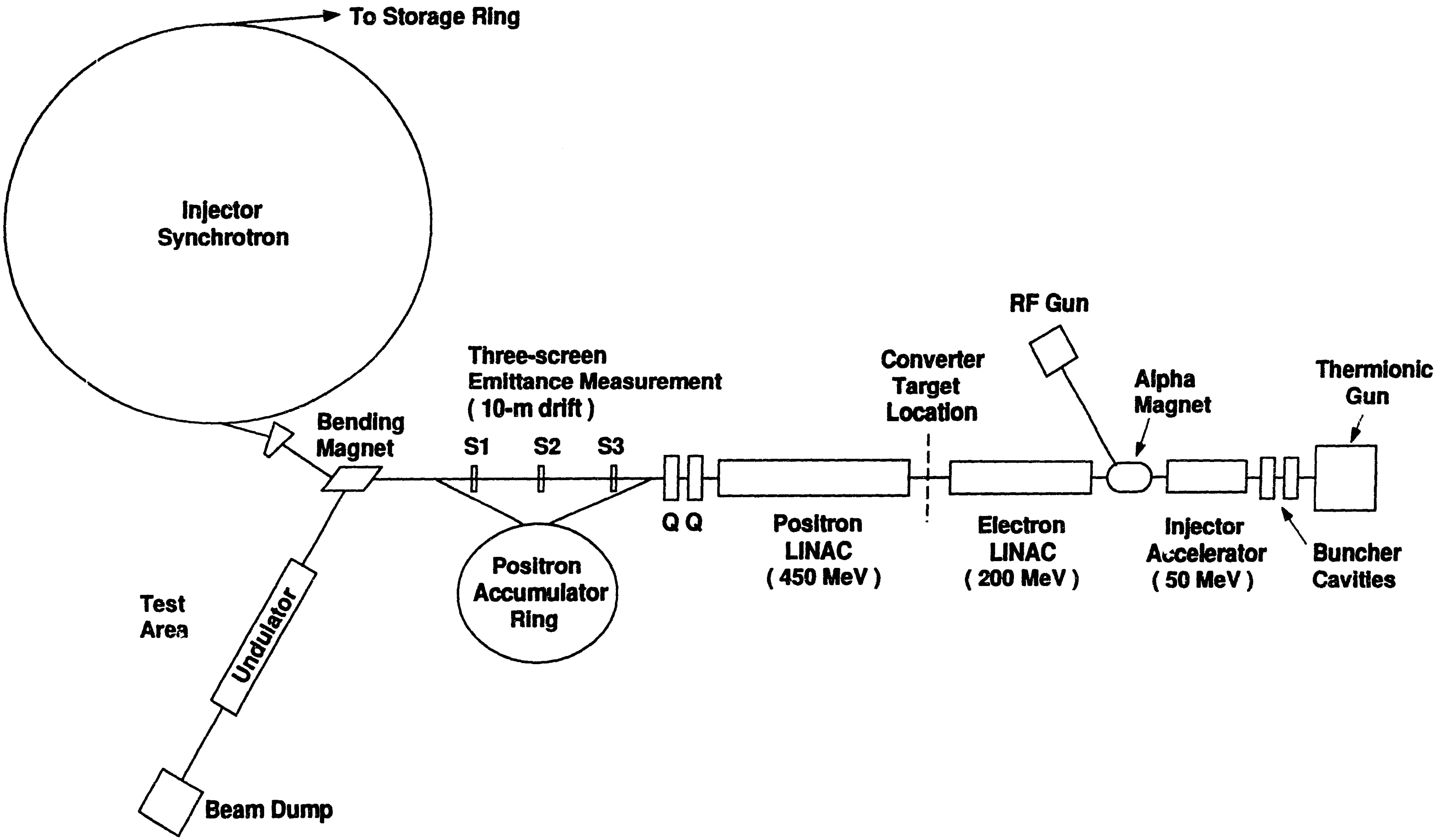
Fig. 2 Simulations of the normalized, rms emittance at the gun exit vs. useful charge per bunch.

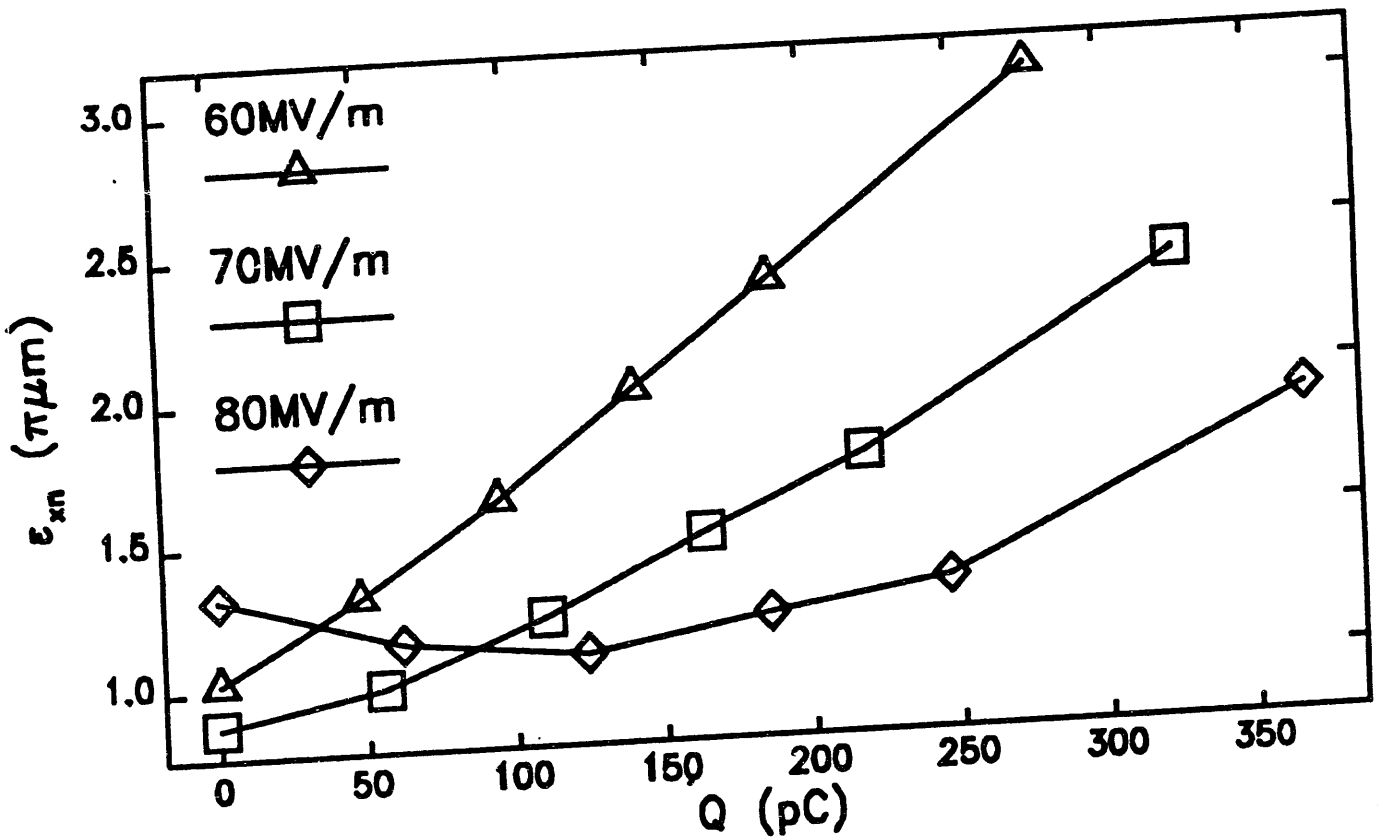
Fig. 3 Schematic of the two-foil OTR interferometer technique for measuring particle-beam divergence. At high γ, the large interfoil spacing will allow direct viewing of the interference pattern formed at the front surface of the second foil.

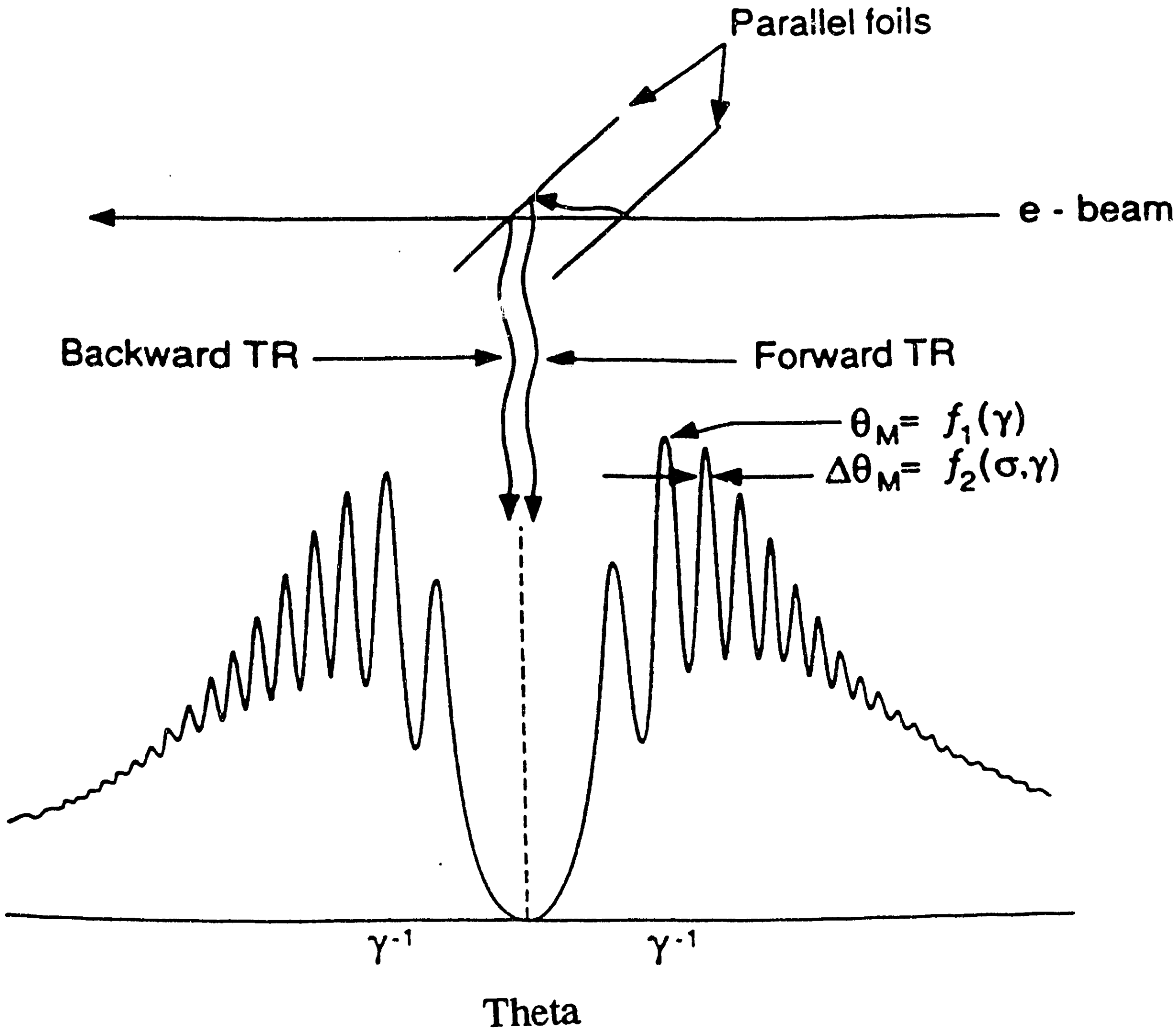
Fig. 4 Calculation of the optical transition radiation interferometer pattern at 650 MeV with an interfoil spacing of 125 cm and using a 650 x 40 nm bandpass filter.

a) $\sigma_{x'}$ = 80 μrad (solid line) b) $\sigma_{x'}$ = 100 μrad (dashed line). The lower beam divergence gives more fringe visibility.

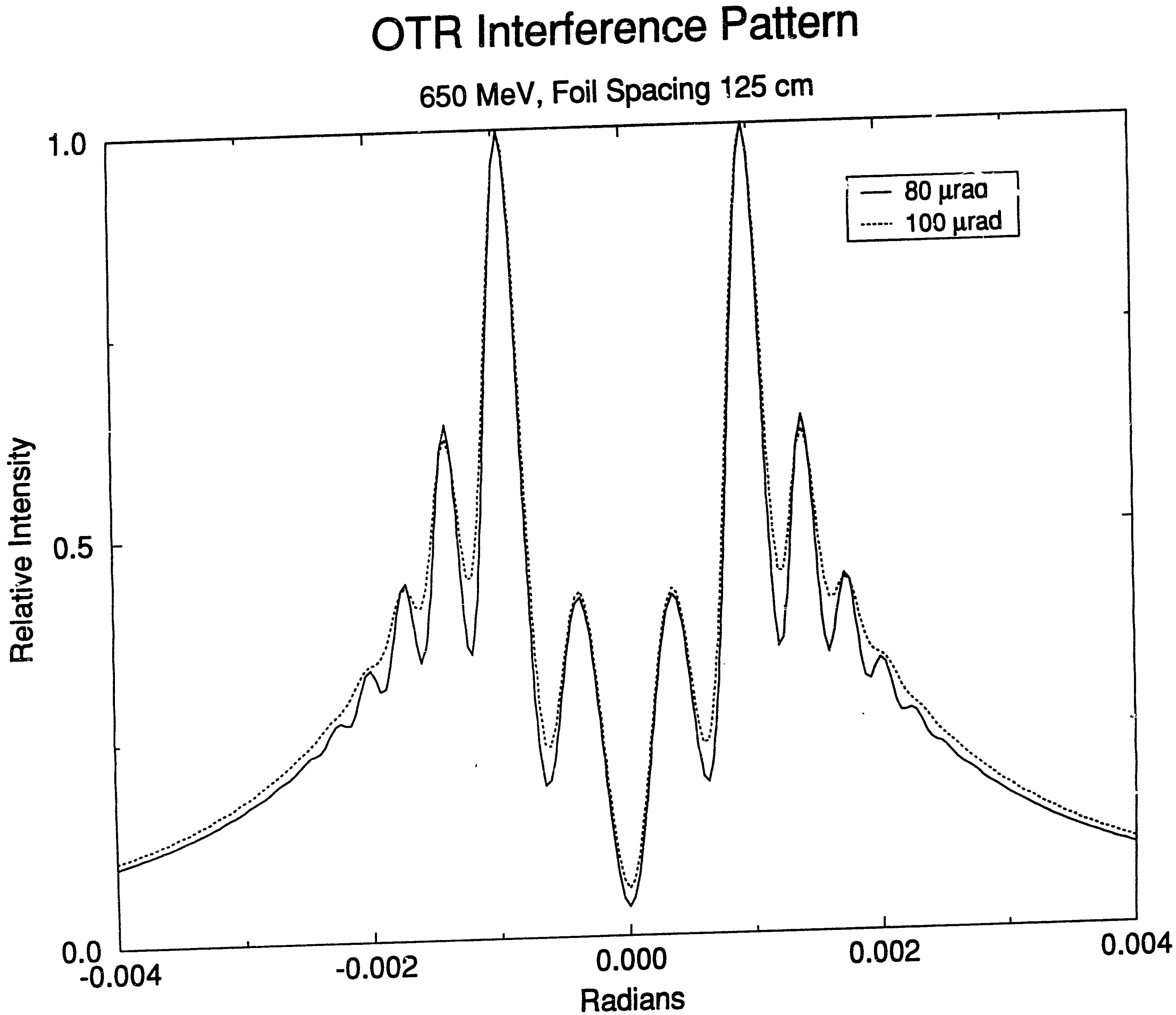
SCHEMATIC OF THE UNDULATOR TEST LINE CONFIGURATION
(LOW - EMITTANCE MODE)




60MV/m
70MV/m
80MV/m
3.0
2.5
2.0
1.5
1.0
ε_{xn} ($\pi\mu m$)
0
50
100
150
200
250
300
350
Q (pC)



Parallel foils
e - beam
Backward TR
Forward TR
$\theta_M = f_1(\gamma)$
$\Delta\theta_M = f_2(\sigma,\gamma)$
γ^{-1}
γ^{-1}
Theta



OTR Interference Pattern
650 MeV, Foil Spacing 125 cm
80 µrad
100 µrad
Relative Intensity
1.0
0.5
0.0
-0.004
-0.002
0.000
0.002
0.004
Radians

DATE
FILMED
10/11/94

END