UvA-DARE (Digital Academic Repository)

Expected performance of FELINA, the Dutch UV-FEL in Amsterdam

A.J. Bakker (et al), A.; Maas, R.; Luijckx, G.; van Amersfoort, P.W.; Litvinenko, V.N.

DOI
10.1016/0168-9002(94)01498-1

Publication date
1995

Published in
Nuclear Instruments & Methods in Physics Research Section A - Accelerators Spectrometers Detectors and Associated Equipment

Link to publication

Citation for published version (APA):
A.J. Bakker (et al), A., Maas, R., Luijckx, G., van Amersfoort, P. W., & Litvinenko, V. N. (1995). Expected performance of FELINA, the Dutch UV-FEL in Amsterdam. *Nuclear Instruments & Methods in Physics Research Section A - Accelerators Spectrometers Detectors and Associated Equipment*, *358*, 358. https://doi.org/10.1016/0168-9002(94)01498-1

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)

Download date:10 Mar 2023

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 358 (1995) 358–361

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Expected performance of FELINA, the Dutch VUV-FEL in Amsterdam

R.J. Bakker [a], R. Maas [a,*], G. Luijckx [a], V.N. Litvinenko [b], B. Faatz [c], P.W. van Amersfoort [c]

[a] *FOM Instituut voor Kernfysica, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands*
[b] *Duke University, FEL Laboratory, P.O. Box 90319, Durham NC 27708-0319, USA*
[c] *FOM Instituut voor Plasmafysica "Rijnhuizen", P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands*

Abstract

The FOM Institute for Nuclear Physics (NIKHEF-K) in Amsterdam currently operates the pulse-stretcher and storage ring AmPS as a continuous electron beam source for nuclear physics experiments up to 900 MeV. Here we review the feasibility to use AmPS as a driver for FELINA (Free-Electron Laser IN Amsterdam) for the generation of narrow bandwidth radiation in the (vacuum) ultra-violet spectral range in a two-stage project. For the first stage we consider a relatively low-cost demonstration experiment in the UV, i.e., $\lambda \geq 200$ nm, where FEL experiments will be performed in parallel with the nuclear physics research program. Lasing in the VUV requires significant modifications to the ring in order to enhance the gain. From preliminary calculations it can be deduced that lasing down to wavelengths less than 100 nm is then possible.

1. Introduction

The Amsterdam Pulse Stretcher project (AmPS) involves the operation of a ring, used as a 250–900 MeV electron beam source for nuclear physics experiments [1]. The ring has been designed for two modes of operation. In stretcher mode the ring is filled every 4 ms in order to provide a continuous external beam with a current up to 25 μA. In storage mode the ring can contain up to 200 mA of beam current, used for interaction with an internal gas-jet target. This current in combination with the dimensions of the ring (a circumference of 212 m with 32-m long dispersion-free straight sections) makes the machine a promising driver for a FEL covering the UV and VUV spectral range.

Until 1998, 2500 h/y are designated for nuclear physics purposes. In the remaining time AmPS could be used for FEL physics. However, the design of the ring has not been optimized for FEL operation in the VUV (e.g., the unnormalized emittance is as high as 160 π nm rad at 900 MeV). Hence, some modifications are necessary. We consider to do this in two stages. The first stage involves a relatively low-cost demonstration experiment addressing the UV, i.e., $\lambda > 200$ nm. This stage takes place without disruption of the nuclear physics research program. In the second stage more drastic modifications are required in order to construct a FEL, capable of lasing to (at least) 100 nm. In this paper we focus on the requirements for the first stage.

2. Machine description

A schematic layout of AmPS is given in Fig. 1 and its parameters are summarized in Table 1. The ring has a "square" shape with a four-fold symmetric structure. The magnetic lattice is of the FODO type and consists of 32 dipoles, 68 quadrupoles, and 32 sextupoles. The electron beam, emerging from the electron linac, is inserted in the east straight section. The north section is occupied by the rf-cavities and extraction devices for the stretcher mode of operation. The west section contains the internal target. At present the south section is still available for the installation of an undulator or optical klystron.

From Table 1 it follows that, for the existing lattice, the FEL gain will be low due to the the low peak current and the high emittance.

Peak current: In storage mode 336 bunches circulate in the ring, limiting the peak current by the maximum average current which can be stored in the ring. A decrease of

* Corresponding author. Tel. +31 20 592 2087, fax +31 20 592 2165.

0168-9002/95/$09.50 © 1995 Elsevier Science B.V. All rights reserved
SSDI 0168-9002(94)01498-1

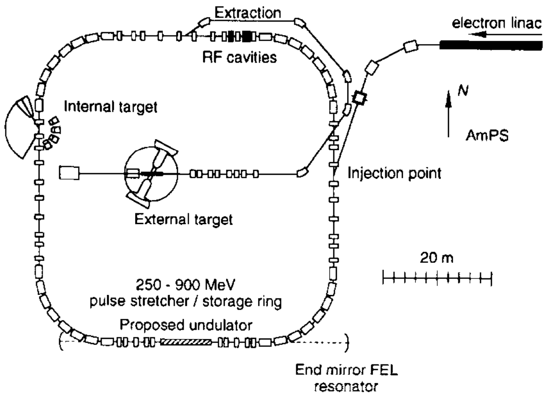

Fig. 1. Layout of AmPS. The 700 MeV injection linac stretches out further to the right.

the number of bunches, while keeping the average current constant, can significantly increase the current per bunch and peak current. With a current of 10–20 mA per bunch, the peak current can easily be increased to 40 A.

Emittance: The present usage of AmPS does not require low emittances and the dispersion in the curved sections and the emittance are high. In order to lower the emittance it is necessary to decrease the dispersion function inside the dipoles. The most economic solution requires an alternative powering of the quadrupoles in the curved sections without changing their position. This leads to a reduction of the emittance by a factor of 3.5, i.e., an emittance of 45 π nm rad at 900 MeV or 26 π nm rad at 700 MeV. A further reduction of the emittance is not possible without installation of additional quadrupoles. From calculations it followed that AmPS can be modified to a high brilliance lattice, i.e., an emittance less than 5 π nm rad at 900 MeV, with the installation of 32 additional quadrupole lenses in the arcs [2].

Table 1
List of important machine parameters of AmPS

	Existing	Update
Beam energy E (MeV)	250–900	250–900
Circumference L (m)	211.618	211.618
Compaction factor α	0.027	0.010
Average current I_{av} (mA)	200	200
Number of bunches n	336	2
Peak current I_p (A)	0.6	40
Horizontal emittance [a] ϵ_x (π nm rad)	≤ 160	≤ 45
Vertical emittance [a] ϵ_y (π nm rad)	< 8	< 2
RF frequency f_{RF} (MHz)	476	476
RF voltage V_{RF} (kV)	350	350
Impedance [b] Z/n (Ω)	< 5	< 5

[a] For $E = 900$ MeV.
[b] Estimated

3. FEL design considerations

Beam energy: In order to reduce the effects of intra-beam scattering, it is thought sensible to strive for operation at energies in between 700 and 900 MeV. Here the lower value enables the most gain, while the higher value is more favorable for a high output power and beam lifetime.

Wiggler period: The choice of wiggler period will be dictated by the required tuning range. The longer wavelength limit is of special importance for an initial experiment. In this case it is desirable to have the option of lasing in the near visible because of the larger choice of available optical materials for a high-Q resonator. The undulator period must not be too long, however, since this limits the shortest obtainable wavelength for later experiments. For the simulations we have taken an undulator with a 11 cm period. With this undulator, the resonance condition can be satisfied between 25 and 600 nm.

Undulator scheme: In order to obtain a flexible but inexpensive device, we consider the use of an optical klystron (OK), i.e., a set of two small undulators, separated by a dispersive section with adjustable magnetic field strength. With an OK, the total undulator length can be reduced significantly while maintaining a high gain. A drawback of the OK, the lower efficiency, can be avoided through adjustment of the magnetic field strength of the dispersive section. During operation both options can be used sequentially. First using a high field strength in the dispersive section to enhance the small-signal gain. In saturation the field strength can be reduced to obtain a higher saturated power level.

Resonator: As will be shown in the next section, the gain will be modest and a resonator is required to amplify the spontaneous emission on successive passes. In order to ensure interaction on every round-trip, the cavity length must be chosen such that the round-trip frequency equals a subharmonic of the micropulse repetition frequency. The solution sketched in Fig. 1 corresponds to a regular laser resonator with a length equal to one quarter of the circumference of the ring. This way, the resonator mirror can be positioned on either side of the straight section. In Fig. 1 the center of the cavity has been shifted with respect to the center of the undulator. This has been done to fit the resonator within the excisting building. A drawback is the stability of the cavity. For optimum gain the resonator will be close to concentric. For the parameters listed in Table 2 we have, therefore, increased the Raleigh length with 70% in order to increase the tolerances on the cavity parameters.

4. Gain calculations

We calculated the gain for both OK and conventional FEL configurations using rigorous 3-D low gain formulae

[3] and compared our results with results obtained with the 3-D multi-particle simulation code TDA [4]. Since the results were similar, we only present the results obtained with our 3-D formulae.

As regards the OK configuration, we took a interaction region with 2 × 24, 11-cm long, periods. The two undulators are separated by a dispersive section with a physical length of 0.6 m. The field-strength of this section is always tuned to give maximum gain. A Gaussian distribution of the electrons in the phase space is assumed as well as the TEM_{00} optical mode in the cavity. The waist of both the optical mode and the electron beam are taken in the center of the OK. Simulation parameters are given in Table 2. For reasons stated in the previous paragraph these values do not correspond with an optimum filling factor. As a result the calculated gains are 20% less than the optimum value.

For a regular FEL the gain is proportional to the peak current I_p. In a storage ring, however, there are no direct means to control the peak current since it is determined by the current per bunch (I_b) and the relative energy spread (σ_e):

$$I_p = \sqrt{2\pi}\, I_b \nu_s / \alpha\sigma_e, \tag{1}$$

where ν_s denotes the tune and α the momentum compaction factor. Both ν_s and α are determined by the lattice. From Eq. (1) it thus follows that I_b must increase in order to increase the peak current. Unfortunately it is not possible to increase the particle density to infinity. Due to the microwave instability the energy spread and bunch length will increase as soon as the peak current becomes too high:

$$I_p < 2\pi\alpha\sigma_e^2 \frac{E}{e(Z/n)}, \tag{2}$$

where E is the beam energy in eV, e is the electron charge, and Z/n is the longitudinal impedance of the ring. For AmPS the impedance is estimated to be less than 5Ω. However, there has not yet been an opportunity to measure the impedance. This will be discussed in Section 5. Due to microwave instability the energy spread becomes:

$$\sigma_e = \left(\frac{1}{\sqrt{2\pi}} \frac{\nu_s I_b e(Z/n)}{\alpha^2 E} \right)^{1/3}. \tag{3}$$

The gain reduction due to energy spread is roughly proportional to σ_e^2. Hence, it remains favorable to increase the current per bunch in order to enhance the small-signal gain. In Fig. 2 the results are shown for the geometry described in the previous section at $\lambda = 250$ nm. It can be concluded that it is favorable to increase I_b to an as high as possible current. Specifically an increase to $I_b = 20$ mA significantly increases the FEL performance. Note that the field strength of the dispersive section must decrease in order to obtain maximum gain. This is due to an increase in energy spread.

Saturation in a storage-ring FEL is induced by gain-reduction self-induced beam heating. The gain formula can thus be used to estimate the equilibrium energy spread, i.e., the energy spread induced by the FEL interaction for the case where the gain equals the threshold losses. Ac-

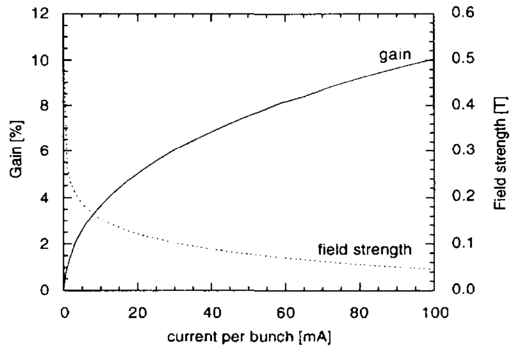

Fig. 2. Gain for $\lambda = 250$ nm (solid line), and the optimum field strength of the dispersive section (dashed line) as a function of the current per bunch.

Table 2
Simulation parameters

RMS undulator strength K	≤ 4.7
Number of periods N	2×24
Undulator period λ_u	11.0 cm
Length dispersive section L_d	0.6 m
Cavity length L_c	52.9 m
Stability parameter g^2	0.93
Raleigh length β_0	3.35 m
Beam energy E	700 MeV
Horizontal emittance ϵ_x	26 π nm rad
Vertical emittance ϵ_y	1 π nm rad
β functions $\beta_{x,y}$	3.35 m
Natural energy spread σ_ϵ	0.03%
Synchrotron power P_{SR}	1.2 kW

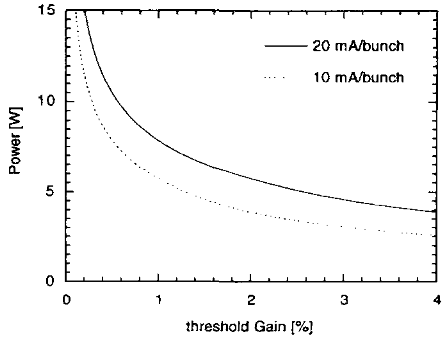

Fig. 3. Power vs the threshold gain for a 700 MeV electron beam at $\lambda = 250$ nm for micropulses containing 20 or 10 mA per bunch, respectively. The average current is 200 mA.

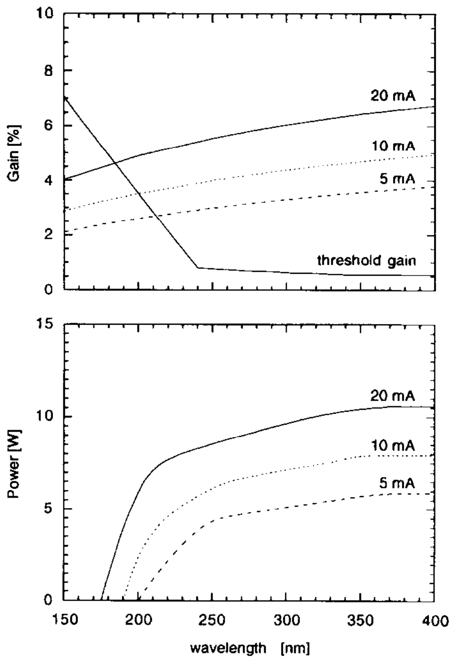

Fig. 4. Power and gain vs wavelength for three different bunch currents.

cording to the Renieri limit the average extracted power is also proportional to the energy spread:

$$P_{\mathrm{FEL}} = 2P_{\mathrm{sr}}\frac{\sigma_e^2-\sigma_\epsilon^2}{\sigma_e}e^{-1/2}, \tag{4}$$

where σ_ϵ denotes the natural energy spread of the ring. P_{sr} denotes the average synchrotron power. It follows that there is a relation between the threshold losses and the maximally extractable average power. In Fig. 3 the results for AmPS are shown. It follows that 5–10 W can be extracted. The extracted optical power is a fraction of this value and depends on the ratio between the total cavity losses and the outcoupling losses.

Finally in Fig. 4 we show the calculated gain and power as a function of the wave-length. Estimates of the threshold gain have been obtained from a combination of results published [5,6] It follows that lasing until $\lambda = 200$ nm is feasible, provided that there is more than 10 mA per bunch available.

5. Discussion

From the calculations presented above we conclude that lasing in the UV and near-visible, i.e., $\lambda > 200$ nm, is feasible. Some modifications are required, though.

Increase of the current per bunch. At least 10–20 mA per bunch should be reached in order to obtain sufficient peak current. Here it is important to state that there is some uncertainty regarding the obtainable peak current. Because of microwave instabilities there is, for high peak currents, a relation between the peak current and the longitudinal impedance of the ring (see Eq. (2)). At present we only have an estimate of the impedance. It is our believe that the value quoted, 5 Ω, is a worst case.

Reduction of the emittance. With the present emittance the expected gain would reduce the gain values quoted in Fig. 4 with a factor of approximately 3.

For the above mentioned mode of operation, the average extracted optical power is expected to be of the order of 5–10 W for an electron beam with an energy of 700 MeV and 200 mA of average beam current. Due to an increase in synchrotron power it is expected that at 900 MeV the power will be of the order of 15–25 W.

In order to reach the VUV more gain is required. For this several options are open which are still under discussion, e.g., a further reduction of the emittance or an increase of the undulator length. Preliminary calculations indicate that lasing for $\lambda > 70$ nm is feasible which makes AmPS competitive with other storage-ring projects, in Dortmund and at Duke University, which are presently in the construction phase.

Acknowledgements

The work described in this paper is part of the research program of the FOM institute for Nuclear Physics (NIKHEF-K), made possible by financial support from the Foundation for Fundamental Research on Matter (FOM) and the Netherlands Organization for Scientific Research (NWO). The authors want to thank Ying Wu of the Duke University FEL for his contributions.

References

[1] G. Luijckx, H. Boer Rookhuizen, P.J.T. Bruinsma, A.P. Kaan, F.B. Kroes, L.H. Kuijer, A. van der Linden, P. Louwrier, R. Maas, J.G. Noomen and J.B. Spelt, Proc. 2nd Europ. Accelerator Conf. (EPAC) 1990, p. 589.

[2] R. Maas and G. Luijckx, Proc. 3rd Europ. Accelerator Conf. (EPAC), 1992, p. 480.

[3] V.N. Litvinenko, Proc. National Synchrotron Radiation Conf. SR-94, Novosibirsk, July 11–15, 1994, Nucl. Instr. and Meth. A, to be published.

[4] T.-M. Tran and J.S. Wurtele, Computer Phys. Commun. 54 (1989) 263.

[5] B.E. Newnam, SPIE Free-Electron Lasers 738 (1987) 155.

[6] W.B. Colson, Laser Handbook, Vol. 6, eds. W.B. Colson, C. Pellegrini and A. Renieri (North-Holland, Amsterdam, 1990) pp. 463–484.