Nuclear Instruments and Methods in Physics Research A 657 (2011) 99–106

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

RF properties of a X-band hybrid photoinjector

B. Spataro [c], A. Valloni [a,b,*], D. Alesini [c], N. Biancacci [a], L. Faillace [d], L. Ficcadenti [c], A. Fukusawa [b], L. Lancia [a], M. Migliorati [a], F. Morelli [a], A. Mostacci [a], B. O'Shea [b], L. Palumbo [a], J.B. Rosenzweig [b], A. Yakub [b]

[a] Dipartimento di Scienze di Base e Applicate per l'Ingegneria, Universita' degli Studi di Roma "La Sapienza", Via Antonio Scarpa 14, Roma (RM) 00185, Italy
[b] UCLA Dept. of Physics and Astronomy, 405 Hilgard Ave., Los Angeles, CA 90095, USA
[c] Istituto Nazionale di Fisica Nucleare—Laboratori Nazionali di Frascati, via Enrico Fermi 40, Frascati (RM), Italy
[d] RadiaBeam Technologies, LLC, 1717 Stewart Ave., Santa Monica, CA 90404, USA

ARTICLE INFO

Available online 7 May 2011

Keywords:
Hybrid photoinjector
X-band
RF design

ABSTRACT

An INFN-LNF/UCLA/SAPIENZA collaboration is developing a hybrid photoinjector in X-band. A hybrid photoinjector is a novel high brightness electron source that couples a standing wave cell cavity (acting as an RF gun) directly to a multi-cell travelling-wave structure. This configuration offers a number of advantages over the split standing wave/travelling-wave system. Most notably the reflected RF transient is almost completely suppressed, thus eliminating the need for a circulator and the bunch lengthening effect that occurs in the drift section of the split system. These properties allow scaling of the device to higher field and frequencies, which should dramatically improve beam brightness. The RF coupling between the standing and the traveling wave sections is accomplished in the fourth cell encountered by the beam, with the SW section electrically coupled to it on-axis. This mode of coupling is particularly advantageous, as it is accompanied by a 90° phase shift in the accelerating field, resulting in strong velocity bunching effects on the beam that reverse the usual bunch lengthening induced after the gun exit in standard 1.6 cell photoinjectors. In this scenario, from the beam dynamics point of view, it is seen that device may produce ten's of femtosecond beams at ~3.5 MeV and the emittance compensation dynamics remains manageable even in the presence of strong compression. We present here a survey of the device characteristics. In particular we show the results of the electromagnetic simulations, a beam dynamics analysis related to the temperature tuning of the SW and TW section, and a RF characterization using bead pull and scattering coefficient measurements of a device prototype.

1. Introduction

Recent years have seen a revolution in the production of high brightness electron beams because of the maturation of RF photoinjector performance. This maturation derives its genesis from a multi-disciplinary approach to the difficult problems presented to by understanding the behaviour of an electron beam under the combined influence of large external applied electromagnetic fields and the self-induced space charge fields. Through these theoretical, computational and experimental investigations, photoinjector physics has established itself at the confluence of a large number of disciplines, including accelerator beam dynamics, plasma physics, large-scale computational physics, surface studies, high-field RF physics and laser engineering. The manifest success of the RF photoinjectors is a testament to this collective understanding.

The most prevalent photoinjector design in use today employs an arrangement of two accelerating structures, a 1.5/1.6 SW gun and a post accelerating section. This scheme presents some inconveniences. The two structures are fed independently and, since the SW structure reflects nearly all of the input power at the beginning of the RF filling process, circulators and isolators are needed in order to protect the RF power source. In addition, scaling the fields of the split system into X-band is not possible due to high electric fields that could exceed the RF breakdown limitations. In order to circumvent these and other limitations in existing photoinjector designs we present a hybrid configuration that consists of one accelerating structure where the TW and the SW parts are tightly axially coupled. The model of the hybrid structure is shown in Fig. 1. In particular the hybrid photoinjector uses a coupling cell to divide power between a high gradient standing wave section for electron emission and collection, and a lower gradient travelling wave accelerator for acceleration to

* Corresponding author at: Dipartimento di Scienze di Base e Applicate per l'Ingegneria, Universita' degli Studi di Roma "La Sapienza", Via Antonio Scarpa 14, Roma (RM) 00185, Italy. Tel.: + 00393291809698.
E-mail address: alessandra.valloni@uniroma1.it (A. Valloni).

0168-9002/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2011.04.057

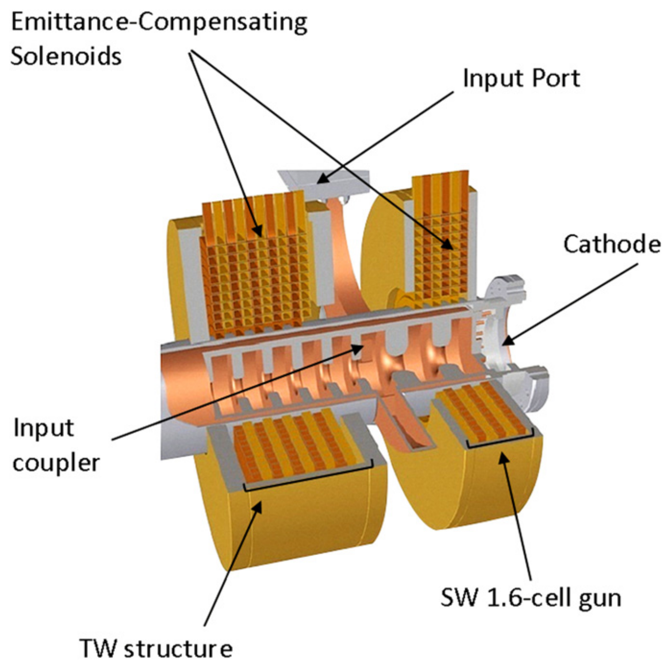

Fig. 1. 3D drawing of the compact hybrid structure showing the relevant parts of the device. It begins at the upstream end with the SW RF gun section in the initial cells (1.6 cell gun in this model), which is coupled to the RF power that is fed from the waveguide into the structure through a traveling wave coupling cell. Emittance-compensating solenoid are included.

desired energies at low emittances. This novel design strongly mitigates the RF reflection problem as the SW section represents a small fraction ($\sim$10%) of the input power, and the existence of the TW section permits near complete matching to the input waveguide. Thus, one can omit the circulator that a SW RF gun generally requires. This feature enables one to build a photoinjector at X-band frequencies, where no circulators, with the relevant high powers, yet exist. To provide an initial summary, therefore, the main advantages of this class of devices are that:

a) they mitigate impedance mismatches, and therefore reflected RF power, both during and after the RF filling and turnoff of the SW section; the almost complete removal of the transient RF reflected power allows scaling to high frequency;
b) they require a much simpler high power RF system than a split photoinjector; there is only one klystron and multiple waveguide sections, attenuators, and phase shifters are avoided;
c) they are more compact than a split system;
d) the acceleration dynamics is robust, this indicates flexibility in operating energy by simply changing RF power and laser injection parameters;
e) they avoid the bunch lengthening observed during the drift in a split photoinjector;

they actually strongly longitudinally focus through velocity bunching, due to the phase shift between SW cell and input coupler. For example in this paper we will show that for a X-band device (with typical peak field of 200 MV/m) the emittance compensation dynamics remain manageable even in the presence of strong compression and ten's of femtosecond high brightness beams are deliverable at $\sim$3.5 MeV. The current initiative in X-band follows that of a S-band hybrid gun, now under construction at LNF and with high power testing/beam production measurements foreseen at UCLA. This S-band hybrid has 1.55 SW cells and 9 TW cells, and it produces strongly compressed 3.5 MeV beam. It can be optionally used with a 3 m TW linac fed from RF output of the hybrid, to boost the energy up to 22 MeV. This device works at 2.856 GHz and presents 60 MV/m of peak field in the SW section and an average field in the TW cells of 13.5 MV/m [1a,1b]. The design strategy of the X-band hybrid photoinjector that we implemented started from scaling the S-band model to the X-band. The RF electric field and the external focusing magnetic field are scaled by a factor 4 in agreement with the scaling laws ($E \propto \lambda^{-1}$ and $B \propto \lambda^{-1}$ [2]). While scaling the design is conceptually simple, practical limits require some changes in both RF and magnetostatic designs. In accordance with the scaling principles applied to the current S-band hybrid structure, the X-band hybrid had initially a 1.6 cell SW part. On this structure at the same time beam dynamics studies and electromagnetic analysis were performed in order to optimize its performances. Afterwards a prototype has been built and measured in order to better understand the device potentialities and the manufacturing difficulties. Then the number of cells of the SW gun section was increased to 2.6 for two specific reasons: to reach higher energy at the gun exit, and to have more space available for focusing magnets, which relaxes the challenge of scaling the magnetic field appropriately. This class of photoinjectors offers a wide variety of applications ranging from multi-THz coherent radiation production to ultra-fast electron diffraction. Relevant details of the applications, as well as considerable further details concerning the beam dynamics in the device, are included in a companion paper [3]. In the following sections of this paper we first illustrate the general procedure to design the hybrid structure. In particular we discuss the results of the electromagnetic simulations obtained with the code HFSS [4] and the main beam dynamics properties. In the following part of the paper we show the electric field measurements using bead pull technique that validate the electromagnetic design produced with simulation.

2. RF design

The device can be conceptually divided into two main parts, *i.e.* the SW and the TW sections. These two parts can be initially designed separately by 2D or 3D general purpose electromagnetic codes solving the Maxwell equations in the structure. One can simulate the two sub-structures separately assuming a perfect magnetic plane in the centre of the coupling iris in order to force the field solution to have the vanishing longitudinal electric field, which is physically sound. The SW cells radius and the iris dimensions are chosen to achieve the proper resonant frequency, the mode separation and a constant maximum field in the cells (the so called field flatness), while the length of the SW cell is chosen to impose a π-mode. The design of the TW section starts considering the single TW cell and deriving the cell radius and length. The requirement is that the TM_{010}-like mode propagates with a phase advance per cell of 120° at the working frequency, *i.e.* the resonant frequency of the SW part (11.424 GHz). This operation mode is found by modeling planes of periodicity (*i.e.* master-slave boundary conditions on the cell walls), where the *E*-field on one surface matches the *E*-field on another with the desired phase difference. The radius of the input/output coupling cells (*e.g.* the input coupler shown in Fig. 1) and the dimension of the hole coupling the feeding waveguide are chosen to meet the request of small reflection at the input port (as in conventional TW structures). The design technique (namely the short circuit method) is based on a simple circuit representation in where each cell of the TW structure is modelled by a two port network; the coupling cell (*i.e.* the cell matching the input/output waveguide to the disc loaded structure) is described with a two port scattering matrix as well. The phase of the reflection coefficient at the input