THE FABRE PROJECT: DESIGN AND CONSTRUCTION OF AN INTEGRATED PHOTO-INJECTOR FOR BRIGHT ELECTRON BEAM PRODUCTION

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Abstract

We present a program for the design and construction of a photo-injector to produce bright electron beams, consisting in the first step toward the possible development of short-wavelength Linac-based FEL sources at ELETTRA. The program is based on a collaboration between Sincrotrone Trieste and INFN-Milan, aimed at the goal to attain a beam quality as requested by IV generation synchrotron light sources based on SASE-FELs. This can be summarized in multi-kA peak current beams delivered in sub-ps bunches, with a normalized rms transverse emittance below 1 mm mrad and an incoherent energy spread less than 0.1 %. As a first step within this mainstream, at Sincrotrone Trieste we are currently designing an advanced multi-cell photo-injector which is expected to deliver 1 nC bunches with emittances below 0.5 mm mrad at 20 MeV. We report the ongoing simulation and design activity, as well as the program schedule, which is articulated in various phases, according to the complexity of the associated photo-cathode laser system.

1 INTRODUCTION

In the frame of a collaboration between Sincrotrone Trieste and INFN-Milan on the design of a source for bright electron beams, mainly oriented toward short wavelength FEL experiments, an R&D activity on the construction of an integrated RF Photo-injector has been recently launched at the Elettra laboratory.

The main scope of this activity is to demonstrate, in the context of a test bench facility for the photo-injector, the capability of this kind of device to attain beam brightness levels as requested by future SASE FEL's in the X-VUV range. A further phase would be the operation of the injector in conjunction with the 1 GeV Linac presently running in the laboratory.

2 DESIGN OF THE PWT RF STRUCTURE

2.1 Preliminary considerations

The Plane Wave Transformer (PWT) structure is going to become a consolidated geometry in the field of high gradient, multi-cell photo-injectors. The theoretical demonstration was given in [1], based on the concept of invariant envelope, that an *integrated* injector is the ideal choice to control the emittance growth, taking the beam from the photocathode to an energy of about 20 MeV within the same electromagnetic structure. The PWT consists of a coaxial cavity in which the central conductor has been sliced to obtain the proper conversion from the TEM mode propagating in the external region to the TM mode that is established in the near-axis region. An artist's view of the structure can be seen in the following picture, representing a short section, with the laser and electron beams represented as sticks.

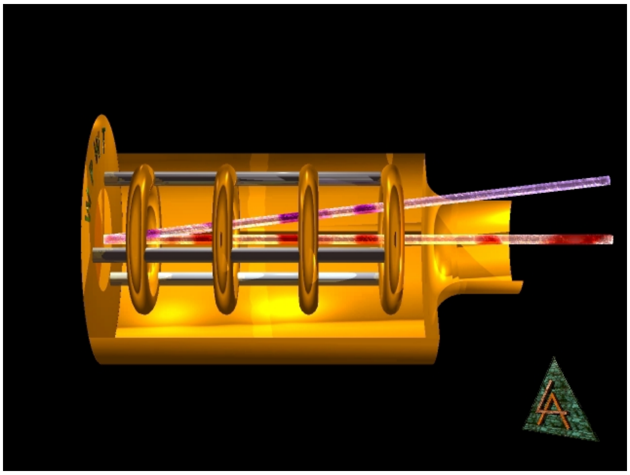

Figure 1: Artist's view of a PWT "bottle".

This kind of structure was introduced for the first time by D. Swenson [2] who proposed it as a novel efficient accelerating structure. Detailed studies were later conducted in UCLA [3] and a PWT is presently in operation at the Neptune experiment in UCLA. In 1994 the adoption of this kind of structure in a photo-injector configuration was proposed [4]. Following this idea a multi-cell photo-injector based on the PWT geometry has been built in the framework of a collaboration between UCLA and Duly Research and is in an advanced test phase at the Plasma Physics Department at UCLA [12].

2.2 The design phase

In the first design phase both a PWT structure and a on-axis Coupled Cavity Linac (CCL) have been considered. The fundamental requirements that are common to the two structures must be good electromagnetic stability, which implies good separation between the accelerating mode and the closest modes on the dispersion diagram, and spectral purity of the accelerating field. A reduced harmonic content will prevent non uniform matching of the beam in the invariant envelope [1]. The theory of emittance compensation indicates the optimum and limit value, $\alpha = eE_0/[2k_{RF}\, m_e\, c^2]$, equal to 1.3, corresponding (at S-band) to a peak field gradient of 80 MV/m and an accelerating gradient of 40 MV/m, which is a critical parameter and heavily influences the choice of geometry.

The optimization of the shunt impedance, which is always an important figure of merit in an accelerator design, is less important in this case, provided that the available power is enough to sustain such a field and the thermal stability is guaranteed.

As far as the CCL structure is concerned a bi-periodic structure has been considered working in the $\pi/2$ mode. Superfish [5] simulations have shown that the optimum compromise between good coupling between the cells and acceptable shunt impedance keeps the third harmonic content (a_3/a_1) of the accelerating field considerably higher than in the PWT geometry. This reason, together with the robustness and simplicity of the mechanical structure, has led us to concentrate on the Plane Wave Transformer.

Table 1: CCL and PWT at comparison

Geometry	**Quality factor**	**a_3/a_1 %**	**ZT^2 (MΩ/m)**
CCL	19000	5.2	44.01
PWT	41942	0.19	35.44

More accurate studies were then required to explore the influence of the bearing rods for the washers, since they break the cylindrical symmetry and can introduce multipolar components in the electromagnetic field. The 3-D modeling has been done by means of MAFIA [6]. The initial geometry has been modified with the purpose of reducing the quality factor, and the structure filling time accordingly. The structure we are presently considering is half a meter long, with 10 cm diameter of the external conductor and ten washers 1.9 cm thick with 8.04 external diameter. The structure begins and ends with half a cell and a washer delimits each cell. The washers have a central hole for beam transmission with 1.2 cm radius; the bearing rods for the washers are four, symmetrically placed close to the electric field null area.

Table 2: PWT MAFIA parameters

Frequency MHz	**Quality factor**	**a_3/a_1 %**	**ZT^2 (MΩ/m)**
2995	17000	1.7	31

The dispersion curve of the adopted structure is shown in fig. 2

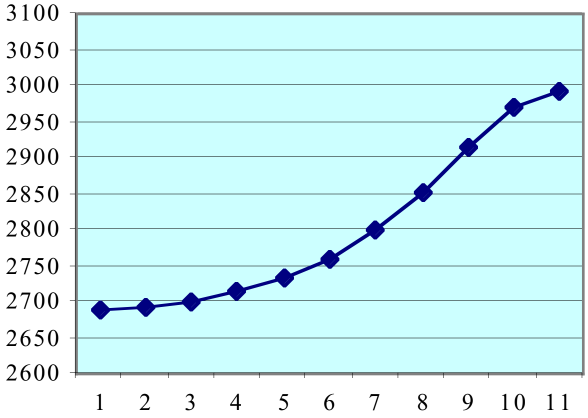

Figure 2: Dispersion curve for the PWT structure. Frequencies (y axis) are expressed in MHz

As can be seen the operation passband is more than 300 MHz wide and the separation between the π mode and closest one is 30 MHz, which guarantees good mode separation.

The dispersion curve is not symmetrical around the $\pi/2$ mode due to the strong coupling between all the cells. The fact that this is a strongly coupled structure produces a positive insensitiveness to mechanical excitations and allow us to correct for the field flatness deviation by acting on a single cell tune: we can do it either by varying the cell length or changing the washer external radius.

Having defined the field flatness deviation as $\Delta E/E_{cathode}$, in the structure we are considering we have corrected a 30% field tilt to 15%, by varying the external radius of the last washer by 1.5%. By the way, we are presently exploring if some benefits in beam dynamics can be obtained by accepting a certain amount of field unbalance.

The influence of the RF coupling slot has not yet been studied, but we expect to compensate for it with the same technique.

3 PRELIMINARY BEAM DYNAMICS

The beam dynamics requirements are based on the demand for a normalized brightness of the order of 10^{14} to 10^{15} A/m^2, which a FEL in the X-band range settles. The fact that brightness is the crucial parameter is recognizable by considering that the efficiency of the SASE FEL process scales with the cubic root of the beam peak current while the beam emittance must be comparable with the one associated to the emitted radiation. This has driven the identification of the “good” qualities, which allow the low emittance with relative high beam current that are needed in the FEL scheme.

In the following diagram, the emittance and envelope behaviour of a beam interacting with the electromagnetic field generated by the PWT structure are reported. The beam pulse length at the generation point is 8 ps and the current at the exit is around 100 A; as can be seen the emittance is lower than 1 mm mrad in the simulation.

The transverse emittance compensation has been obtained with a solenoid field of 2200 Gauss with a buckling coil to set to zero the residual field in proximity of the cathode emitting surface.

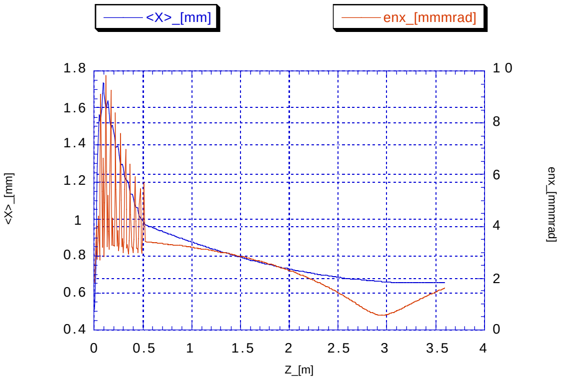

Figure 3: HOMDYN simulation. The PWT structure ends at 0.5m, then the beam has been let drifting performing the emittance oscillation.

The code used for this simulation is HOMDYN [7] that gives a 1D semi-analytical description of the beam dynamics adopting an envelope description of the beam motion, but comparable results have been obtained with ITACA [8], which is a 2D Cloud-in-Cell code.

More detailed studies are foreseen to confirm the structure characteristics with resulting beam quality. Deeper insight in the final beam characterization is expected with the employment of fully 3D codes like PARMELA [9] and TREDI [10].

4 THE FABRE COLLABORATION SCHEDULE

The first phase is concentrating on theoretical studies, both of the electromagnetic structure and of related beam dynamics. Detailed investigation of the crucial parameters in the interaction between the electromagnetic field and the beam is in progress.

The second phase will begin with the engineering and set to operation of the photoinjector electromagnetic structure in order to start the first beam tests. These will be performed in a long pulse regime using a Q-switched Nd:YaG laser (<8 ns, 20 mJ, 266 nm). We are modifying the available commercial laser system in order to shorten and smoothen the pulses. In this long pulse regime there is no need to synchronize the laser pulse with the RF phase. Preliminary simulations indicate that currents in the range of 100 – 200 A and emittances of about 5 mm mrad can be achieved in this way.

It should be noted that already during this phase it will be possible to perform FEL-CSE [11] experiments, besides interesting and original measurements on the bunch length.

The goal of phase II is to obtain, within the year 2002, an electron beam with energy between 12 - 20 MeV, normalized emittance close to 5 mm mrad and a bunch charge of at least 0.5 nC.

The fulfillment of the goals of phase two will open the possibility to start with the third phase of the project that will allow to fully exploit the potentialities of the photo-injector. At this stage the use of a short pulse laser excitation will be essential, so it is planned to utilize a laser system delivering in the UV pulses with lengths of several picoseconds, risetime and jitter with respect to the external reference better than 1 ps and energy of about 200 μJ.

The expected beam parameters in this phase are 1 nC of electron charge, within 1% energy spread and less than 1 mm mrad emittance at 20 MeV; the beam current within the bunch should be around 150 A.

5 CONCLUSION

The first step towards a high brilliance integrated photo-injector has been undertaken at Sincrotrone Trieste under the FaBrE collaboration.

The expected quality of the beam produced could allow the startup of an ambitious program, that, taking advantage of the availability of the ELETTRA injector, a 1 GeV Linac, can lead to the development of a SASE-FEL in the X-ray region.

REFERENCES

[1] L. Serafini et al., Physical Review E55, 1997.
[2] D. Swenson, The Plane Wave Transformer Linac Structure, EPAC 1988 Rome.
[3] R. Zhang et al., Study of a Novel Compact Standing Wave RF Linac, NIM A394 1997.
[4] L. Serafini, A Novel Laser Driven RF Structure for the Generation of Bright Electron Beams, NIM A341 1994.
[5] K. Halbach et al., SUPERFISH a Computer Program for the Evaluation of RF Cavities with Cylindrical Symmetry, Par. Acc. 1976.
[6] CST, MAFIA Manual v4.0, Darmstadt 1997.
[7] M. Ferrario et al., Multi-bunch Dynamics in Accelerating Structures Including Interaction with Higher Order Modes, PAC 1993.
[8] L. Serafini et al., ITACA: a New Computer Code for the Integration of Transient Particle and Field Equations in Axis-symmetrical Cavities, EPAC 1988 Rome.
[9] L. Young, PARMELA user's guide, LA-UR-96-1835.
[10] L. Giannessi et al., TREDI: Fully 3D Beam Dynamics Simulation of RF Guns, Bendings and FELs, NIM A436 1999.
[11] N. Piovella, *Physics of Plasmas* **6**, 1999.
[12] J.Rosenzweig, these proceedings, poster THP3A07