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METHOD OF CREATING LARGE APERTURE, SMALL PERIOD RF UNDULATORS USING POWER EXTRACTED FROM MULTIBUNCH BEAMS

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Abstract:
A method of creating millimeter and sub-millimeter period rf undulators with apertures in the order of a centimeter is described. This method opens possibilities that are impossible to reach with state-of-art static field undulators. The undulator could be used to create spontaneous or coherent synchrotron radiation in multibunch accelerators and storage rings, including energy recovery linacs or multibunch (even 2 bunch) linear accelerators. First, rf energy is extracted from the accelerator's bunches, then the rf energy is used to create deflecting field in the rf undulator. The undulator field is then interacts with trailing bunches. This method could be used to create multi-stage devices, where rf power generated in a previous stage rf undulator is used to produce deflecting field in the next stage of the rf undulator, with frequency of generated rf increasing with each stage. RF pulse compression schemes are expected to be used to increase efficiency of undulator-bunch interaction. This scheme could be SLED (Z.D. Farkas, Brief History of SLED, SLAC-TN-74-016, 1974) like or variants of resonant rings.

Field of Invention

The present invention relates to methods and apparatus for generation of electromagnetic radiation with wavelength from cm to sub angstrom using bunches of charged particles.

Introduction:

Undulators with static magnetic field are widely used to produce spontaneous and coherent synchrotron radiation in storage rings and free electron lasers. Magnetic field amplitude in such devices is usually on the order of 1 Tesla and both period and gap are on the order of a centimeter. Energy of generated photons is determined mostly by the period of the undulator and energy of the bunch in the accelerator, and for undulators with $K < 1$ ($K = 0.093\ B[\text{tesla}]\ d[\text{mm}]$, B is the undulator field strength, d is the undulator period), weakly on the undulator's magnetic field strength. To increase the energy of the photons for the same bunch energy, it is desired to make the period of the undulator smaller. For several reasons, such as beam instabilities and radiation damage to the undulator magnets, the aperture of a practical undulator cannot be made too small. For the same aperture, with reduction of the period, the field strength in a static undulator drops exponentially.

An RF undulator is a waveguide with high frequency electromagnetic field counter-propagating with the beam. Since rf undulators use dynamic electromagnetic fields, their maximum field does not drop with undulation period, and even could be increased with increased aperture for devices that employ overmoded or open overmoded waveguides. The practical field amplitude on metal surfaces of an rf undulator is limited by rf breakdown and field emission currents, and will likely range from 30 to 200 M/m. Here

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we assume an rf undulator made of copper. This electric field to creates bunch deflection that corresponds to deflection from a static magnetic field ranging from 0.1 to 0.7 Tesla, not taking into account enhancements due to combination of deflection from both electric and magnetic field.

Let us consider static and rf undulators with the same aperture, say 5 mm. For undulator periods of a centimeter, the static undulator will have higher maximum deflecting field strength then the rf undulator, but for periods smaller than a few millimeters, the rf undulator will have stronger fields.

RF undulators have other advantages over static undulators, such as ease of generation of a helical deflecting force with two polarizations of deflecting field and absence of magnetic materials that could be damaged by the beam. Since the external size of the rf undulator waveguide can be small (~cm), it is possible to use focusing quads or other magnetic devices, even static magnetic undulators, to guide the bunches inside the undulator.

Feasibility of the concept was shown in an experiment on generation of spontaneous synchrotron radiation with an rf undulator [T. Shintake *at al*., Jap. J. Appl.Phys. 22:844-851, 1983]. The undulator was powered by an S-band 300 kW pulse (4 μs at 10 Hz), giving 15 MV/m, equivalent to static magnetic field of 480 Gauss.

To sustain electrodynamic fields, a practical rf undulator requires a source of coherent, multi-megawatt, rf power with frequencies from few GHz to hundreds of GHz. Since such sources are not widely available, practical realization of an rf undulator is difficult. Recent development of 500 MW X-band rf sources for the Next Linear Collider [S. Tantawi *et al.*, Phys. Rev. STAB, V. 8, issue 4, April 2005] generated discussion of the possibility of an X-band rf undulator for a free electron laser (C. Pellegrini of UCLA and S. Tantawi of SLAC, April 2005).

Summary of the Invention

The present invention solves a number of difficulties related to realization of practical rf undulators. It opens the possibility of building undulators without an external multi-megawatt rf source, with undulator parameters unreachable by static field undulators.

Beam power in modern storage rings and linear accelerators with rf photoinjectors can range from hundreds of MW to hundreds of GW. Let us consider two bunches out of a multibunch beam. A fraction of its power is extracted from the leading bunch by a mm-wavelength slow wave structure. This power is usually carried by a non-deflecting waveguide mode. This mode is then transformed into a deflecting waveguide mode. The deflecting mode is injected into a waveguide or slow wave structure, where it undulates the trailing bunch. This undulating trailing bunch produces high frequency electro-magnetic radiation (depending on energy of the bunches this could be hard X-rays). This radiation is then extracted from the beam line. To increase the power in the deflecting mode, power enhancement schemes are used both for the deflecting mode and for the high frequency radiation.

The main parts of the apparatus are: a mm-wavelength slow wave structure, a mode converter that transforms the non-deflecting mode into the deflecting mode; a waveguide or slow wave structure that carries the deflecting mode, and power enhancement circuits.

The slow wave structure for power extraction could be a corrugated waveguide, or a variant of an open waveguide. There are properties of the corrugated waveguide [K.L.F. Bane, A. Novokhatsky, SLAC-AP-117, LCLS-TN-99-1, March 1999] that are beneficial for the method. In such waveguide non-deflecting and deflecting synchronous modes have almost the same frequency, and the bunch-waveguide interaction is dominated by one mode. Both deflecting and non-deflecting modes mode have high group velocity. Open waveguides have similar advantages: just a few (even one) modes strongly couple to the beam even in overmoded waveguide, and the frequencies of synchronous deflecting and non-deflecting modes also could be close by design.

The slow wave structure for the defecting mode is of the same type as for the non-deflecting mode. Deflecting and non-deflecting slow wave structures could be the same waveguide or different waveguides, with properties of each tuned to interact more with either mode.

Non-deflecting mode to deflecting mode converters could be transmission or reflection type. The transmission type has two ports; the non-defecting mode launched into one port generates the deflecting mode in the other port. The reflection type has one port; rf power falling on the converter in the non-deflecting mode reflects back in the deflecting mode.

Power enhancement circuits can be of resonant ring type, where power extracted from the bunch is recirculated and losses replenished by the next bunch. These circuits could be traveling wave or standing wave. In the standing wave type, power is bounced between two reflectors, or reflective mode converters. In a traveling wave resonant ring, power generated by a bunch goes through a mode converter, deflects a bunch in the deflecting structure, converts back to the nondeflecting mode, and got replenished by the next bunch.

The power enhancement circuit could be also of a SLED type. Power generated by the beam gets injected into a SLED pulse compressor. Increased power is then converted to the non-deflecting mode. Phase modulation required by the SLED circuit could be built into the power generating slow wave structure by proper phasing of the structure cells.

Use of a particular power enhancement circuit for an rf undulator would be determined by the specifics of the driving accelerator or storage ring.

Below are presented several possible implementations of such rf undulators. Obviously, a skilled professional could extend this list of the devices using the same method.

Operation of an inline rf undulator is shown in Fig. 1. The first bunch passes through a power extraction slow wave structure and generates rf power in a non-deflecting mode. This mode is converted into a deflecting mode and interacts with the second bunch in a backward slow wave structure. Synchrotron radiation is produced as a result of this interaction. The process repeats for subsequent bunches.

Operation of an rf undulator with reflective mode converters is shown in Fig. 2. This device uses a reflective power enhancement circuit. The first bunch passes through a power extraction structure and generates rf power in a non-deflecting mode (see Fig.2a). This mode is converted into a deflecting mode in the reflective mode converter (see Fig.2b). Then the deflecting mode interacts with the second bunch in a deflecting structure (see Fig.2c). Synchrotron radiation is produced as a result of this interaction. Then the deflecting mode is converted into the non-deflecting mode by the second mode converter (see Fig.2d). Power in the non-deflecting mode gets replenished by the next bunch. In a realization of this rf undulator the same corrugated waveguide can be used for power extraction and deflection.

Operation of an rf undulator with a resonant ring is shown in Fig. 3. This device uses recirculation of power in a traveling wave resonant ring. The first bunch passes through a power extraction structure and generates rf power in a non-deflecting mode. Then the non-deflecting mode is converted into a waveguide mode (or modes) of the recirculating ring. Then the power is launched into the deflecting structure, where a second bunch interacts with the deflecting mode and produces synchrotron radiation. After that, the deflecting mode is converted into a ring waveguide mode and guided back to the power extracting structure. In the structure, power gets replenished by the third bunch. The process repeats for subsequent bunches.
Operation of an rf undulator with a SLED pulse compressor is shown in Fig. 3. The first bunch passes through a power extraction slow wave structure and generates rf power in a non-deflecting mode. A phase shifter in the power extraction structure forms the rf phase profile required by the SLED pulse compressor. A power enhanced pulse is used to launch a mode into a deflecting structure. The deflecting mode interacts with the second bunch and produces synchrotron radiation. The process repeats for subsequent bunches.

Example Application of Beam-Powered RF Undulator

For this example of a technical design of a reflective rf undulator is chosen (see Fig. 2).
Design of the undulator depends on specifics of an accelerator and beam parameters. Here bunch train from NLC is used as an example. For NLC parameters see ILC TRC Report, SLAC-0606, 2003. One of the NLC designs have bunches with 10^{10} electrons each, and 2.8 ns bunch spacing. The bunch spacing and group velocity of modes in the

waveguide determine the undulator length. For the dimensions of the corrugated waveguide used in this design the length should be multiple of 32 cm.

For chosen beam parameters, the basic parameters of the undulator are: period 2.624 mm; aperture 10 mm, equivalent magnetic field amplitude about 300 Gauss. Motivation for use of an rf undulator instead of a static undulator is apparent from Fig. 5 showing maximum magnetic field that could be obtained in permanent magnet undulators of the same aperture. One can see that magnetic field in a static undulator is more than three orders of magnitude smaller than the field of an rf undulator with this aperture. Another advantage of the rf undulator over the static undulator is simplicity of its construction, since most of the body of the rf undulator is just a corrugated copper pipe that could be made with conventional machining.

The undulator consists of corrugated waveguide with mode converters at both ends of the waveguide. The corrugated waveguide serves as both power extraction structure and deflecting structure. The mode converter transforms monopole decelerating mode into deflecting mode. RF power in the undulator is replenished by consequent bunches.

Power extraction structure

The dimensions of the corrugated waveguide are shown in Table 1. The waveguide dimensions are chosen so it has a monopole mode synchronous with relativistic beams at 57.12 GHz. Parameters of the waveguide as power extractor are shown in Table 2. The parameters calculated by 2D Finite Element Code SLANS. Power generated in the waveguide by a 1.6 nC bunch is shown in Fig. 6.

Parameter	**Value**
Aperture radius (*a*)	5 mm
Large radius (*b*)	5.6012 mm
Period (*D*)	1.7495 mm
Iris thickness (*t*)	0.7495 mm
Iris radius (r)	*t/2*

Table 1. Waveguide dimensions.

Parameter	**Value**
Frequency	57.12 GHz
Q value	6217
Effective impedance	1.221 kOhm/m
Shunt impedance	7.59180 MOhm/m
Phase advance per cell	120 degree
Loss factor	461 V/pC/m
Group velocity	.762*c*
Dissipation length	396 cm

Table 2. Parameters of corrugated waveguide as power extractor calculated by 2D Finite Element Code SLANS. Here *c* is the speed of light.

Field amplitudes calculated by 3D Finite Element Code HFSS in the waveguide for power of 1 MW are shown on Fig. 7. At this power, maximum surface electric field is 8.3 MV/m and maximum surface magnetic field is 13.7 kA/m, both are well below known breakdown limits.

Deflecting structure

Corrugated waveguide has a convenient property for using it for both power extraction and deflection of the beam: first monopole and first dipole modes are synchronous with the beam and have almost the same phase velocity. It should be noted that an rf undulator does not require these velocities to be the same. The properties of the waveguide as a deflector were calculated using HFSS and are summarized in Table 3.

Parameter	**Value**
Frequency	57.23 GHz
Q value	7724
Maximum deflection	0.02 Tesla/sqrt(MW)
Phase advance per cell	120 degree
Group velocity	.813*c*
Dissipation length	524 cm

Table 2. Parameters of corrugated waveguide as a deflector calculated by 3D Finite Element Code HFSS.

Field amplitudes calculated by HFSS in the waveguide for transmitted power of 1 MW are shown in Fig. 8. At this power maximum surface electric field is ~10 MV/m and maximum surface magnetic field is ~16 kA/m. As in the monopole mode these fields are comfortably below known breakdown limits.

Mode converter

There are a number of methods that could be used to convert the monopole mode into the dipole mode. For this particular design, the following ideas were used: first, input and output beam pipes are round and cutoff for the TE_{11} dipole mode (diameter 3 mm); second, mode conversion is done in circular waveguide with diameter 4.8 mm; third, taper connecting the 4.8 mm diameter waveguide and 10 mm diameter waveguide is optimized for minimal mode conversion. The converter was designed using HFSS and it has power conversion efficiency of 0.8 dB. The 3D model of the mode converter and electric field in it are shown on Fig. 9.

The size of the input and output beam pipe and finite emittance of the beam set limits on value of transverse beta function of the accelerator lattice at the beginning and end of the undulator. In Fig. 10 the beta function *vs.* beam energy is plotted. Assumptions are follows: beam emittance is 2 mm*mrad (typical for an S-band rf gun) and transverse beam size is 0.3 mm (one tenth of beam pipe size). It is obvious that required lattice is straightforward to design.

Resonant operation
Resonant operation of the rf undulator is assumed. Steady state power in the undulator and corresponding deflecting field for different lengths of undulator section are shown in Fig. 11. This power is calculated for a bunch length of 0.2 mm, bunch charge 1.6 nC, losses due to resistivity of copper and parasitic mode conversion in the mode converter.

Summary for the application example
The rf undulator design described in this paper allows dramatic reduction in expensive energy required from the electron beam to generate high energy X-rays. For example, in order to generate photons with wavelength of 15 Angstrom (800 eV), Linac Coherent Light Source (www-ssrl.slac.stanford.edu) requires 4.54 GeV electrons or more than 200 m of accelerator. With the rf undulator this energy could be 470 MeV or just 23 m of the same accelerator. Recent advances in X-band accelerating structures and power sources have made accelerating gradient approaching 100 MV/m practical. With this gradient and using the rf undulator, 800 eV X-rays could be obtained with a 5 m long accelerator.

Brief description of the figures

Figure 1: Schematic view of large aperture, small period rf undulator that utilizes power extracted from a multibunch beam. Inline undulator is shown.

Figure 2: RF undulator with reflective mode converters.

Figure 3: RF undulators with resonant ring.

Figure 4: RF undulators with SLED pulse compressor.

Figure 5: Maximum magnetic field for permanent magnets undulator *vs.* its period. Undulator gap is 1 cm, and permanent magnet Br = 0.9 Tesla.

Figure 6: Power generated in the corrugated waveguide by 1.6 nC bunch *vs.* the bunch length.

Figure 7: Field amplitudes of first monopole in the corrugated waveguide for 1 MW of transmitted power.

Figure 8: Field amplitudes for the first dipole mode in the corrugated waveguide for 1 MW of transmitted power.

Figure 9: TM_{01} to TE_{11} mode converter.

Figure 10: Maximum transverse beta function *vs.* beam energy.

Figure 11: Steady state power (boxes) and undulator magnetic field (circles) *vs.* undulator length. To be resonant with 2.8 ns bunch spacing the undulator length is in multiples of 32 cm.

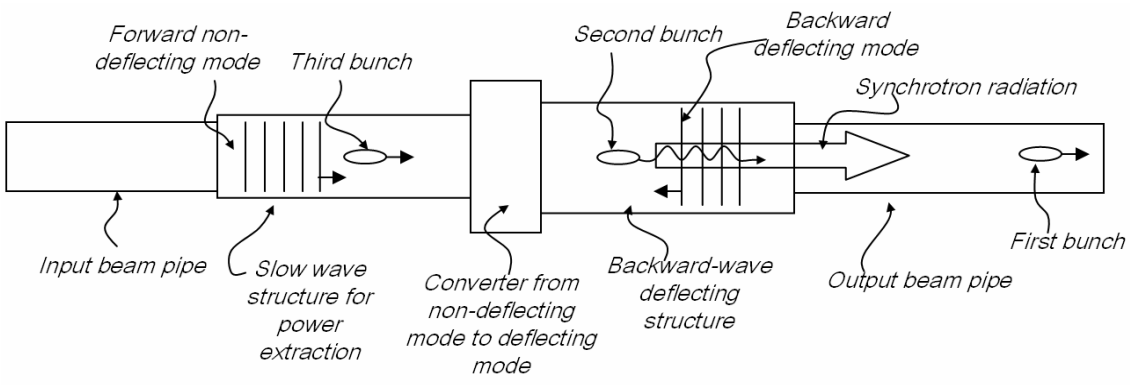

Figure 1: Schematic view of large aperture, small period rf undulator that utilizes power extracted from a multibunch beam.

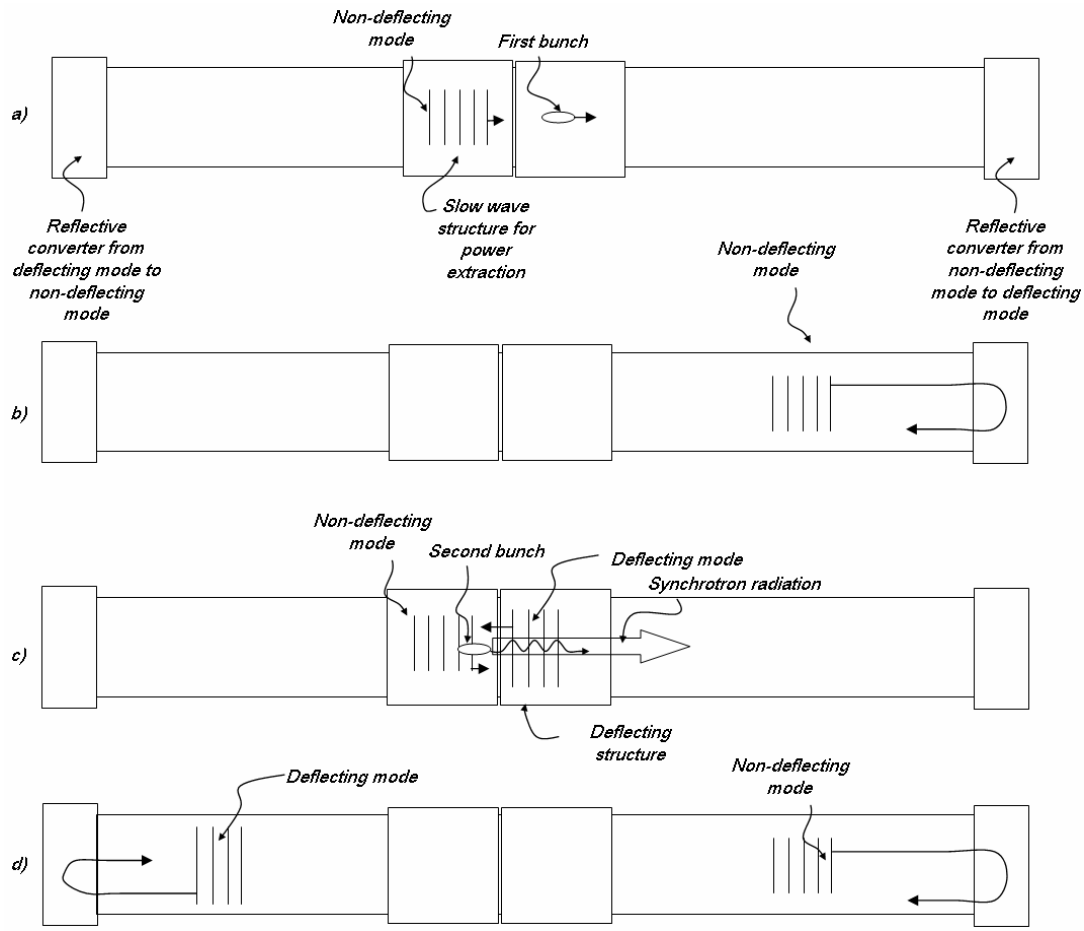

Figure 2: RF undulator with reflective mode converters.

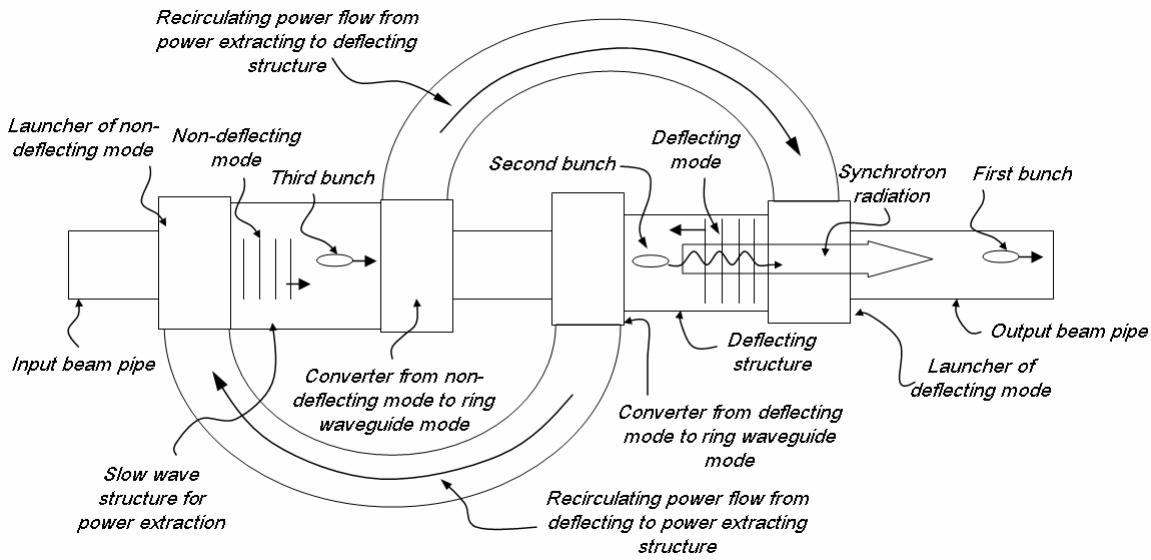

Figure 3: RF undulators with resonant ring.

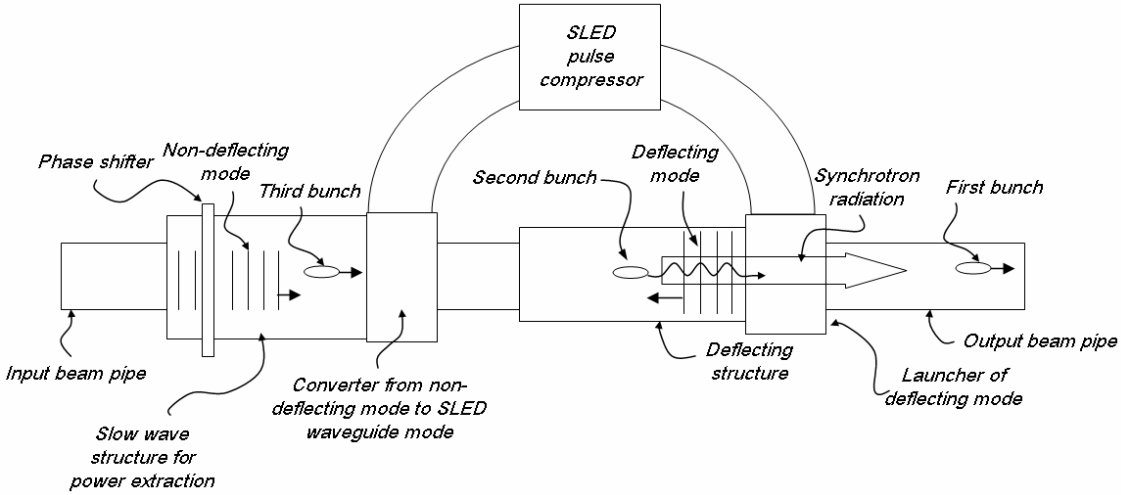

Figure 4: RF undulators with SLED pulse compressor.

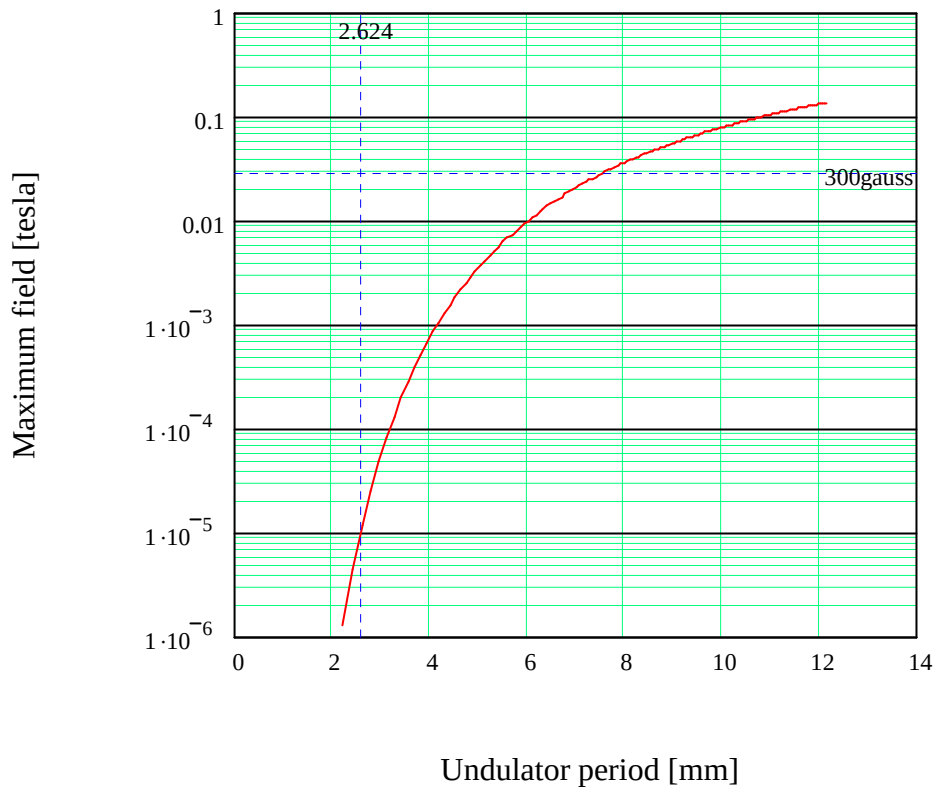

Figure 5: Maximum magnetic field for permanent magnets undulator *vs.* its period. Undulator gap is 1 cm, and permanent magnet Br = 0.9 Tesla.

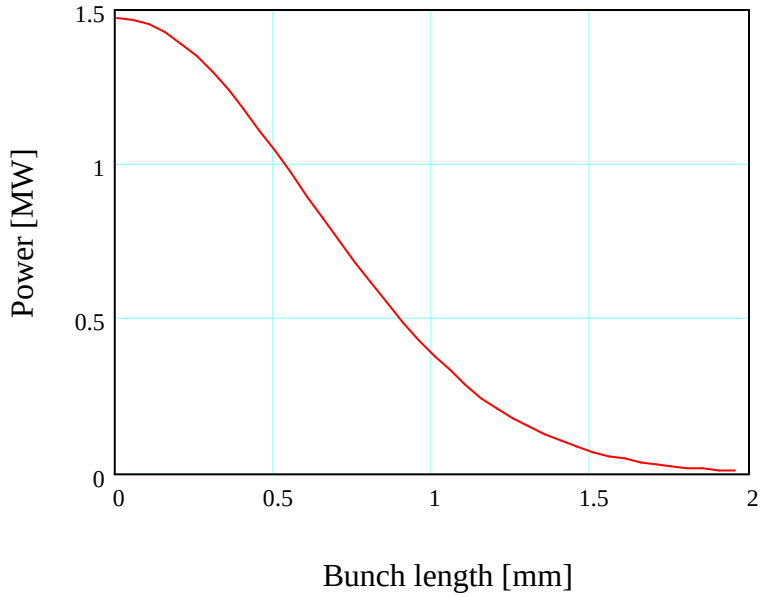

Figure 6: Power generated in the corrugated waveguide by 1.6 nC bunch *vs.* the bunch length.

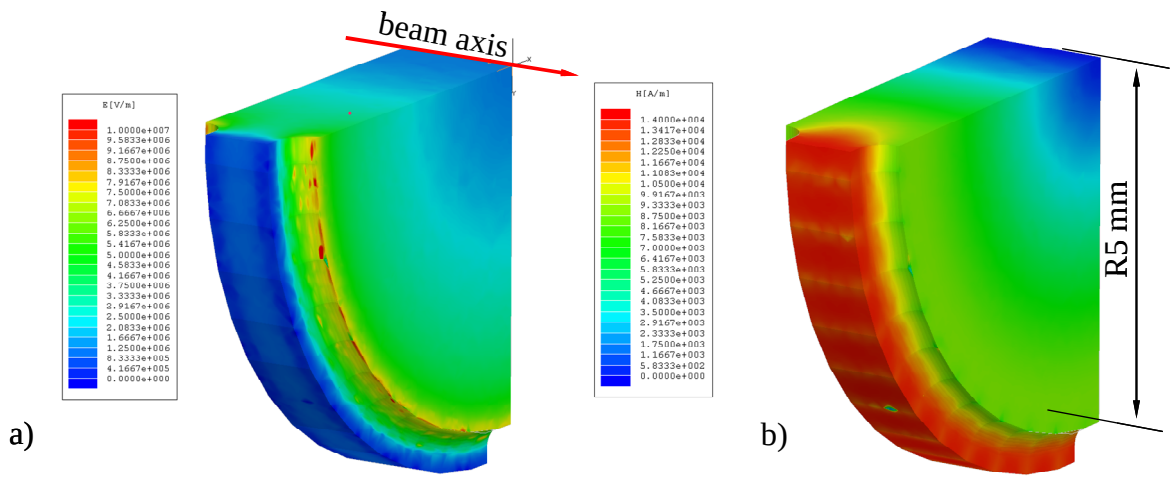

Figure 7: Field amplitudes of first monopole in the corrugated waveguide for 1 MW of transmitted power: a) amplitude of electric field; b) amplitude of magnetic field.

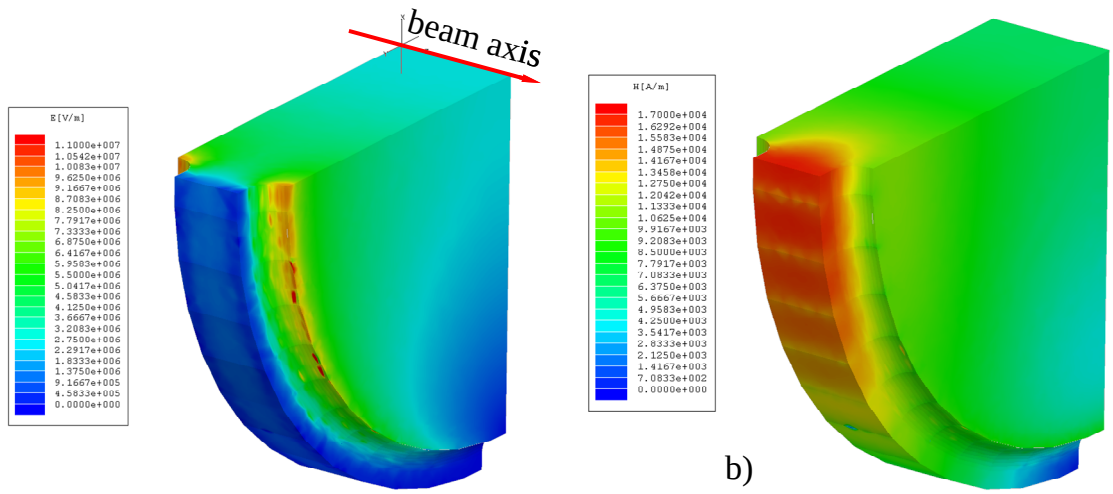

Figure 8: Field amplitudes for the first dipole mode in the corrugated waveguide for 1 MW of transmitted power: a) amplitude of electric field; b) amplitude of magnetic field.

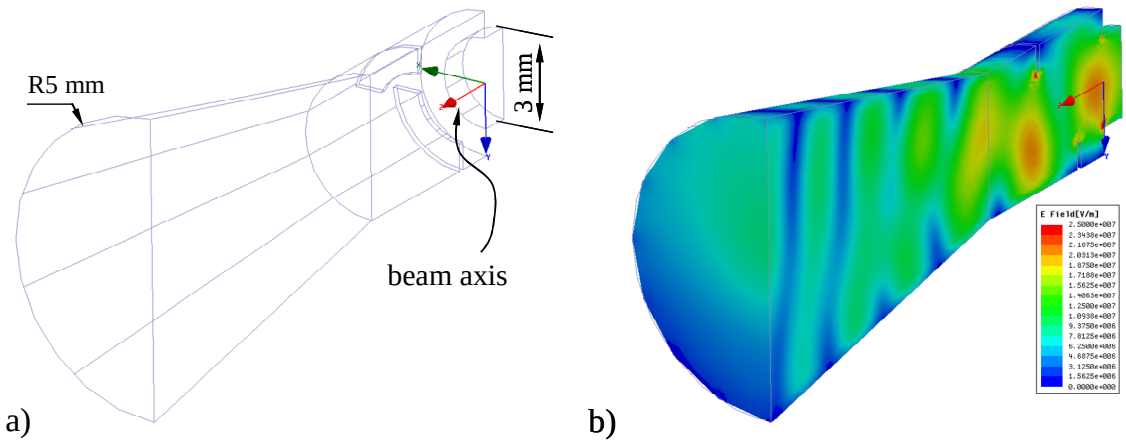

Figure 9: TM_{01} to TE_{11} mode converter : a) 3D model; b) amplitude of electric field for 1 MW of incident power in TE_{11} mode.

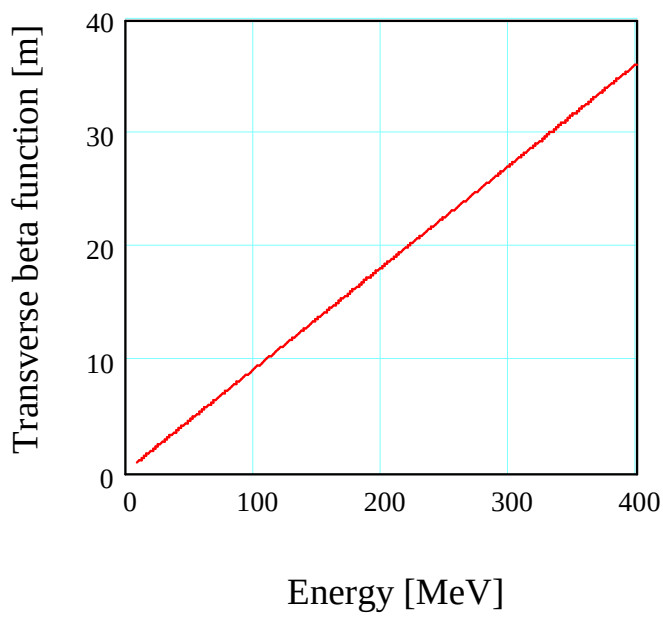

Figure 10: Maximum transverse beta function *vs.* beam energy.

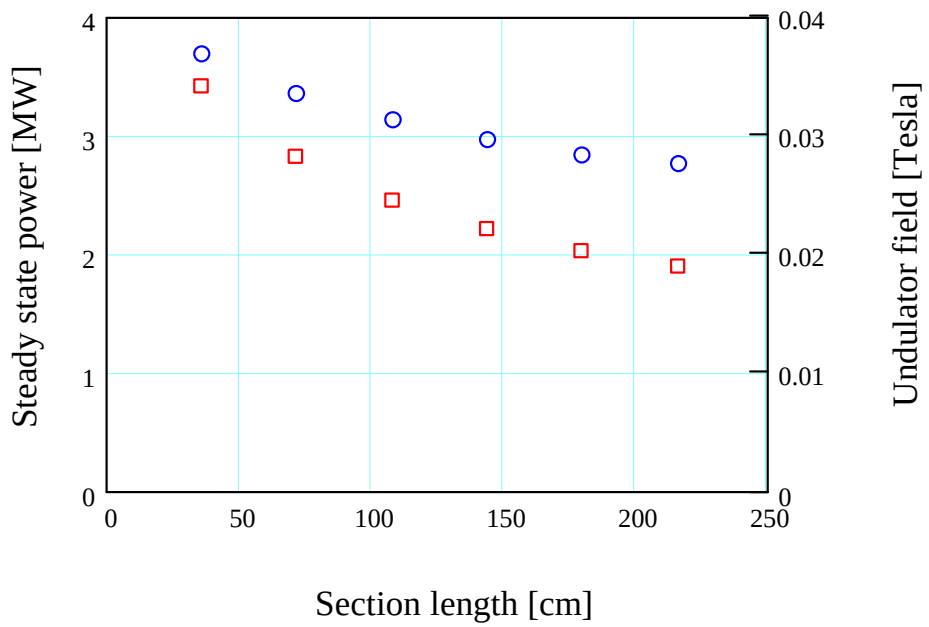

Figure 11: Steady state power (boxes) and undulator magnetic field (circles) *vs.* undulator length. To be resonant with 2.8 ns bunch spacing the undulator length is in multiples of 32 cm.