CW 100MW Microwave Power Transfer in Space

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Abstract

A proposal is made for high-power microwave transfer in space. The concept consists in a microwave power station integrating a multistage microwave free-electron laser and asymmetric dual-reflector system. Its use in space is discussed.

Introduction

Recent successful experiments of microwave free electron laser[1] (MFEL) at LLNL have triggered world-wide research activities on this kind of microwave amplifier. As one of applications of a single-stage MFEL, LLNL has focused themselves on the electron-cyclotron resonance heating of plasma[2]. We can expand our view into another fields of physics and technology. Quite remarkable properties of extremely high peak power, very short wavelength, and relatively narrow band width will enable us to realize a powerful planet radar. The horizon of radar measurements will be extended with the one fourth power of the emitted antenna power. By employing a MFEL capable of producing 1000 times larger output power than that of the conventional millimeter wave power source, the six times more extended scope of vision is expected. In addition, such a planet radar may play a important role in measuring the longitudinal struture of atmosphere of giant planets and study for Saturn's rings which are collecting big interests[3] of planet scientists, or in active search for the time-dependent behavior of flare on the Sun's surface.

A linear multistage MFEL[4] has been considered as a possible power source for future linear colliders; however, the single-stage experiment cannot be straightforwardly extrapolated to the multistage MFEL, as discussed in detail in Ref.5. Nevertheless, extensive theoretical and computational studies have demonstrated the feasibility of multistaging. Based on our current understanding of the MFEL, we develop the idea of a circular microwave power station (MPS) driven with a single high current beam where many FEL stages are placed along a circle and the remarkable high power of microwave (*mw*) is generated at each stage. The total power produced is linearly proportional to the number of FEL stages. This huge *mw* power can be emitted from a large parabola antenna; propagates in space and can be received by a receiver such as parabola antenna or rectenna.

The motivation for developing such a MPS is quite simple. In the next century or two centuries later, a large group of humankind will leave the Earth, construct permanent facilities in space, live there, and explore the solar system by themselves. At this time they will face a severe problem of energy shortage. The MPS presented here seems to be capable of providing the demanding power requirements.

A decade ago, an extensive report[6] to assess the feasibility of Satellite Power System (SPS) which employs a tremendous number of S-band klystrons, say, 10^5, was published by the committee on SPS. Most of discussions developed there are still very useful and instructive. However, there are essential differences between the SPS scheme and ours. High frequency ($10 - 100GHz$) and multistaging in our scheme can result in big figures of merit such as a small receiver size, high efficinecy, and reducing of a number of finite lifetime materials. Laser beams with visible, soft UV, infrared wavelengths which are generated in the chemical laser, the excimer laser, the RF linac FEL oscillator, and the induction linac FEL amplifier are potentially atractive because of their small divergence when propagating in space. However, the intrinsic efficiency of those lasers is relatively low[7]; for former two lasers 3-5% has been demonstrated and for other two lasers their efficiency is estimated to be in the range of 20-30%. High efficiency is crucial for reasonable power transfer. Thus, the high frequency laser beams are ruled out.

It is noted that the received *mw* beam's size is almost uniquely determined by the dispersive solid angle of the emitted *mw* , $2r = L\lambda/D$, where $2r$ the receiver size,L the distance from source to receiver,λ the wavelength,D the aperture size of parabola antenna. For a typical case of $D = 100m$, $\lambda = 3mm$, $2r = 300m$, the possible transfer distance L is $10^4 km$.

Directed Energy Transfer in Space

We assume human activities of ten thousands people, or an equivalent power consumer in space, who requires an averaged power of $100MW$. A primary energy source for the MFEL would be nuclear power, solar energy (if near the Sun), or others (if on the Earth). As a possible use of the MPS, we can consider the following cases: (a) from the ground into space beyond ionosphere, (b) from space to the ground, and (c) from space to space. Here we focus ourselves on case (c) because big advatageous features of the MPS are expected for this case. There are two typical situations: the shadow of solar radiation (see Fig.1a) and space missions or space colony far from the Sun (see Fig.1b). In the former where solar energy is not available, the MPS is stationed at a place irradiated with the solar radiation, but within $10^3 - 10^4 km$ of where the power is desired. The latter may be the most important application of the MPS. The solar energy is no longer available there. We must resort to nuclear energy as a primary. To minimize the risk of radiation leak or catastrophic damages due to accidents in the nuclear power station, however, the region of human activity should be dispersed and placed far from the primary power source. If the MPS is employed, it will be unnecessary for each mission or colony to approach their resource for energy supply, as shown in the configuration of Fig.1b.

Possible Microwave Power Station

A possible MPS operating at $17GHz$ is briefly depicted in Fig.2. The *mw* generating section of the station consists of the $15MeV$ induction linac as an injector which is capable of accelerating electron beams of $3kA$ with pulse length $100nsec$ and a mutistage FEL; each of stages cosists of a $1m$ long planar wiggler with a peak field of $3.8kG$ and wavelength of $26cm$, *mw* septum, and induction unit with an accelerating voltage of $500kV$.

A small *mw* signal from the magnetron is fed in at the start of each period and amplified by the FEL. Near the end of the period the amplified *mw* is removed by the so-called *mw* septum. The electrons of the driving beam go on from period to period. The lost energy is replenished with the induction units. The signal phase is externally adjusted at the input stage so that the output phase becomes the same for all periods. The extracted *mw* is guided to the *mw* parabola antenna and emitted toward the specified subreflector. The subreflector does reflect the *mw* on the specified region in the large output parabola antenna of $100m$ in diameter. Finally the *mw* is reflected toward the objective. The region irradiated by the *mw* changes clockwise with circulation of a single driving beam along the machine. *mw* beams reflected by neighboring subreflectors overlap each other on the same region of the output aperture, because the beam of $100nsec$ pulse length occupying 15 FEL stages simultaneously fires these 15 pairs. Therefore, the uniformity in output *mw* phase is very important.

This device is a single-shot one-turn machine. After single turn, the beam goes to the beam dump. Even if the beam quality does not degrade, the finite saturating time (typically $100nsec$) of magnetic core material embedded inside ionduction units restricts further use of the beam.

This is just an example of possible multistage FELs. Using these parameters, the FEL performance has been numerically studied by so-called multiparticle simulations. Preliminary results have demonstarated this system can produce the required *mw* power with tolerable jitter in power and reasonable fluctuation in phase.

Physical Key Issues

In order to realize the MPS, a lot of physical and technological key issues of the MPS and dual sub-reflector system must be investigated. We summarize, below, what have been solved, what can be extrapolated from the current technology, and what is left unsolved. a) Beam dynamics and *mw* phase stability in the multistage FEL are almost similar to that in the two-beam scheme. Since they have been discussed in Ref.5 and references are given therein, we do not repeat here. It is noted that additional beam dynamical problems of orbit matching and optics matching arise because driving beams are steered to run along a circle. b) Methods of *mw* extraction are also similar to that in the two-beam scheme at least for the low frequency which is currently under design[8]. For higher frequency of $100GHz$, new ideas so as to mitigate effcts on driving beams are necessary. c) The dual sub-reflector system as indicated here has not been so far constructed. *mw* beam overlapping on the output aperture may require seriously delicate design[9] of the subreflector such as phase adjusting function. d) The receiver will be an array of distributed parabola antennae or rectennae. The capability of rectenna is not known for high frequency. e) Wast heat which is generated throughout the system and can not be recovered, will be ultimately emitted toward space.

Concluding Remarks

Key components of a mutistage FEL of high intensity electron gun, magnetic switch with high repetition rate, and *mw* extraction system will be first developed in the two-beam scheme. In addition, the nature of the mutistage FEL as a *mw* generator will be well understood in actual performance there. The design of asymmetric dual subreflector system may be complicated. However a small scale experiment on the ground is possible and the design will be confirmed.

A real MPS in space may be constructed by the following steps. First of all, a full-size power station will be constructed on the ground and demonstrate its capability; then, each component will be brought upto some orbit in space by cargo shuttles as described in detail in Ref.6 and be reassembled there. For the sake of early demonstration in space, the power station will employ solar cell energy as a primary. Thus, we can achive the first huge artificial *mw* emission in space.

This speculation is very optimistic. There are a lot of problems that must be seriously considered and overcome. We suppose most of issues addressed by the committee on the SPS will revive here but in notably small scale.

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Table

Injection energy	$15MeV$
Beam current	$3kA$
Energy loss per period	$0.5MeV$
Output power per period	$1.5GW$
Pulse length	$100nsec$
Number of periods	135
Frequency	$17GHz$
Wiggler length	$1m$
Perid length	$2m$
Circumference	$300m$
Repetition Rate	$5kHz$
Averaged power	$100MW$
Efficiency	81.8%
Duty factor	0.068

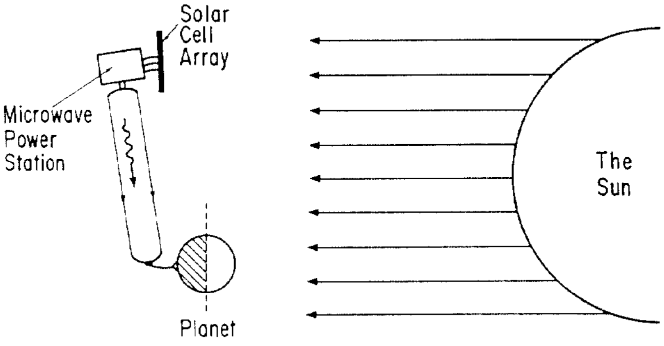

Fig.1a Scematic view of power transfer into a shadow of the solar radiation.

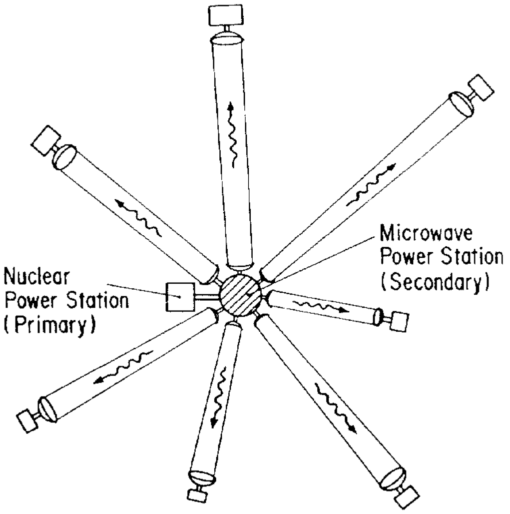

Fig.1b Schematic view of power transfer from resource to missions

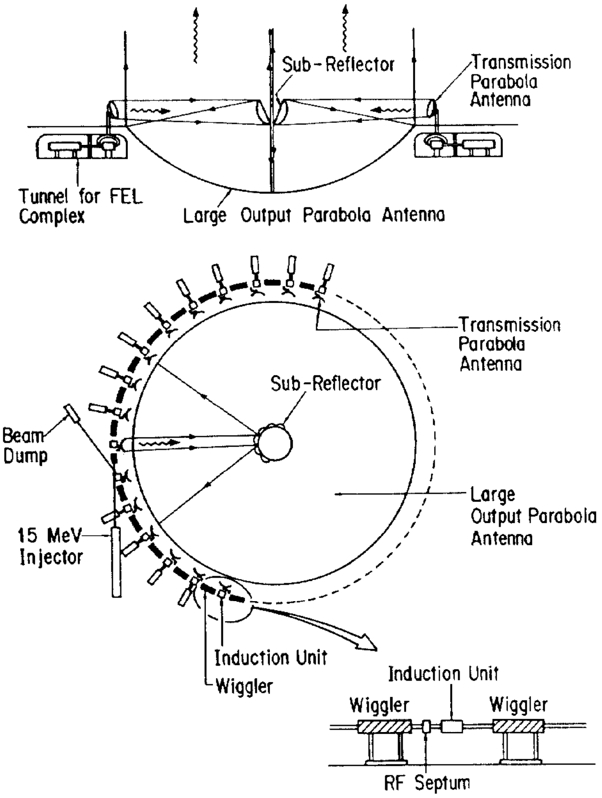

Fig.2 Microwave power station.