

WIRELESS POWER TRANSMISSION ON THE MOON

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MOON BASE WORKSHOP

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OUTLINE

- ← **BACKGROUND**
- ← **LASER POWER TRANSMISSION**
- ← **MICROWAVE POWER TRANSMISSION**
- ← **POWER TRANSMISSION TESTING SYSTEM**
- ← **CONCLUSIONS**



BACKGROUND

"The transmission of power without wires is not a theory or a mere possibility, as it appears to most people, but a fact demonstrated by me in experiments which have extended by years"

Nikola Tesla, October 16, 1927

TESLA'S MAIN RESULTS

- ✦ Alternating current
- ✦ Wireless power transmission experiments



OTHER SIGNIFICANT PROGRESS STAGES

- World War II** Energy conversion to microwaves using a magnetron
- 1964** William C. Brown demonstrated a rectenna to convert microwave power to electricity
- 1940-50's** Development of photovoltaic cell
- 1958** First US satellite using solar power
- 1968** Peter Glaser proposed the use of microwaves to transmit power to Earth from solar powered satellites
- 1978-1981** US Department of Energy research program to build solar power stations in space
- 1980's to Present** US, Japan and other Countries studies on Solar Power from Space (SPS)



SOME RESULTS OF NASA FRESH LOOK STUDY

- SPS competitive with other energy sources
- An SPS system of 250 MW would cost around \$ 10 billion and take 20 years
- Collector area should be between 50 and 150 square kilometers, with about 50 Tons of material
- Possible generation of 5 to 10 GW

POSSIBLE SOLUTION
RETURN TO THE MOON



SPS OVER EARTH-BASED SOLAR POWER

ADVANTAGES

- Sunlight intensity
- SPS would be illuminated over 99% of the time in GEO
- No costly storage devices are required for when the sun is not visible
- Possibility of beaming the power where it needs
- No pollution is created

MAIN ISSUES

- ◆ Complexity (~ 30 years project)
- ◆ Size of the transmitting antenna
- ◆ Cost of the prototype
- ◆ Interference with electronic devices, health and environmental effects in microwave transmission



LASER POWER TRANSMISSION

Solar Power from Space (SPS) + Wireless Power Transmission (WPT) may be
the solution of major energy problems on Earth

Radio- and light-wave WPT offer specific advantages for beaming energy
from geostationary Earth orbit to Earth,
from space to Moon surface and
from one station to another on the Moon

Light-waves can be generated with a reasonable efficiency, and beamed and
transmitted using appropriate wavelength windows

Laser photovoltaic WPT requires a large solar array area to collect sunlight



Long (50 Km) satellites need
In this case WPT is ensured by a huge number of small lasers
running the length of the satellite



All the laser beams carrying energy cover a 6 Km diameter area



A large area receiver is needed
collecting some 500 W/m²

Photovoltaic cell efficiency is around 40% because the
WPT wavelength can match the photovoltaic cell band-gap

Large photovoltaic WPT systems do not require large transmitter apertures



Same power on Earth (or Moon) could be obtained using
a large number of smaller co-orbiting satellites



DEMONSTRATION CONCEPTS AND EXPERIMENTS

LAMP spacecraft experimental 100 kWe space-based energy beaming system for WPT to its own propulsion system and to other aircrafts

Lunar Lander to transmit power via wireless to a robot operating in a lunar shadowed crater

Early 1990's NASA carried out studies on laser power transmission from synchronous lunar orbits to a manned long-range rover
M.D. Williams et al., "Power transmission by laser beam from Lunar-synchronous satellite", NASA Tech. Memo. 4496, Nov. 1993)

Late 1990's Japan also started to study the laser transmission satellite system to supply electric power to the Moon
"Study of space laser power transmission or the lunar surface", NASDA Report N.65, 1997



Manned exploration of the Moon, and mostly manned lunar outpost will require electrical energy for a large variety of uses

Technology that optimizes the systems providing the desired amount of energy is most needed

Studies started at NASA since 1972

C.E. Backus, "Laser activation of solar cells",

Proc. 9^o IEEE Photovoltaic Specialists Conference, Silver Spring MD, May 1972

To supply power to a lunar rover with extended range capability one could generate power on board or storage energy on board.

In both cases huge on board mass would be necessary for long missions

An **additional issue** is due to the long lunar day (15 Earth-days) and night (15 Earth-days)
Lunar temperature is very high daytime and very low nighttime



An appropriate solution would be laser wireless power transmission system
which can be realized both from space to the Moon
and from the Moon surface

In outer space sunlight can always be exploited except during solar eclipses



Laser power transmission from satellites to the Moon seems to be
the solution ensuring supply of electrical power on the Moon nighttime

Solar arrays on board a satellite orbiting the Moon provides
electric power to drive the lasers

The laser beam is then directed toward a probe on the Moon
to convert light beam into electrical power



Advantages of WPT from lunar satellites (to lunar rover or any other lunar probe)

- ☀ Not having to produce power on board the lunar vehicles
- ☀ Large mass saving on board the rover (lightweight of laser-to electric converters)
- ☀ Large amount of power available
- ☀ Rover highly maneuverable
- ☀ Continuous (day or night) operation of the rover



Locations of the satellite power station

There are **5 locations (Lagrange points)** where the satellite remains motionless with respect to the Earth and Moon

Lagrange points = points where gravitational and centrifugal forces of the Earth-Moon rotating system have no effect

Moon orbit radius:	~385,000 Km
L1 to Moon center:	~58,000 Km
L2 to Moon center:	~64,000 Km

When in **L1** a satellite would remain in a stationary position above the Moon.

At L1 about 49% of the Moon surface would be visible at all times

Also at L2 the satellite would give similar power beaming capabilities



Laser diode array

Laser diode array can be used to give **> 100 kW optical power**
with a drive power of around **4 kW**.

An intermediate amplifying driver stage would require
additional few hundreds Watts

Such a laser system generates a large amount of heat
Water can be used as coolant

The system can operate at a temperature of $20^{\circ} \pm 0.25^{\circ} \text{C}$
with an efficiency of 50%

Attention must be paid also to the laser beam, pointing accuracy and mass



Laser beam


The far field of a collimated coherent light emitted from a circular aperture shows an Airy disk pattern

With a transmission aperture of 50 m, the Airy disk has a diameter < 2.4 m

Pointing accuracy

Pointing error is $< 0.025 \mu\text{rad}$  At 61,000 Km pointing error radius 1.5 m



Receiver dish just as large  Airy disk will be within a circle 5.4 m in diameter

Desired pointing accuracy can be obtained by using appropriate gyroscopes

Mass

Total mass M of the satellite is approximately the sum of the masses of major components and depends on the transmitter diameter



With smaller transmitter diameter M is dominated by
the mass of power source

At larger diameter M depends mostly on the transmitter dish

When the receiver dish diameter increases,
the minimum satellite mass decreases

Ex.: receiver diameter 4 m
transmitter dish diameter 17 m

The transmission dish is a 17 m diameter circular aperture
parabolic surface composed by many small hexagonal
reflective facets



To conclude this Section

Placement, control, orientation, laser diode array and transmitter dish technologies are within present capabilities

Even mass issues can be overcome using new generation satellites employing a number of new technologies

(e.g. Laser diode, gyroscopes, photovoltaic system)



MICROWAVE POWER TRANSMISSION

- ☉ Solar power can be transmitted to Moon using a microwave source
- ☉ A rectenna on the Moon converts microwave power into electric power
- ☉ A microwave beam at 2.45 GHz has been used to sent power to Earth
- ☉ The control of back reflected beam is required
- ☉ Power level must be kept below safety standards



Microwave vs. Laser Power Transmission

Microwave

- ☀ More developed
- ☀ High efficiency (85%)
- ☀ Safe exposure to beams
- ☀ Interference with satellite communication systems

Laser

- ☀ Recently available efficient high power semiconductor lasers
- ☀ Efficiency around 20%
- ☀ Within limits on eye and skin damage



Legal issues

International agreement

geosynchronous satellites would fill large
portions of space
interference with satellite communication s
systems rectenna locations

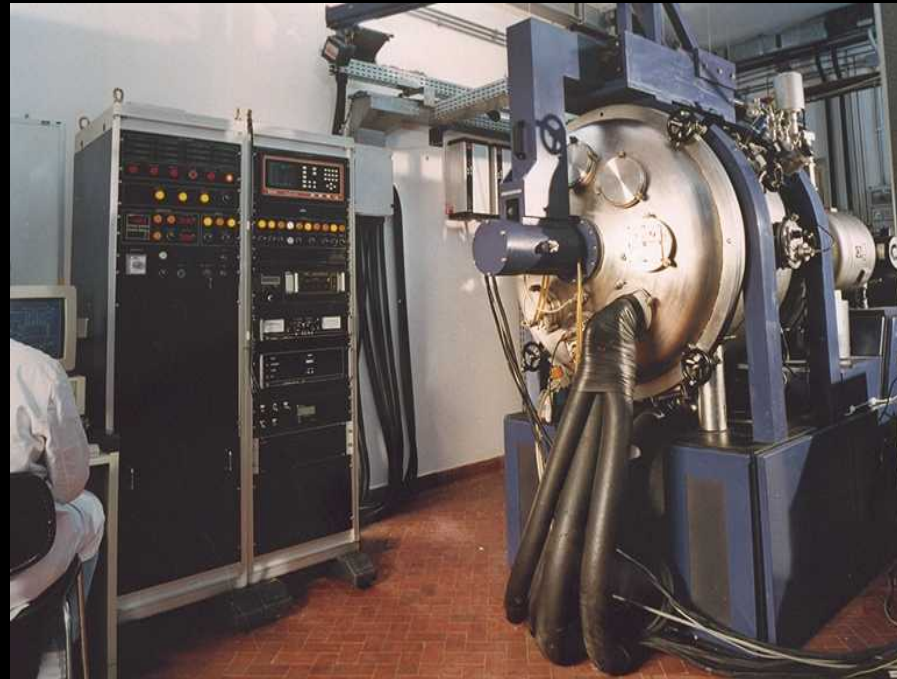
Environmental concerns

health hazards (long term exposure)

Who will oversee



POWER TRANSMISSION TESTING SYSTEM



Test a new technology

- The new generation of laser diode array and transmitter dish technologies need to be tested and validated to the lunar environment
- The positioning and pointing accuracy are critical aspects and the remote control performance must be evaluated in the dusty moon surface environment

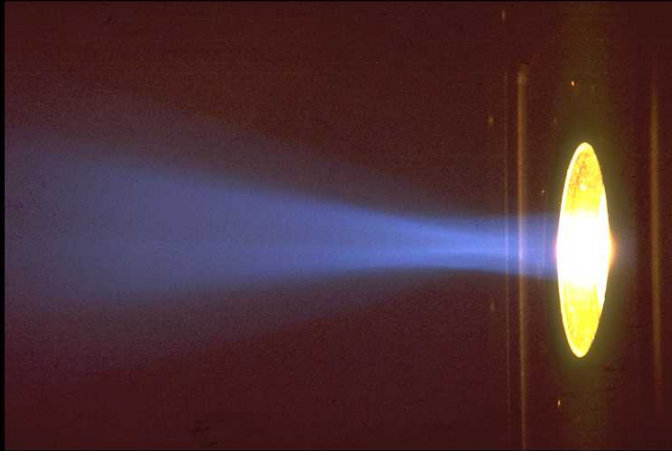


Heritage

- ✿ The EGA (Electron Gun Assembly) has successfully flown in 2 space missions (TSS-1, in 1992 and TSS-1R, in 1996). This very special (high purveyance) electron gun has been conceived, developed and qualified for allowing the closure of the electrical circuit between the two ends of the ITALIAN "Tethered Satellite System" and the ionosphere, in order to experiment the generation of electric power on board at the expense of the spacecraft orbital energy.
- ✿ The EGA has unique features (there is no equivalent device in the world), in particular:
 - beam current: 0-1A, controllable in step of 3 mA
 - Voltage Range: 1-5 kV
 - beam divergence: 10 deg, half angle
 - pulsing rate: 0-1 Hz (in the diode configuration).



Heritage

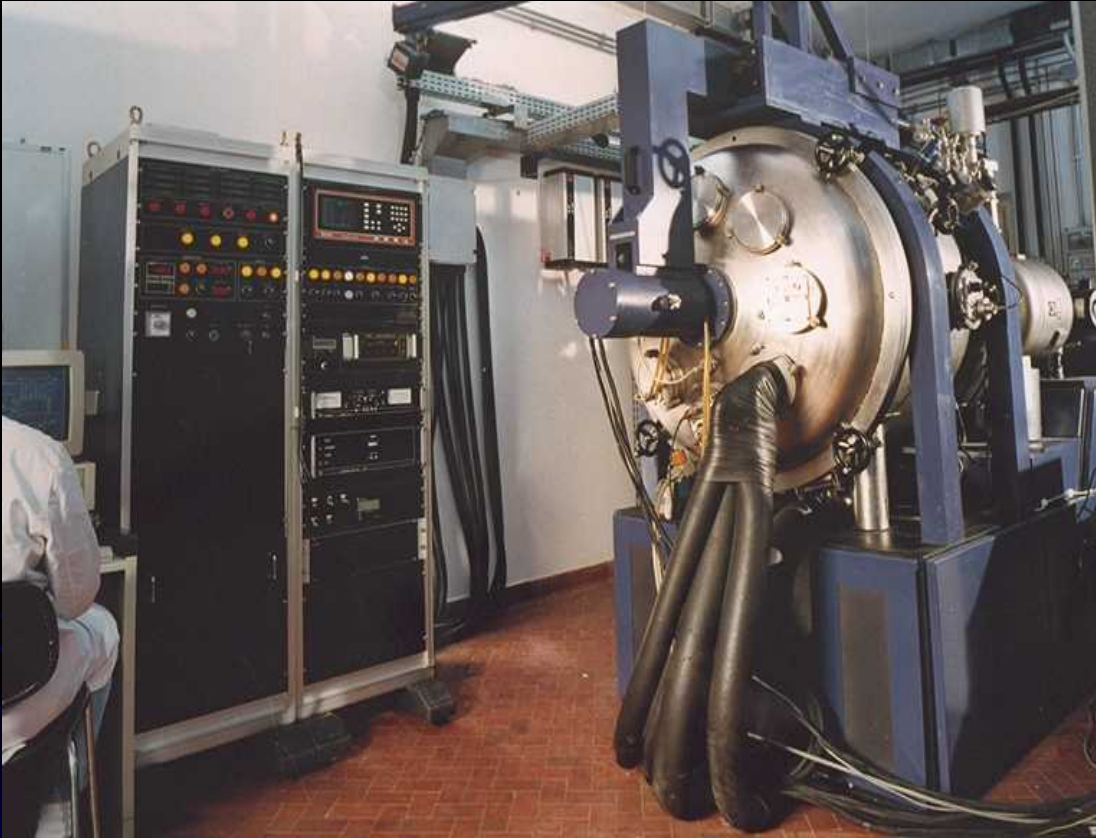


The Electron Beam generated by EGA during on ground test



The EGA payload before delivery for the flight mission (TSS-1 and TSS-1R)

Heritage



The Test of the EGA in diode (continuous emission) and triode (modulated emission) configuration has been performed on ground in the thermal vacuum chamber available at AAS-I Florence Site

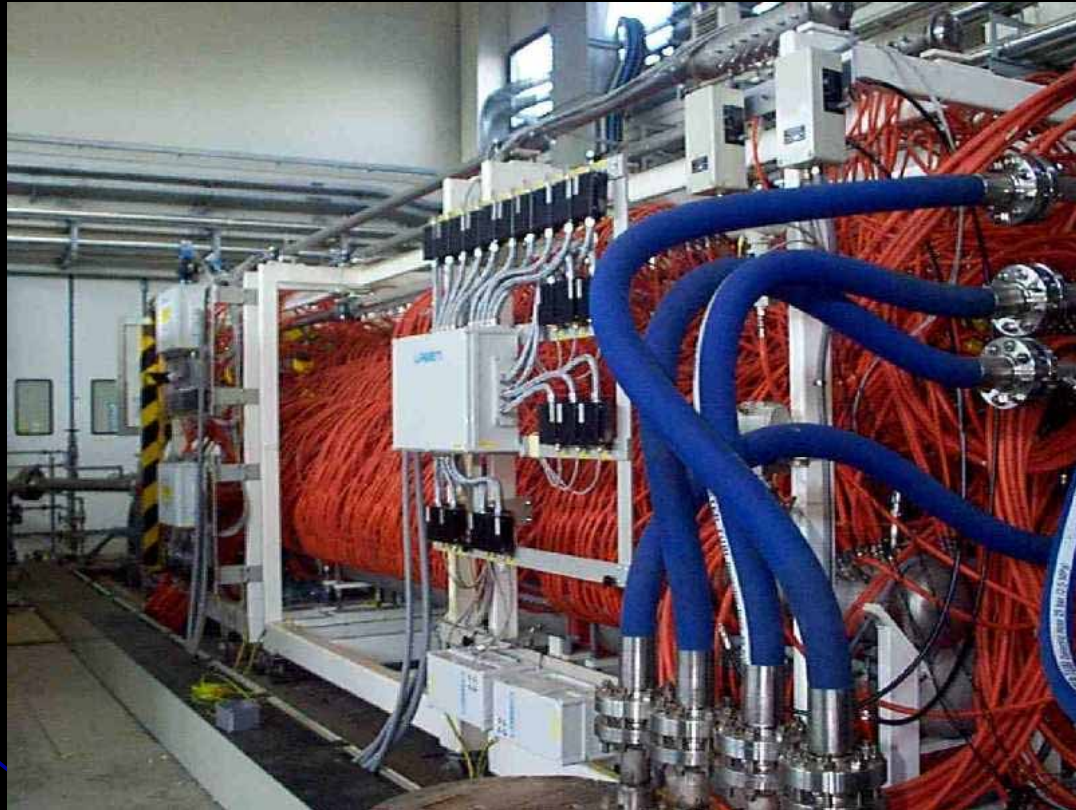
Heritage

Performed tests on EGA

- ✿ Voltage-current characterization
- ✿ Functional Test in presence of a simulated ionospheric plasma. Now the PWT and its Test System in Capua (close to Naples) is a new available asset
- ✿ Functional test in presence of gases at different partial pressures
- ✿ Thermal Test



PWT-Plasma Wind Tunnel



- A new generation of test facilities is requested
- The test campaign of the WIRELESS POWER Transmission on the Moon must face:
 - Critical environmental test (vacuum and plasma)
 - Critical pointing performance
 - A network of new technology
 - A wide System of knowledge and competences



CONCLUSIONS

- ◆ SPS is more reliable than ground-or-lunar based solar power
- ◆ New generation satellites would be greatly helpful in realizing SPS systems
- ◆ Support of the Governments
- ◆ Reduced launch costs
- ◆ Involvement of private investors

