Nuclear Power Supply For Directed Energy Devices *

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Abstract—* *Photon and beam based directed energy weapons require compact, solid-state power supply, in order to assure battle-space portability and flexibility.

The development of the new space force will require the use in outer space on LTE or exo-planetary orbits of directed energy devices to be used as conflict deterrence and aggression denial systems as well as for planetary protection against space threats, as meteorites.

The use of these devices in outer space requires high efficiency on all systems from the power supplies to directed energy devices that may be lasers, accelerators or plasma jet devices, each having own features and application range.

***Novel families of meta-materials for direct nuclear energy conversion to electricity, presently in TRL=3 stage may drive to the construction of ultra-high efficiency, solid-state, compact fission, transmutation or fusion batteries, as a prime condition of obtaining a compact portable tool for seamless operation on airborne, or space crafts equipped with a high efficiency directed energy device, in order to minimize the heat sink size, and increase maneuverability in tactical field*.**

Keywords—* *Nano-hetero structure; meta-material, nuclear energy; accelerator; space applications; alpha voltaic; directed energy

I. Introduction

The development of war technology based on hyper velocity carriers of nuclear charges and the competition among the nations for the extension of battlefield in the outer space made the use of airborne directed energy devices as the only viable defense alternative.

Modern battlefield designs contain a plurality of weapons and space monitoring and control systems, integrated under a unique command, where all information is shared among participants creating a holistic view and dominance of the battlefield. The complex use of terrestrial, naval, undersea, air and space resources to dominate the battlefield may be drastically altered by the adverse usage of directed energy devices. The ultra-high speed of energy and power projection makes all airborne and space targets fully available, and denies their usage reducing the available battlefield resources to classical weaponry and observation systems. A multi-LED high power portable lasers can make a difference in the battlefield operation, leaving only some terrestrial operations possible. The problem with laser is related to absorption and reflection of the beam by ad-hoc plasma mirrors, that is requiring modified power cycles.

Space applications of directed energy is complementary to intra-atmospheric application, and opens the way for particle beam applications that are more efficient than lasers, but the process is more complex, because a DES (Directed Energy System) is applying an electromagnetic beam, say laser beam, it goes in an approximatively straight line, while an ion or electron beam is bending in the extra-terrestrial magnetic field, that is continuously changing, and is position dependent, therefore detailed knowledge of the space is required prior to shooting.

The energy efficiency is higher, for example 1 GeV protons at 4 mA deliver energy of 4MW (about 1kg TNT) that may be balanced only by the IR emission via object's surface. More, one has to know that space objects behave as spherical capacitors of about few pF capacitance, and may be easy polarized, making that only a fraction of a charged particle beam to reach it, therefore requiring neutral or charge-alternate quasi-neutral beams. Fig. 1 shows what few GeV beam may do to a satellite, having stopping range of several cm in iron or Al, therefore, the beam penetrates almost the entire structure, instantly upsetting any electronics on-board, with no recovery.

A 4 mA at 1 GeV the power deposition is about 4 MW, able to vaporize 1 kg of steal or Al per second, if the radiant power does not match the input power. When the beam's surface is about 1 m^2 the temperature of the object is about 2,000 K at equilibrium, where iron is melt and everything else inside is melt also. The beam may be maintained for seconds on a target, if the necessary beam transport knowledge and capabilities requirements are met. If vaporization occurs, that acts as propulsion, taking the satellite out of orbit ending in atmosphere where the burnout process is accomplished. For 1 ton space-object, 1 kg/s evaporation, produces an acceleration of ½g. A satellite may also explode because energy is high enough to trigger potential chemical reactions on board.

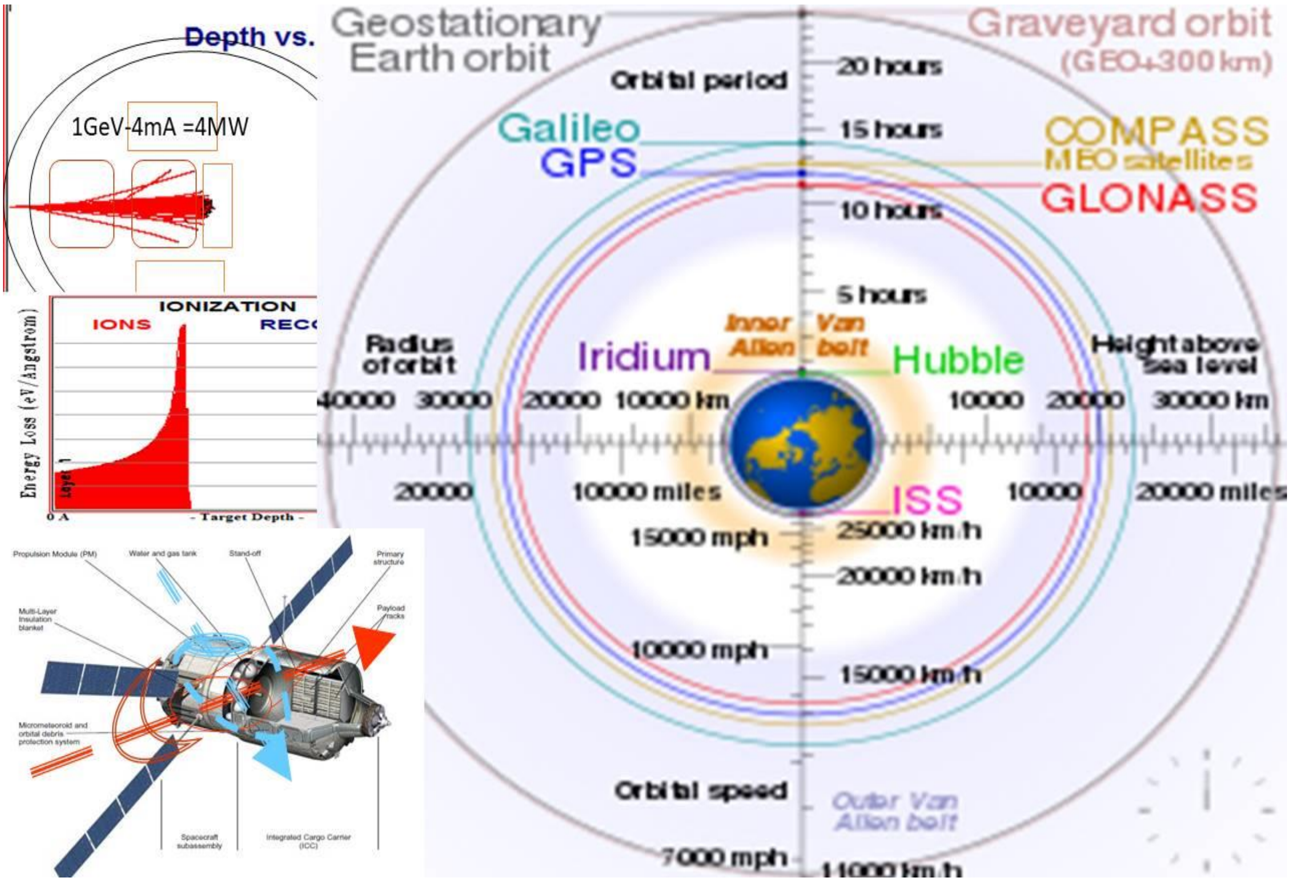

Fig. 1 Distribution on main application on Terrestrial Orbits and Beam stopping in satellites.

The knowledge refers to the presence and distribution of magnetic fields in the area of operation, which are bending the beams, in a time variable manner, due to permanent change because of planetary field modifications as well to space weather, and plasma accumulation in belts.

As one may see here, outer space is crowded with all kinds of objects, therefore, in-depth knowledge on them is important, in order to use the right energy and beams intensities. It is desired that the entire energy to stop inside the targeted object [1] and not pass through and create an ionic cloud around that may disrupt the efficient beam pulses application. In upper left side of Fig. 1 is presented the nuclear beam stopping inside the satellite, and immediately under it is presented the energy deposition by ionization. That was also shown in the ideogram of a space craft where a positive beam in red hits it in one direction and the focal point of the negative beam hits from other direction, in order to compensate for different beam bending in the space magnetic field and plasma plumes, forming the local space weather. The schematic view on the right shows the planet dimensions and how various trajectories and distances are used mainly for peaceful applications, because the present military use is unregulated, due to lack of balance of force in space, and the race for terrestrial outer space militarization.

II. Efficiency And Heat Removal In Space

No matter the type of application in space, efficiency is dictating the amount of power on board, type of power supply, power delivered on board and size of heat sinks.

The equipment cooling in space is limited to IR radiation that follows Stephan-Boltzmann law that is briefly presented by the blue line, in Fig. 2 and gives the radiated power density as function of temperature difference in Kelvin and Rankine degrees. On the right ordinate is the wavelength of the maximum of the Plank spectral distribution which was plotted on the chart as an example for usual temperatures up to 6,000 K.

It turns obvious as all operations in space are about high efficiency only, because low grade heat is difficult to remove, requiring large heat-sink surfaces, passing about 1- 3 kw/m^2.

There are many types and constructive versions for radiators used in space, but finally all is reduced to the capability of emitted IR radiation to carry power away, that makes the object visible in IR spectrum and on thermo-imaging systems, being recorded under FOF (Friend or Foe) protocol.

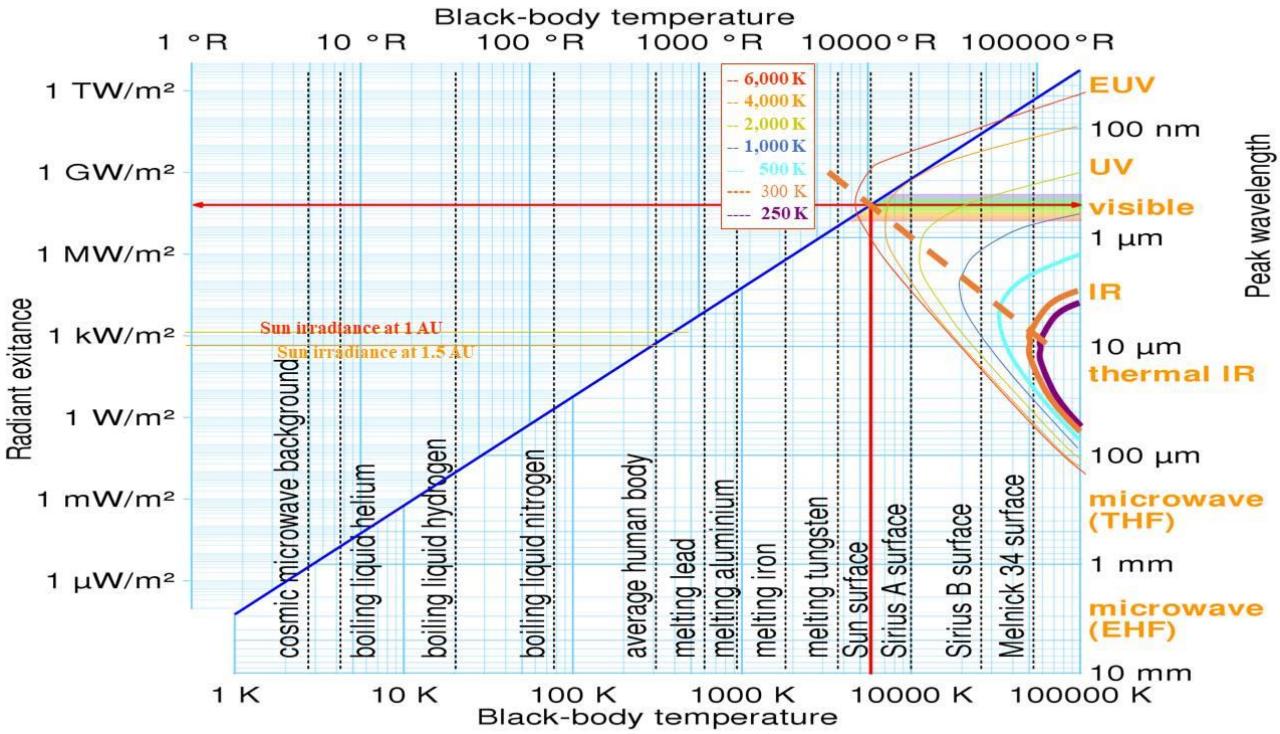

Fig.2 Infra-Red (IR) heat sink performance and Plank energy emission curves for blackbody.

III. Nuclear Power in Space

Among the most attractive power supplies for space is nuclear power, in close competition with photovoltaic energy at 1 Au (Astronomic Unit, Earth average distance from Sun), but clearly dominating deep space, outside Mars trajectory.

The big advantage of Nuclear energy is the fact that it is by 1 Million times more compact than chemical based energy, making it cheaper to place on orbit, and having a long life [2]. The best-known actual power supplies are ARTG and compact small reactors as recently deployed Kilopower that is a thermo-stabilized supply, using Sterling engine to convert heat flow in electricity, with an efficiency of about 30%, by a factor of 2-3 times higher than of RTGs.

As it is well known, nuclear power is mainly known for nuclear bombs, developed since 1940s, and largely produced on various types, dimensions and applications, changing the power balance and politics, where peace is mainly maintained by MAD (Mutual Assured Destruction).

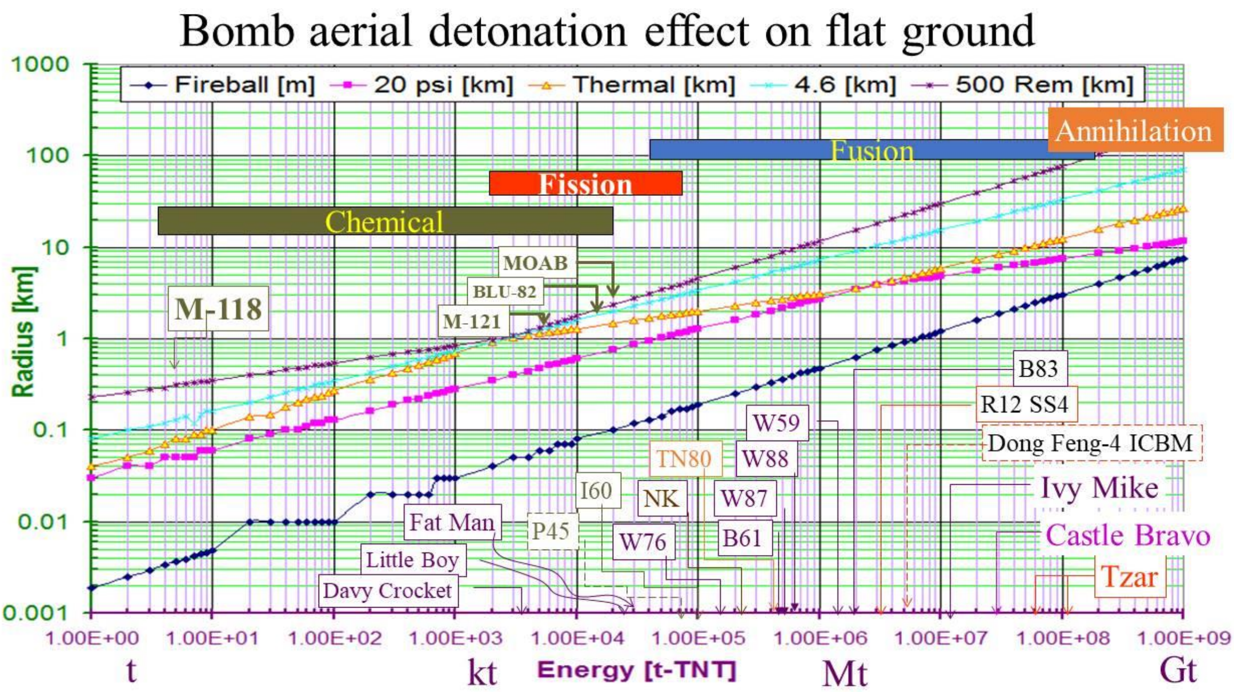

Fig. 3 – Energy distribution of various bombs and the main effects on target for aerial use.

Performances of previously tested nuclear devices are shown in Fig. 3, which reached the limit of 6 kt/kg (25 TJ/kg) after many optimizations, where the yield of fission bombs is limited at about 100 kT and everything above is a dual cycle fission/fusion devices. Aerial use is not very efficient, because most of the energy reflects on the ground and is lost in atmosphere, practically 30% of the released energy is delivered to surface, and strategical-tactical considerations limit the blast energy at ½ Mt.

As a synthesis of the bombs development is presented in Fig. 3, shows the position of different types of bombs and their terrestrial inflicted damage or radius of influence. It is observed that the energy is growing by 2 orders of magnitude for the effect to grow by 1 order of magnitude. It is also well known that Mt bombs are missing strategic and tactic practicality. On ordinate is the radius on target for various after blast effects, as “fireball, or plasma space, with dark blue, where target is evaporated, the pressure shock wave at radius where it reaches 1.3 bar (20 psi) with pink, where the walls are flattened, the radius of thermal space, where the temperature of air is over 100 C, producing burns and igniting wood structures and fuels, in orange and the radius where the pressure wave is 1/3 bar (4.6 psi) in light blue that is slightly smaller than the 500 Rem (5 Sv) in violet.

This chart was presented to create a comparison scale of the non-explosive use of nuclear power in electricity generators, and directed energy applications in ions, neutrals and photon beams, which will deliver the desired impact on target without destruction and collateral damages.

IV. Meta Material For Direct Nuclear Energy Harvesting

Starting in 1980s accelerator based researches and computer simulations showed that for engineered nano-materials may mimic a supercapacitor structure that to charge from the energy deposited in the structure by the moving nuclear particles stopped in the structure and further discharged as electricity. Fig. 4 shows on the upper right side fission products energy, for the lower and higher mass fission product as function of mass difference from the median mass, as they share about 170 MeV as kinetic energy. Alpha particles from fusion have various energies lower than 22.4 MeV depending on nuclear reaction type, while produced by nuclear decay are in the range of 4.5-6 MeV. Most of the energy is deposited by ionization, where a stopping ion produces knock-on electron avalanches that leave the nano-layer in which they are produced and stop in another layer along the path. On the upper left side is presented a simulation of a planar capacitor structure, formed of a modulus of 4 nano-layers, where the first is an electric conductor that has a large electron availability producing a large electron shower that passes through the next layer an insulator, stopping in the third layer that is a conductor with low electron availability producing a small to nothing shower and becomes negatively polarized. A fourth nano-layer is used to insulate the conductive layer and the cell.

Detailing into operation principles, one has to know that moving nuclear entities (fission products, ions, neutrals) behave like accelerated charged particles in interaction with matter, making the power deposition mainly by ionization of material lattice. In a nano-engineered hetero-structure where the high electron availability conductive layers are interlaced with insulating layers and low electron availability conductive layers, nuclear entity power deposition occurs in high electron availability layers. This generates electron showers that are tunneling through

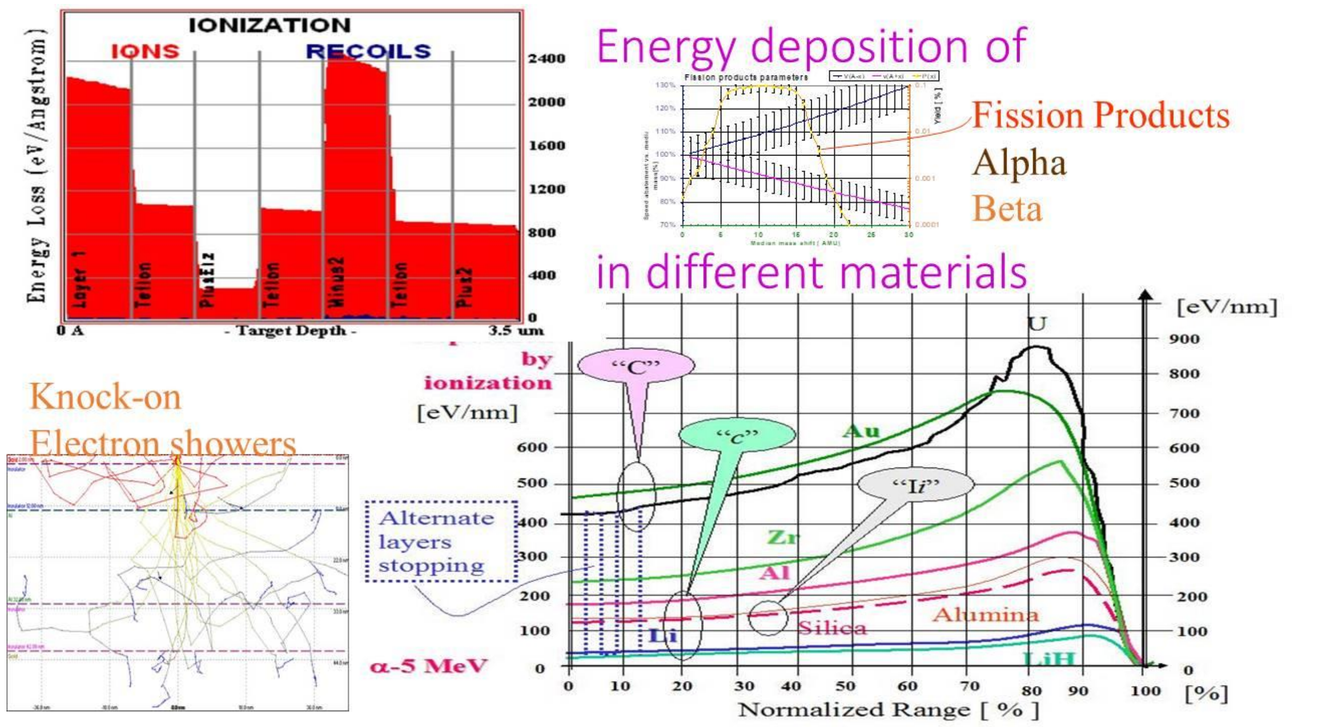

Fig. 4 Energy deposition in nano-layered materials and materials selection

insulating layers and are stopped in the conductive, low electron availability layer polarizing it negatively, while the other layer remains positive polarized due to electrons departure. The charge returns to the departure place via an external circuit that harvests the energy. In the lower left chart is presented a simulation of the knock-on electron paths in the meta-material, in the process of generating electron showers by frequent collisions with atomic orbital's electrons, sharing and degrading their kinetic energy [3].

The lower right chart shows basic criteria of selecting materials to build such a structure, where materials with high ionization are used for positive electrode "C", while conductive materials with low electron availability are used for negative electrode "c", and dielectric materials with low electron availability are used for insulating the electrodes "I, i", finally forming a "CIci" cell.

suspended inside a dielectric. This is more robust structure, of one thing about tungsten-alumina that may operate up to 2,000 C.

In the top-left side is shown a hybrid between direct fission product separation micro-structure that has embedded direct nuclear energy conversion into electricity hetero nano-structure, all immersed into a drain liquid. The development of structures with spherical geometry is rising radiation design issues, and a structure with a 5 μm diameter Uranium or Plutonium dioxide or carbide core coated in metallic tungsten surrounded by tungsten beads immersed in Alumina, having a thickness of about 10 μm, immersed in a drain liquid. This system may operate at temperatures up to 2,000 K, where a part of power is removed thermally and another part as electricity. If the bead efficiency for direct conversions 90% and the thermal conversion efficiency of about 70%, with 2

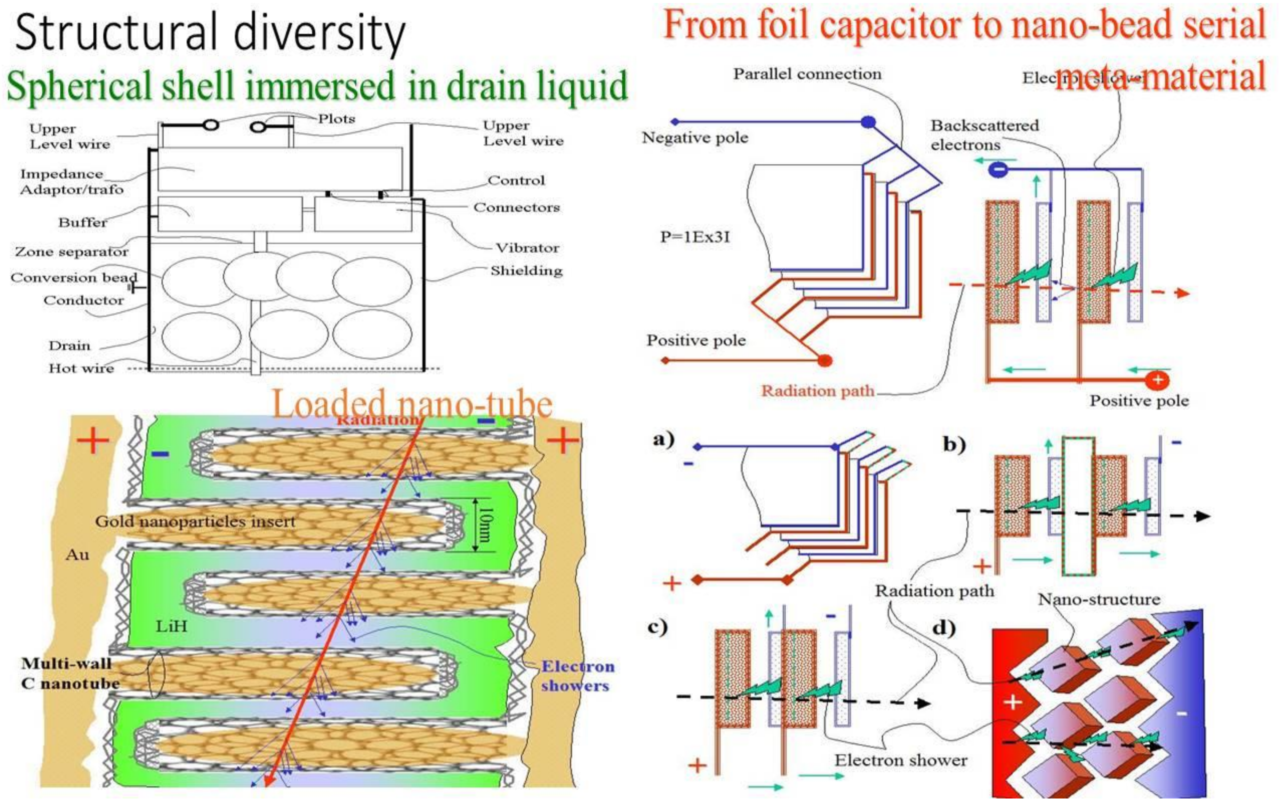

Fig. 5 - Various constructive solutions to build the direct energy conversion structures

Theoretically, the energy conversion efficiency is very high, over 99.9%, but practically there are many constructive details that impact the efficiency, and in depth know-how is needed. In Fig. 5 there are presented several construction possibilities for these materials. In the planar structure, the geometric coefficient of radiation release is about 3π, limiting the efficiency of an isotropic particle emitter collected by a planar supercapacitor at 75%. This planar capacitor may have the modules connected in parallel as is seen in Fig.5 top-right, or may be connected in series as one can see the a schematic connection, where the intensity of current remains constant but voltage build-up. Evolving the structure one may observe inter-cells insulator is not needed and finally the structure may be evolved to a beaded structure, where the beads are

kW/cc power density, that will drive to a maximum power density of 20 kW/cc, from which 19 kW are delivered as electricity. Underneath, on left lower structure is a loaded multi-wall nano-tube immersed in LiH that is expected to exhibit a higher than 95% energy conversion efficiency, due to its near 4π geometric factor, but it is very difficult to build it. The problem is that a minimal critical structure reaches 2 ft radius using enriched fissile materials, at an average density of 10 g/cc, having to be built with nano-micro hetero-structures, that represents another challenge of the present technology.

Such a device will have about 1 m^3 (950 litters) a maximum power of 19 GW, and a weight of 12 tons for the reactor core only. Possible operation in space will be at maximum 10 GW, with a square heatsink with

600 m to 1 km length, when used with an accelerator that shoots out almost all energy, but when used to power a space colony a 10 km length heatsink square may be required to remove the entire low grade heat generated after the power being used in various devices on-board. The present development status of the device is TRL3, being in need of important design and capabilities to be developed in advance. The advantage of a nuclear reactor structure is that it may produce energy on demand, compared with isotopic batteries where the power and energy are predetermined by construction, and flow of energy cannot be interrupted based on demand, and have to be used, accumulated or dumped in environment as heat.

V. Nuclear Isotope Powered Batteries

The simplest structure is a planar capacitor that may harvest alpha or betta particles' energy. The total energy and power is set by the type and amount of radioisotope as Fig. 6 shows.

A planar design of a super-capacitor for solid-state radio-batteries/alpha-voltaic is schematically presented in Fig. 6. Alpha particles with energy from 4.6-6 MeV have a range of about 20 microns in the energy harvesting meta material, requiring about 200 "Cici" cells, of about 100 nm thick to fully convert the energy, delivering a voltage up to about 200 V and a current proportional with radioactivity and surface of the battery. The smallest battery may be a parallelepiped of 0.1 x 0.1 mm lateral and 0.05 mm thick, delivering power- time dependent of the radioisotope that is used.

Some features of the batteries –a first by-product of DEC structures, are listed in the chart. Almost all alpha emitters delivers an energy of about 5 MeV, therefore, the power density depends of the radioactivity, or the inverse of halving time, and the smallest battery may have a power on 100 nW, for about 90 years if 238Pu is used, or 0.01 mW for a half of year if 210Po is used, where from the energy point of view this type of battery is equivalent to about 100,000 chemical batteries in the same power range.

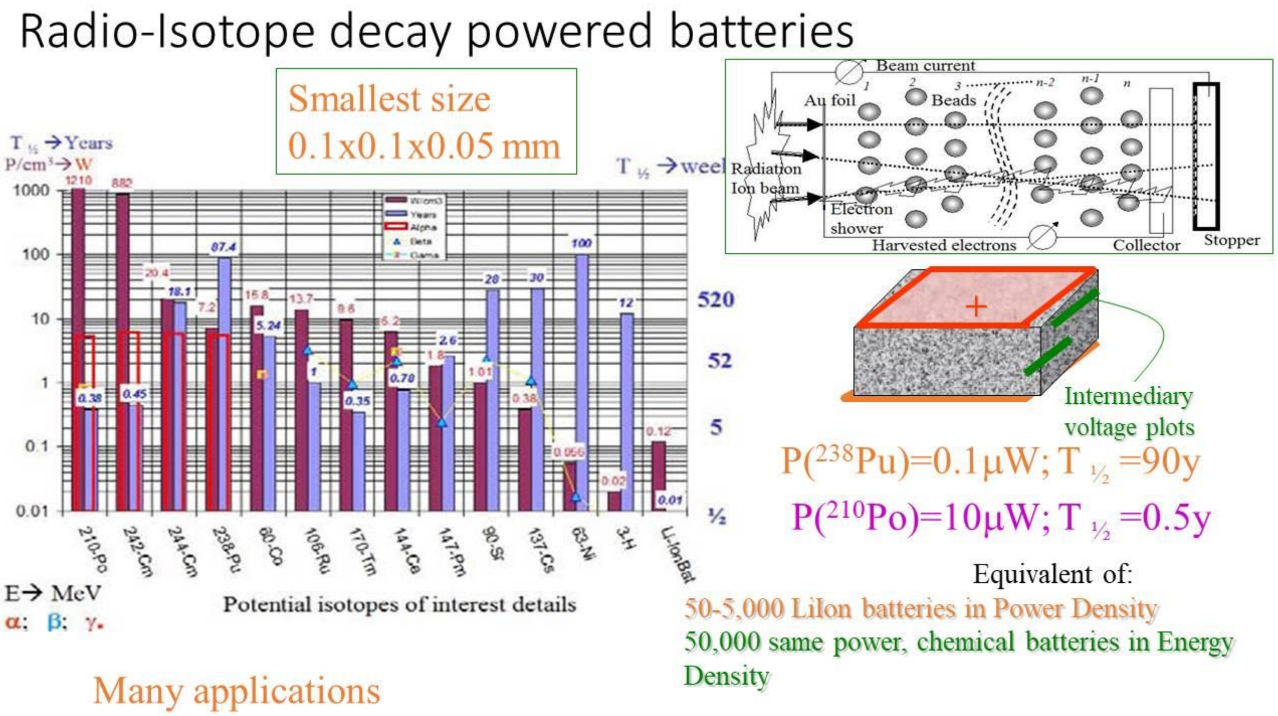

Fig. 6 Isotope induced features of alpha, beta voltaic

VI. Powering Accelerators In Space

Most of the actual space interceptors are kinetic developer as weapon systems for ballistic missile defense, some carrying explosive charges and projectiles to act as a grenade in the vicinity of target and increase chances, but all the process takes over 10 min., and in outer space when the target become a meteorite, process timing becomes days to weeks, with costly redundancy. For small size objects a nuclear blast of 10 ktTNT may deliver an effective energy on target in the range may deliver about 10 kgTNT if exploded nearer than 500 m radius, but with very narrow window of opportunity, compared to a directed energy device that may load about 1 kg TNT/s for extended time inside a feedback loop, and controlling continuously the target evolution. Very efficient accelerator structures are needed for this application, in order to form neutral or photonic beams or dual charged particle beams, as RFQ (Radio Frequency Quadrupole), FEL (Free Electron Laser).

Fig. 7 presents a generic view of a planar multi-stage accelerator that uses fission products energy to charge a planar capacitor that delivers the energy to a linear accelerator that has a beam mixer and gantries for forming neutral or dual beam and aiming.

Connecting a direct nuclear energy harvesting device to an accelerator as Fig. 7 shows might be the best match for space as long as both efficiencies are high, over 90%. That will drive to a residual thermal energy of about 20% that has to be evacuated with a low grade heat sink, with a power flow of about 3 kW/m2, that makes possible 12 kW/m^2 to be produced as useful power. We will need about 3,600 m^2 of heat sink to handle 4 MW beams that is a 60 m square, and if combined with high efficiency (about 30%) solar, will provide another 1 MW of power.

The picture exemplifies how a meta-structure that resembles a supercapacitor charged from nuclear energy, from the moving particles generates electron showers that charge the capacitor which delivers power into a dc/dc converter that customizes for the accelerator. If an RFQ or Alvarez inter-digital structures are used a radio-frequency is needed to accelerate the beam. The problem is that the smallest solid –state-compact nuclear reactor structure as previously described that has 1 m^3 of nano-structures,

looks. Magnetic field interacts with moving charged particles and bends those beams depending on their rigidity, while plasma and solar flares interact with neutral beams by electric collisions turning a part of them into charged particles that are lost from the beam. Photonic beams, in spite they are less sensitive, and follow almost the same path as light in space have skin depth issues, being prone to forming plasma mirrors, that reflect the continuous beams, and require specific beam modulation. EM waves directed energy in atmospheric transmission bands may be used to interfere in planetary conflicts “tilting” the battlefield power balance and denying to a part or another access to airborne technology. The FEL UV to X ray photonic emissions are limited to outer-space applications because they have high absorption in atmosphere.

It is known that electron gyration radius is a function

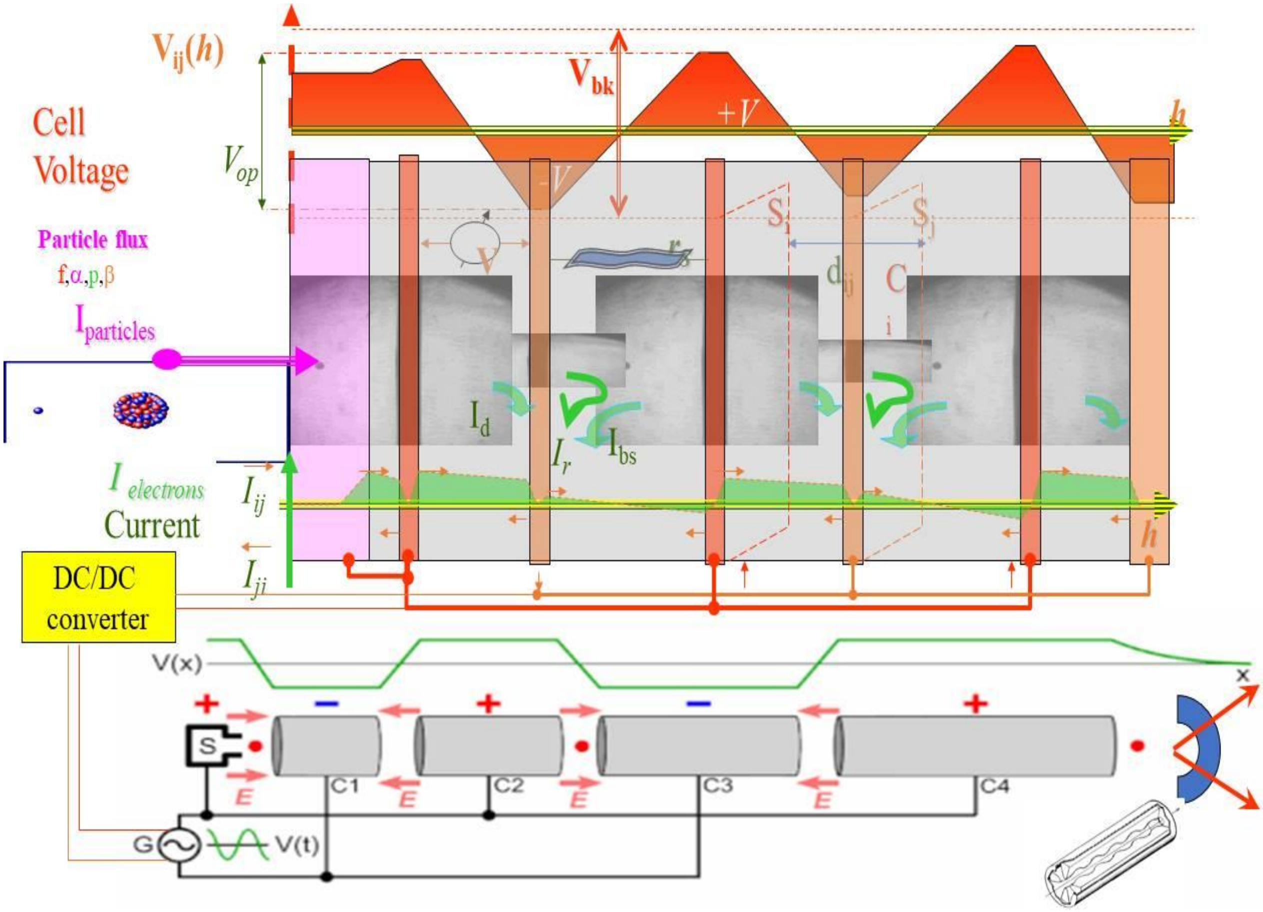

Fig. 7 A directed nuclear energy harvesting device powering a n inter-digital accelerator or an RFQ

and is able to deliver 10 GW of power, suitable for the application. From the actual technology point of view, in spite it is a very efficient device that combines a ultra-hot nuclear reactor with a cryogenic resonant cavities accelerator, the endeavor is large well over actual planetary capabilities, and over present space weather prediction and mapping knowledge.

VII. Directed Energy As Beams In Space

Of course, shooting ion beams in space is an efficient use of nuclear power to deny undesired space objects action, but the operation is not as simple as it

of electron energy and magnetic field in which beam is traveling. On Earth’s surface a 10 keV electron beam has a 10 m gyration radius while a 1 GeV is turning in about 10 Km radius. This makes electrons unsuitable for shooting at ranges of 20 km, which in outer space represents less than 1 second of travel for a space object.

For proton beams gyration radius on LTO (Low Terrestrial Orbit) is about 10 km for 10 keV and 300 km for 1 GeV, making it suitable for about 600 km on LTO and 10,000 km in deep space. Of course, more

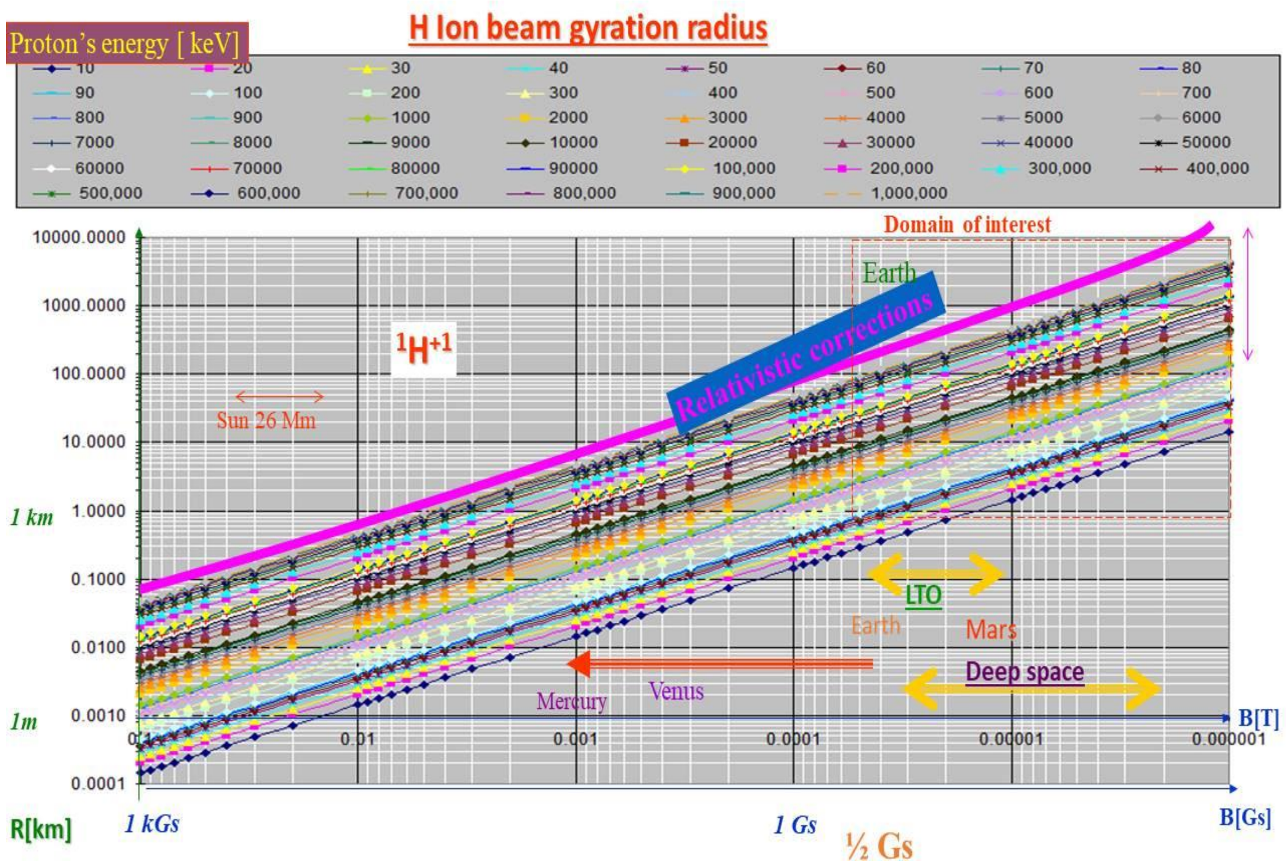

Fig. 8 Proton beam bending radius in the extra-terrestrial magnetic field

complicated helicoidally trajectories may be conceived, in order to increase the firing range with the condition of maintaining the beam's emittance at a minimum. Higher energy in TeV domain and heavier ions are required in order to obtain reasonable shooting ranges, but that will require the replacement of a pair of linear accelerator with a storage ring.

This is not quite what we needed I terms of planetary defense, where the interaction range to be at several AU (astronomic units) which will require gamma and neutral beams, which are not bended by space magnetic fields, but are still damaged by interaction with space plasma driven by "space weather". Having a suitable power supply these applications become possible.

VIII. Outer Space "Ballistics"

The presence of various range of weaponry in space will extend the terrestrial "ballistics" over a new frontier into outer space ballistics, with its rules and requirements different from Earth's one.

As I have mentioned at the beginning, shooting beams in outer space is not a simple task, an in-depth knowledge of the space is needed in order to have an accurate "beam ballistics". As Fig. 8 shows, Earth has a complicated magnetic field, in continuous change due to Earth's internal movements that is in interaction with other space magnetic fields, and continuously modified by space weather. It is possible to shoot long range helical beams, as long as we are aware of its trajectory and may hit a target within acceptable emittance. This complex "ballistics" may be reached only based on a detailed knowledge of outer-space's magnetic fields at the moment beams are passing through, even at the level of interaction with Alfven waves, which may enlarge beams' emissivity, and generate low energy photons.

IX. Summary

As one may see, the development and interest for new materials is strongly correlated with the desire for new applications because without high performance materials, top-notch applications are impossible.

The development of nuclear power for space relies on several families of nano and micro-structures engineered such as to create functional materials that work together to assure the energy production in a reliable, safe and high efficiency manner.

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