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Radiation Sources Working Group Summary

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Abstract. The Radiation Sources Working Group addressed advanced concepts for the generation of RF energy to power advanced accelerators. The focus of the working group included advanced sources and technologies above 17 GHz. The topics discussed included RF sources above 17 GHz, pulse compression techniques to achieve extreme peak power levels, components technology, technology limitations and physical limits, and other advanced concepts. RF sources included gyroklystrons, magnicons, free-electron masers, two beam accelerators, and gyroharmonic and traveling wave devices. Technology components discussed included advanced cathodes and electron guns, high temperature superconductors for producing magnetic fields, RF breakdown physics and mitigation, and phenomena that impact source design such as fatigue in resonant structures due to RF heating. New approaches for RF source diagnostics located internal to the source were discussed for detecting plasma and beam phenomena existing in high energy density electrodynamic systems in order to help elucidate the reasons for performance limitations.

INTRODUCTION

The Radiation Sources Working Group sessions consisted of eighteen short talks by working group members and discussion sessions on specific topics. Joint sessions were held with the working groups on Novel Structure-Based Acceleration Concepts (on W-band structure work and diamond coating) and Particle Beam Sources (on ferroelectric cathodes). Approximately one-third of the 15 hours of time spent in the working group sessions was dedicated to discussing specific topics of importance to advanced radiation sources and systems. Each discussion session had a designated leader to stimulate and guide the discussions.

The four discussion sessions explored the following questions and issues:

- What are the engineering and physics limitations to the generation of high power and high frequencies? Where should our R&D efforts be focused?

- Slow wave device scaling issues.

- What in-situ diagnostics could be useful for high power devices? Should there be a marriage between the high power conventional tube and the plasma physics communities?

- Fast wave device scaling issues.

The topical area discussions and the individual talks are individually summarized below.

DISCUSSION SUMMARY:
WHAT ARE THE ENGINEERING AND PHYSICS LIMITATIONS TO THE GENERATION OF HIGH POWER AND HIGH FREQUENCIES? WHERE SHOULD OUR R&D EFFORTS BE FOCUSED? SLOW WAVE DEVICE SCALING ISSUES.

This set of discussion topics, led by Danly, covered a number of subject areas. These areas are individually summarized.

Beam Confinement and Compression

As frequency increases RF sources generally shrink in size. The result is that beam power (beam voltage x beam current) needs to be confined to smaller crossectional areas in RF tubes. As beam size shrinks, we would like the beam power to remain high and incur no degradation in beam quality. The limitation in emission current density from thermionic cathodes to 5-20 A/cm^2 necessary to achieve reasonable cathode lifetimes consistent with reliable accelerator operation (greater than 50,000 hours) dictate that one use large cathode areas if high beam currents are needed. Therefore it is essential to do beam compression in the electron gun to get hundreds to thousands of amperes of beam with 10 A/cm^2 cathode loading. The questions arising are

- How does the maximum value of beam power decrease as operating frequency increases?

- What is the limit to area convergence in solid beam electron guns such as klystrons and magnicons? In annular beam guns such as magnetron injection guns (MIGs)?

In magnicons an area compressions of 3000 appears to be do-able, with 2300 actually demonstrated in Nezhevenko's 7 GHz magnicon at IAP. New magnicons at 11.4 and 34 GHz are being designed and built for 2500-3000 compression ratios. These beams are focused down to roughly 1-mm diameter, and in the case of the 11.4 GHz magnicon, represent a current density of 12 kA/cm^2. Gold's 11.4 GHz thermionic gun magnicon requires a 25 μm tolerance between the cathode and focus electrode. With a bias on the focus of 10^{-3} of the cathode voltage, this tolerance goes from 25 μm to 2000 μm.

In magnetron injection guns the limit appears to be around 25-40 because of pole tip saturation. Can these limits be pushed and if so how far? These limits are based on experience with thermionic cathodes. New cathodes currently under development could be better or worse in terms of beam quality and ultimate compression ratios. The evidence from this workshop is that very little development is occurring on advanced cathodes for microwave tubes. One exception is the PZT ferroelectric cathode work reported by John Nation, but this work is in its infancy.

Mode Competition

As tubes go up in power and as overmoded structures become more common, the problem of spurious modes competing with the desired mode for proper beam interaction becomes a serious issue. How can one avoid dipole modes in linear beam devices (e.g. BBU modes)? In practice it has been observed that tubes with gains in excess of 60 dB (such as Balakin's IAP 15 GHz klystron) have considerable difficulty achieving stable operation. High order modes need to be carefully suppressed and loaded-out. Designers need to employ suppression and loading in the drift tubes, cavities, and also external to the device. Non-magnetic stainless steel cavities and drift tubes have proven useful for mode suppression in numerous applications. Some of the experience with damping accelerator structures (Shintake cavity, SLAC damped/detuned NLCTA structure) should be examined for applicability to RF sources. It was suggested by Danly that perhaps a secondary beam could be introduced into the tube and tuned to the appropriate voltage to act as a load for suppression of undesired modes; or multi-beam tubes could place beamlets to achieve the desired mode selectivity. This suggestion is not a simple one to implement, but certainly causes one to think about the mode suppression problem in a new and different way.

Haimson provided some guidance for avoiding BBU modes. When building a circuit one should study the R and Q of the next 3 or so modes. When round trip time in a structure is ~1/2 ns, one needs to couple HOMs out from the ends. Other alternatives are to change the circuit geometry in a way to alter the growth of HOMs or to introduce HOM incoherence. Damping can also be added to the body of the circuit, the cavities, or the mode can be extracted in the drift tubes.

Annular Beams

Annular beams present a wealth of possibilities for the generation of extreme power levels, but need a lot more research. For one to consider 100's of megawatts to several gigawatts of RF out of a single tube, the use of an annular beam is practically a necessity. Much more beam power can be transported in an annular beam than in a solid beam of similar diameter without approaching the space charge limiting current. Approaching the space charge limiting current results in potential depression of the beam. In other words, since the total beam energy (kinetic + potential) must be constant, increasing the potential component means a reduction in kinetic energy. Since the kinetic is what is converted to microwave energy, the efficiency of the device can be strongly impacted by a large beam potential depression. Using a larger diameter annular beam (than a solid pencil beam) allows one to open up the structure bore resulting in a reduction in energy density in the structure.

Several interesting ideas were suggested:

- Why not marry the annular beam MIG with a linear interaction circuit?
- Are inverted MIGs a realistic approach? In this configuration the emitting surface is on the inside surface of the outer conductor. The cathode could be at ground potential and the center conductor anode could be pulsed positively.

There was a discussion of annular beams versus sheet beams. The relatively uncontroversial conclusion reached was that the annular configuration was preferable over the sheet. The principle reason cited was the higher tolerance of the annular geometry to misalignment. Mechanical misalignment of sheet beam guns tends to result in beam instabilities much more readily than annular beams.

Very high power single pulse klystrons have been demonstrated at Los Alamos (Fazio) and NRL (Friedman) with intense annular beams using explosive field emission cathodes. At Los Alamos, 475 MW in a long pulse (600ns) was produced. NRL produced around 3 GW in a much shorter (100 ns) pulse. These sources are not viable for accelerator applications as long as they employ explosive emission cathodes, but if these sources can be implemented with high quality, constant impedance, high current cathodes they become viable options for accelerator drivers.

Using an annular beam effectively lowers the perveance, or the perveance per square, of the beam. This is taken advantage of by CPI in building the high order mode Inductive Output Tube. This is a low peak power, high average power (~1MW) tube that uses a segmented annular cathode and hopes to reach 70% efficiency.

Fabrication Issues and Components

Submicron accuracy will be required for high frequency structures. For example the KEK cavity's tolerance is 0.5 μm at X-band. Tubes at 94 GHz have a tolerance of +/- 5 μm which results in a frequency tuning variation of 118 MHz. Electric discharge machining (EDM) may be a good fabrication approach and diffusion bonding needs to be considered as an alternative to brazing.

W-band components have an attenuation of 1 dB/ft and better ways to couple in and out of devices are needed. It was pointed out by Nusinovich that an extensive amount of work on HOM devices, couplers, etc., has been done by the fusion community for high peak power applications and we should not re-invent what has already been developed.

DISCUSSION SUMMARY:
WHAT IN-SITU DIAGNOSTICS COULD BE USEFUL FOR HIGH POWER DEVICE DEVELOPMENT? SHOULD THERE BE A MARRIAGE BETWEEN THE HIGH POWER CONVENTIONAL TUBE AND THE PLASMA PHYSICS COMMUNITIES?

The second discussion group led by Gold explored the topic of in-situ diagnostics for high power tubes that could be utilized to develop an understanding of problems like RF pulse shortening. Are there common problems shared between the high power conventional tube community and the high power microwave (HPM) community and are there any new approaches for solving them? Things that need to be measured include RF fields, plasmas, electrons, x-rays, and light (including the spectrum). Sophisticated spectroscopy techniques, such as measuring Stark shift, is being done by Carmel at the University of Maryland. It was noted that intense photon generation that accompanies high power beams could dramatically reduce RF breakdown voltage levels. Possible causes of pulse-shortening were discussed including time dependent beam parameters such as cathode plasma expansion, field emission and breakdown in the microwave circuit, plasma loading of cavities or slow-wave structures by gas desorption and multipactor, space charge buildup by trapping of low-energy electrons, growth of parasitic modes, and beam disruption caused by instabilities, ExB drift, or halo formation. Pulse shortening may be mitigated by: good vacuums; proper choices of materials, fabrication techniques, and vacuum processing such as sputter cleaning and high temperature bakeout; RF conditioning of the circuit; designing to limit RF fields at surfaces; and suppression of BBU and other HOM modes.

DISCUSSION SUMMARY:
FAST WAVE DEVICE SCALING ISSUES

The final discussion group led by Fazio covered fast wave device topics including limits to device power and efficiency at the higher frequencies of 35 and 90 GHz. Other topical questions included the phase stability of fast-wave devices, pulse heating, and the adequacy of current design tools. More questions were raised than

were answered and many of the questions can provide directions for future research. The question was posed that if higher order modes such as the 28, 8 mode work well for gyrotron oscillators, why won't they work for amplifiers as well? Can a gyroklystron run at the 4th harmonic?
Can an FEL compete with a gyrotron at millimeter wavelengths? It was stated that MAGY is a better code than it was 10 years ago and is pretty good now.

Goals were discussed and it was a consensus that 100 MW at 35 GHz is a good one for the community. Sources are also needed for testing structures at 90 GHz and some effort should be put on meeting this need.

PRESENTATION SUMMARIES

RF Sources

RF source development has experienced significant recent progress. Gyroklystrons and magnicons in particular have demonstrated very encouraging results. The gyroklystron effort at the University of Maryland led by Lawson has resulted in both designs and experiments over the impressive range of 8 to 95 GHz. Gyroklystrons scale favorably to higher frequencies. The linear dimensions scale ~ λ, the magnetic compression as ~ $(\lambda)^{-2/3}$, and the cathode loading as ~$(\lambda)^{-1/3}$. Because TE_{0np} modes have zero surface electric fields, peak electric fields leading to breakdown are not an issue. Peak power scales ~ λ as long as the magnetic compression limit is not exceeded (~ 40) and the cathode loading is not exceeded.

The X-band (8.6 GHz), first harmonic, three cavity coaxial gyroklystron has produced 75 MW at X-band. Castle described a 2nd harmonic tube at 17 GHz with one buncher cavity that was tested with an output of 100 MW. This tube was gain limited so the design was improved by adding a second bunching cavity. A 2nd harmonic, three cavity coaxial design about to undergo testing seeks to produce 150 MW at 17GHz with a beam voltage of 500 kV and current of 770 A at 41 % efficiency. The magnetic compression ratio in the magnetron injection gun is 9x. A 35 GHz, 60 MW, 40 % efficiency design is being developed that is scaled from the 17 GHz/150 MW design. Beam voltage and current are 500 kV and 300 A.

For high rep-rate operation at 17 GHz, Xu described a new design with several dramatic innovations including a triaxial input system. In order to obtain the high mode purity of a TE_{011} mode in the overmoded X-band input cavity while maintaining high coupling efficiency, a coaxial dual-cavity input structure with an outer TE_{411} mode and an inner TE_{011} mode coaxial cavity has been designed to get a low Q while avoiding mode distortion from the coupling aperture between the input waveguide and the input cavity. There are four coupling slots between the gyroklystron input cavity and the coupling cavity. The design uses two buncher cavities and a 4th harmonic penultimate cavity. The coaxial TE_{021} output cavity employs radial extraction into the inner conductor that is designed to convert the TE_{02} mode to the TE_{01} in coaxial waveguide.

Aryona presented a design for a 94 GHz, three-cavity cylindrical 8 MW gyroklystron that should produce a peak power of at least 100 times the current state of the art. The design approach is to scale the MIG and circuit design of an experimentally successful 20 GHz, two-cavity, 2nd harmonic tube. The beam power and cavity dimensions are scaled proportional to wavelength to 95 GHz. This tube has a predicted gain of 52 dB and 34% efficiency with three cavities and a 9-cm-length. The voltage is 500 kV and the current is 45 A.

Progress on magnicon development has also been encouraging. Nezhevenko reported that the Budker INP 7 GHz 2nd harmonic magnicon has produced 55 MW with 72 dB of gain and an efficiency of 56% operating at a 3 Hz rep-rate with a 1.1 μs pulse length. A beam area compression of 2300 is used. A 34 GHz, 3rd harmonic, 45 MW magnicon is in the design phase with a 3000:1 beam compression, 55 dB gain, 1.5 μs pulse length, and a 10 Hz PRF. The beam diameter is 0.8mm and the output cavity has a 2.3 T magnetic field. The cathode loading has been kept to 15 A/cm^2 and peak surface $E < 800$ kV/cm. To avoid mechanical stress, the temperature rise due to pulse heating of the conductor walls is kept to < 150 C.

Gold described the project underway at the Naval Research Laboratory that is preparing to test a 2nd harmonic 11.4 GHz magnicon with a thermionic cathode. The voltage is 500 kV and the current is 600 A. Projected peak power is 63 MW. The beam radius is 0.75 mm with a compression ratio of 2500:1 and a current density of 12 kA/cm^2. Litton built the high convergence electron gun. The tube is designed for a 10 Hz PRF, 62 dB gain, and 60% efficiency.

Schachter presented a theoretical investigation of a 35 GHz TWT amplifier that had the aperture diameter comparable to an X-band structure. This results in a high group velocity and low interaction impedance. The lower impedance requires a longer interaction length which leads to a higher sensitivity to beam quality, but at the same time lowers the probability of electrons hitting the structure's walls. In comparing the performance of two amplifiers, one at 35 GHz and one at X-band, the sensitivity of the former to beam quality is higher but its operation is feasible.

LaPointe discussed experiments involving the generation of harmonic radiation from a 300 kV electron beam produced by a cyclotron autoresonant accelerator (CARA). A TE_{411} cavity tuned to the fourth harmonic of the CARA drive frequency (11.4 GHz) has produced 0.5 MW. Beam quality and mode competition are major obstacles to generating the expected 3.5 MW at X-band. A third harmonic experiment is underway using a TE_{311} cavity tuned to 8.5 GHz which shows only the TE_{311} spectrum on a 3.3 MW beam. The theoretical efficiency estimates are 25 to 45% depending on beam quality with up to 3.6 MW possible under optimum conditions from a 9.2 MW beam.

Gyrating electrons can excite standing waves in resonators. Nusinovich described a double resonance condition that can exist in relativistic gyrodevices because the standing wave consists of the superposition of forward and backward waves that have opposite Doppler shifts of the operating frequency in the moving electron frame of reference. Therefore for certain axial wavenumbers both forward and backward waves can simultaneously be in cyclotron resonance with gyrating electrons at different cyclotron harmonics. In the case of azimuthally symmetric modes the efficiency of the double resonance interaction can be higher than in the case of a single resonance. With non-symmetric modes the efficiency is always lowered.

Fazio presented results on a 17 GHz free electron maser amplifier experiment. The experimental goal was several hundred MW at 17 GHz with phase stability. The 6.5-cm-dia, 8-mm-thick intense annular electron beam supplied by an explosive field emission cathode was 600 kV and 5 kA. A 6-port input structure was used to couple input power into the rippled wall structure to modulate the beam for the FEL interaction. At full beam current it proved impossible to produce a stable interaction. The RF input drive power coupled into the tube disappeared when the electron beam was injected. The reason for this phenomenon was undetermined. When the beam current was reduced to 1.5 kA by an aperture placed in the drift tube, a phase stable interaction was observed, although the power level was only a few megawatts. The performance of the tube would probably benefit from the availability of a constant impedance thermionic electron gun and a better understanding of intense annular beam physics. Further work is needed to evaluate the potential of the free electron maser.

Bogacz discussed a scheme for generating electromagnetic radiation in the ultraviolet and x-ray regions using a relativistic beam of hydrogen-like ions having a single bound electron in which a population inversion is achieved by the application of laser radiation tuned to the Doppler-shifted 1s to 2p transition. When the laser beam and ion beam are moving in opposite directions the required pump laser frequency is reduced by a factor of 2γ (for example in the infrared). Subsequently short wavelength radiation moving in the same direction as the inverted population ion beam will be amplified by stimulated emission. The emitted radiation in the laboratory frame is shorter than the original laser wavelength by a factor of $1/(2\gamma)$.

The relativistic klystron two-beam accelerator (RK-TBA) prototype was described by Westenskow. The challenge in this effort is in the propagation of the drive beam over long distances through multiple extraction sections. A 1 MeV, 1.2 kA, electron induction prototype injector is under construction with a 3.5-in-dia, flat surface, thermionic cathode. The pulse length flat top is 150 ns with 1% energy variation. The flat cathode is used to achieve a lower emittance because with a curved cathode the emission is lower in the center because of the lower voltage seen by the beam causing the emittance to rise. The RK-TBA approach scales favorably to 30 GHz and the wall-plug efficiency for a 5 TeV design appears to be in the range of tens of percent. Also described was the new TBA approach recently developed by the CERN Linear Collider group. The novelty lies in storing the energy for RF production in the form of a long-pulse electron beam that is efficiently accelerated to 1.2 GeV by a fully loaded, conventional linac operating around 1 GHz. The beam pulse length is about two times the length of the high–gradient linac. Portions of the drive beam are compressed using combiner rings to generate a sequence of higher peak power drive beams with gaps between them. The train of drive beams is appropriately distributed to low impedance decelerator structures where the drive beam energy is converted to RF power which is used to accelerate the high-energy beam in the main high-gradient linac.

While resonant ring systems have enabled the high peak power testing of specialized waveguide components, the testing of high gradient accelerating structures and the investigation of coupler cavity RF breakdown at very high peak powers has been limited by the availability of suitable 200 to 300 MW RF test facilities. Haimson described a compact, economical, high peak power amplification system based on a dual hybrid bridge configuration that eliminates the need for power splitters at the accelerator dual feed couplers and also provides a convenient interface for installing high gradient accelerator test structures. Using a 75 MW, 1/2 μs RF source, and two hybrid bridges, one can produce a 280 MW, 1/4 μs pulse for testing dual feed traveling wave accelerator sections. An additional benefit is that the RF source always sees a matched load.

Pulse Compression

The high peak power per meter in short pulses required by linear colliders and the limitations of microwave sources such as klystrons to deliver that power has led to the development of pulse compression technology. These schemes allow one to store a lower peak power from the source over a longer time (1-2 μs) and then switch it to the accelerator in a pulse that is a hundred or so nanoseconds long with a peak power level many times higher (3x-8x) than the klystron output. Important parameters of pulse compression schemes are pulse flatness and efficiency.

Vikharev described an approach at IAP which stores the energy in oversized Bragg resonators operating in the axially symmetric TE_{0m} modes in circular waveguide. The use of Bragg reflectors allows one to use oversize waveguide resonators while retaining control of the spatial mode structure. Electrically controlled gas discharge tubes in the output Bragg reflector are used to switch the stored energy to the load. Demonstrated parameters are 100 MW, 100 ns output at 11.4 GHz, 60% efficiency and power gain of 17. The waveguide storage section is 1.5 m long. Phase stability needs to be measured.

An alternative approach by Tantawi uses a delay line distribution system (DLDS), rather than compressing pulses in time,. This approach reduces the length of cylindrical waveguide for the NLC from 560 km for SLED II pulse compression to 115 km. The power of several klystrons (for example, eight) can be combined into a single delay line using a multi-mode launcher. The output mode of the launcher is determined by the phase coding of the klystron output power signals. The combined power is extracted at the appropriate places along the linac using several mode extractors. Each extractor extracts only a single mode. Hence the phase coding of the klystrons determines which output mode converter is employed at any given time. The DLDS allows pulses, much shorter than the klystron output pulse length, to be time multiplexed down the length of the linac to particular accelerating sections. A 600 MW peak power system has been designed. In conjunction with the DLDS a high power phase shifter/switch has been designed using a series of six three-port networks. The active element is the switch is a silicon wafer, which can be optically switched using a short pulse laser.

Pulse Heating in Structures

Nezhevenko presented a discussion on RF induced pulse heating and the resultant mechanical stress induced in the 3 to 20 μm surface layer of the conductor. Once pulse heating exceeds a "safe" temperature determined by the elastic limit, coefficient of linear expansion, and Young's modulus, plastic deformation occurs which leads to accumulation of defects causing destruction of the surface after some number of pulses. The destruction has been observed in microwave tube collectors. Calculations indicate that temperature rises of several hundred degrees C, at frequencies above 45 GHz, can reduce structure lifetimes to hours or even minutes. These issues need to be carefully considered when designing high peak power devices, especially at high frequencies.

High Temperature Superconductor Progress

Fortgang provided a brief review of high temperature superconductor (HTSC) technology. Since most microwave power tubes require some type of magnetic field, the availability of HTSC magnet technology could greatly impact the viability of particular RF sources for advanced accelerator applications. The state of HTSC technology is such that in ten years we will probably be using HTSC magnets equivalent to copper magnets currently operating at 1 kA/cm^2. HTSC YBCO ribbon with dimensions of 2.0-μm-thick by 1-cm-wide by 83 cm long is now operating at 210 A, which corresponds to a current density of 2.1 MA/ cm^2. Researchers are working with industrial partners to develop commercial fabrication methods for producing long lengths of the tape. Danly noted that closed-cycle cryocooled magnets with no cryogenic liquids are commercially available that use about 1 kW in steady state. He also noted that PPM focused coupled cavity TWTs at 94 GHz are commercial products.

SUMMARY

The Radiation Sources Working Group had some lively discussions on a wide variety of topics. Some of these discussions and topics may provide issues for the next Advanced Accelerator Concepts Workshop to delve into in two years. Several sources, particularly the gyroklystron and the magnicon have shown considerable progress in the last several years and their futures look bright. A number of other source concepts look interesting, but need further investigation and development to establish their feasibility for accelerator applications. These sources include: the two beam accelerator and the ability to do multiple extraction and reacceleration; the free-electron maser and the ability to generate high power with phase stability and efficiency; high order mode concepts such as a high harmonic gyroklystron and very high order (such as 28,8) gyro-amplifier devices. Breakdown in components is a problem that requires more development and testing. Annular beams may prove to be very useful for future very high power tubes but much R&D is needed on generating and transporting intense annular beams and understanding the beam physics and the impact on tube performance.

Experimental efforts should focus on producing 100-200 MW at 35 GHz and designs should be developed for 90 GHz. A 1 MW source for testing components and structures at 90 GHz is needed. The Working Group believed that the accelerator structure people and RF source people should be more closely integrated. This could be useful for helping to address some of the accelerator issues such as frequency choice, and for applying microwave solutions to problems such as energy spread compensation in the final focus.