相对论返波管研究进展

西北核技术研究所

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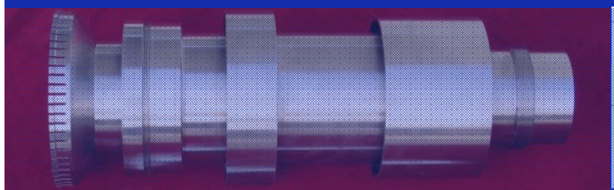
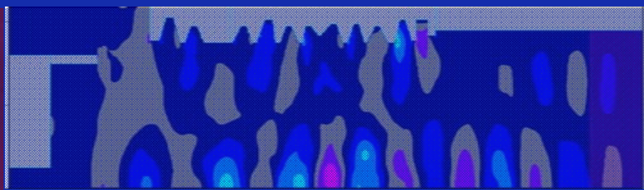
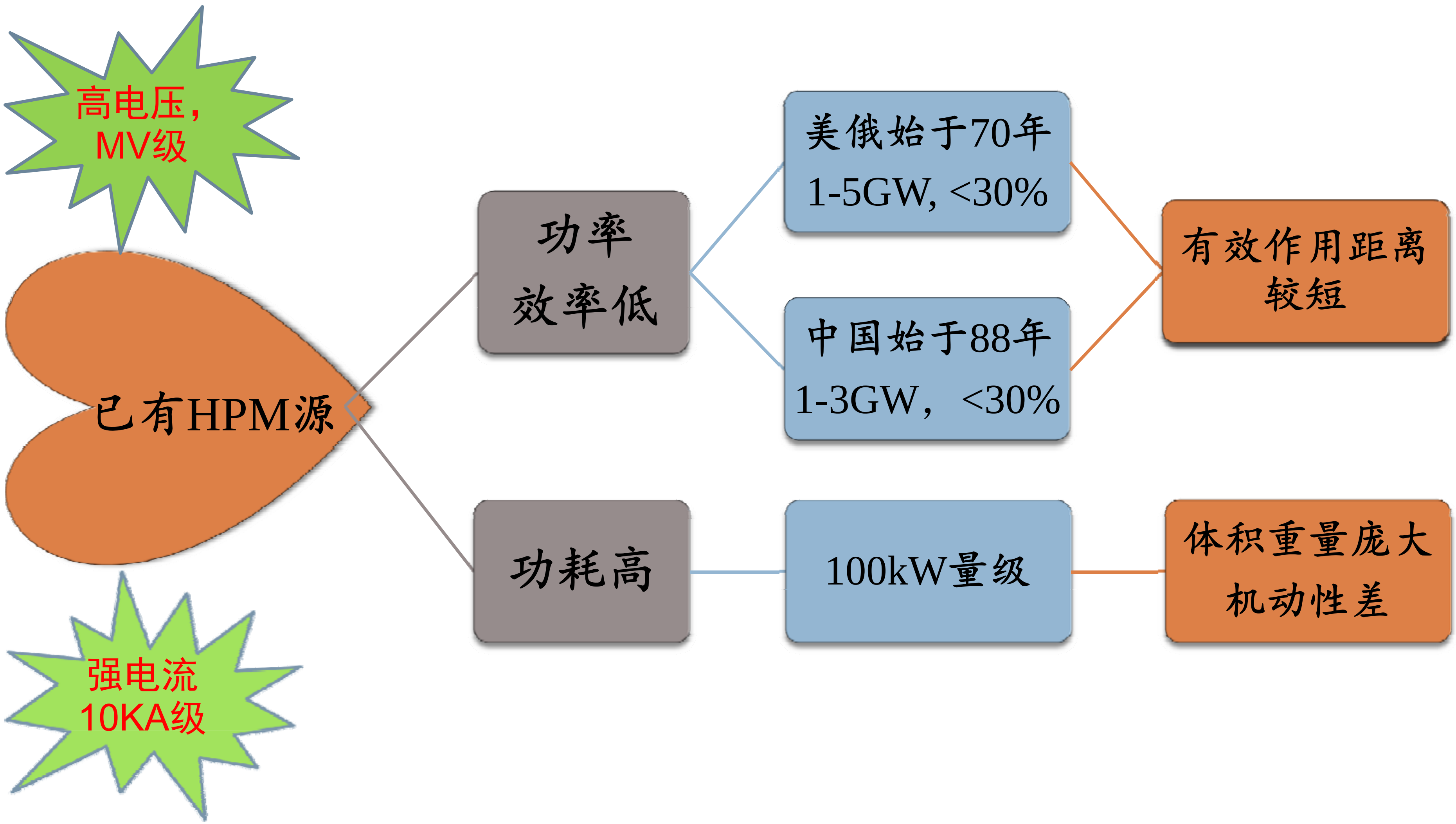



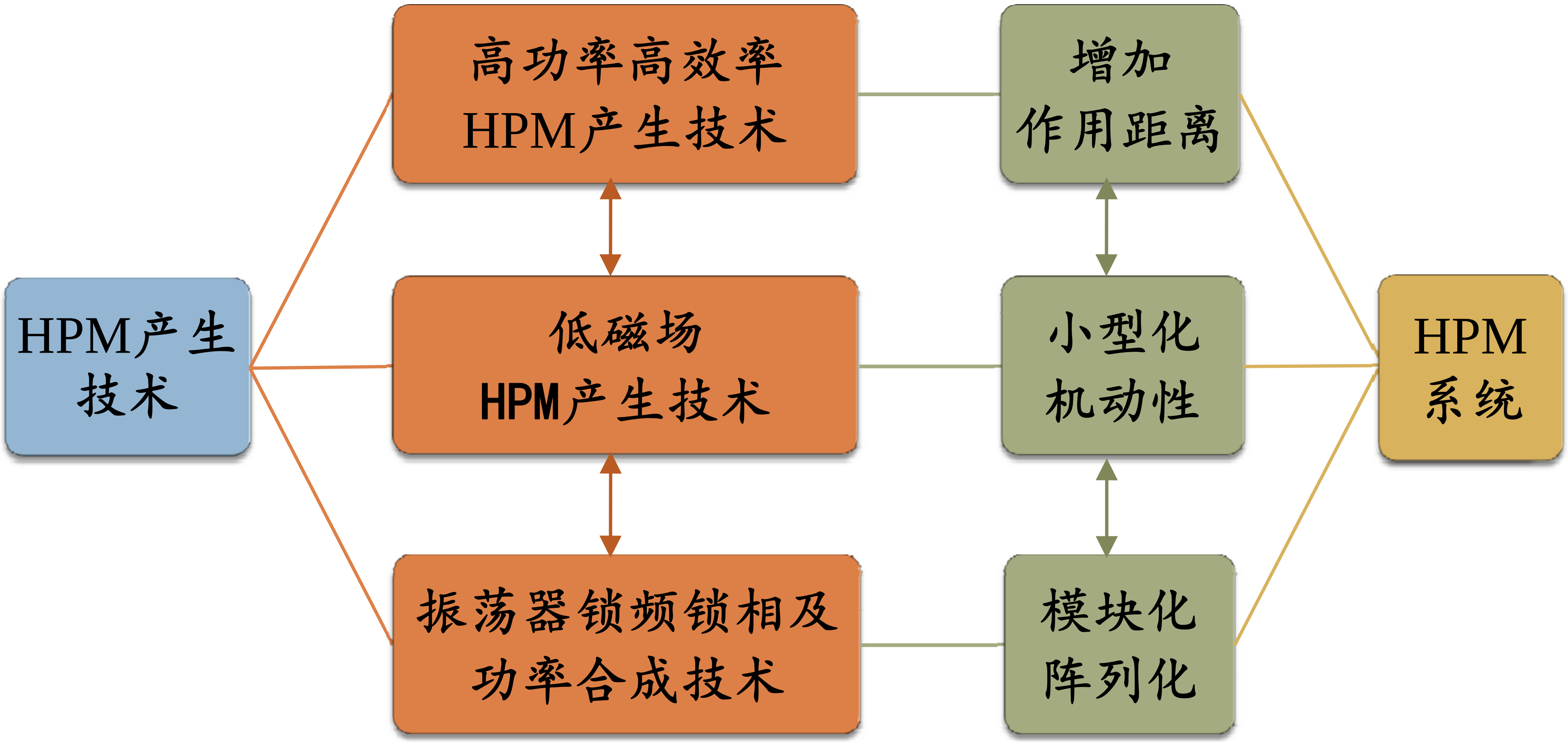

报告内容

- 一 研究背景
- 二 速调型RBWO
- 三 双模工作RBWO
- 四 牵引锁相RBWO
- 五 总结展望

一. 研究背景


高电压，
MV级
强电流
10KA级
已有HPM源
功率
效率低
功耗高
美俄始于70年
1-5GW, <30%
中国始于88年
1-3GW，<30%
100kW量级
有效作用距离
较短
体积重量庞大
机动性差

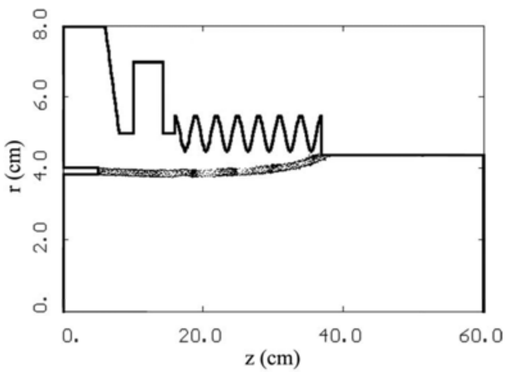
一. 研究背景


高功率高效率
HPM产生技术
增加
作用距离
HPM产生
技术
低磁场
HPM产生技术
小型化
机动性
HPM
系统
振荡器锁频锁相及
功率合成技术
模块化
阵列化

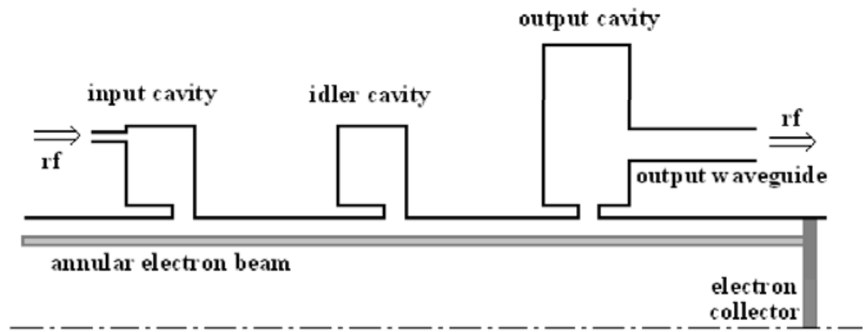
二. 速调型RBWO

- 两类主要的HPM源：同时获得高功率和高效率是一个国际性难题。

器件类型	工作机制	功率容量	效率
相对论返波管	切伦科夫辐射	较高	<30%
相对论速调管	渡越辐射	较低	30-40%



相对论返波管



相对论速调管

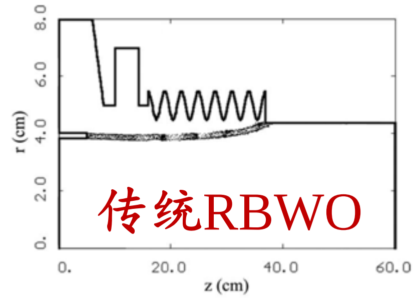
二. 速调型RBWO

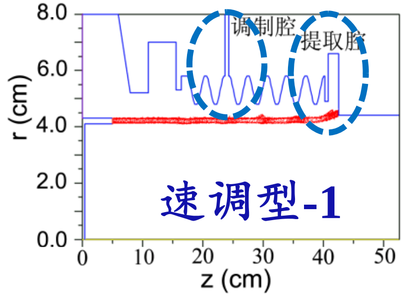
- 效率三要素：调制电场、谐波电流以及二者之间的相位。

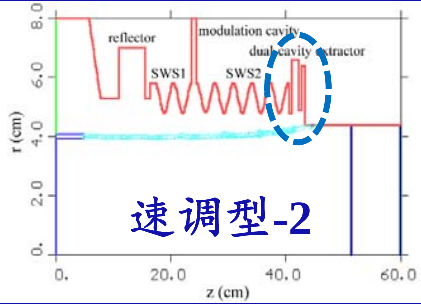
$$\eta \propto \int_0^L \left(E_z I_1 \cos\delta \right) dz \Big/ \left(U_0 I_0 \right)$$

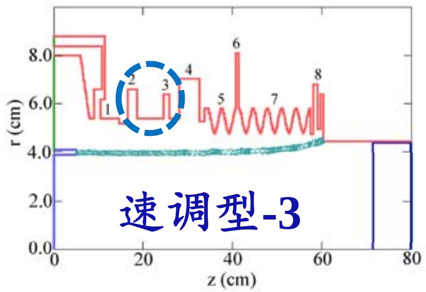
- 创造性地提出**切伦科夫辐射和渡越辐射混合产生HPM的新原理**，发明了速调型相对论返波管(RBWO)。

二. 速调型RBWO



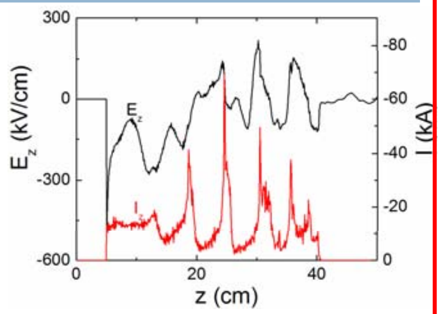


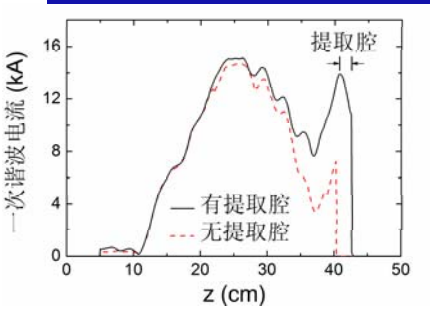


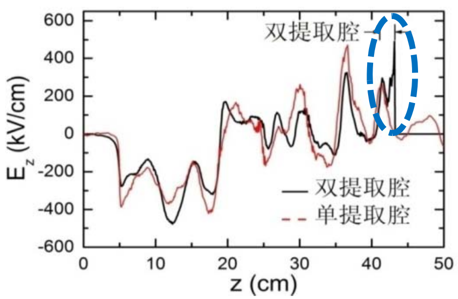


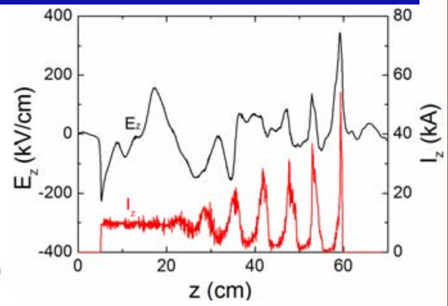
电流电场小

提高谐波电流　增大调制电场　改善相位匹配









切伦柯夫辐射

切伦柯夫辐射+渡越辐射

传统RBWO
20-30%

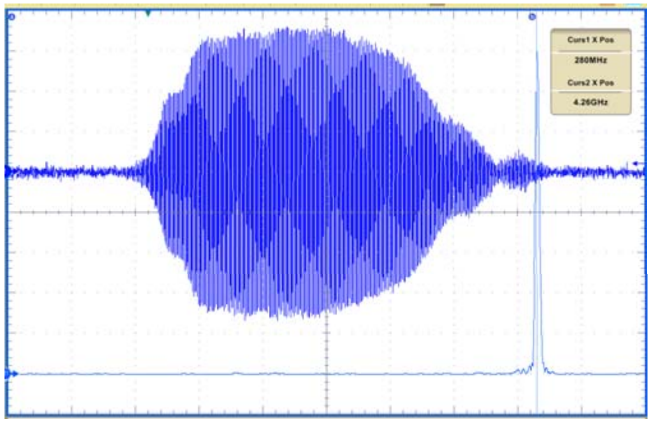
调制腔
提取腔
40-50%

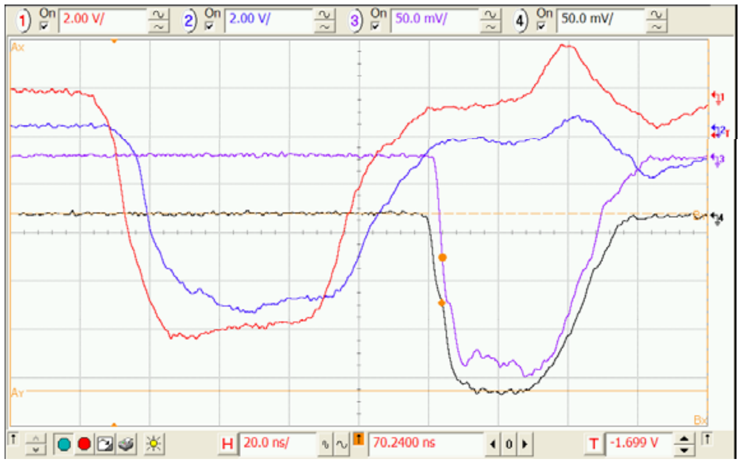
双提取腔
50-60%

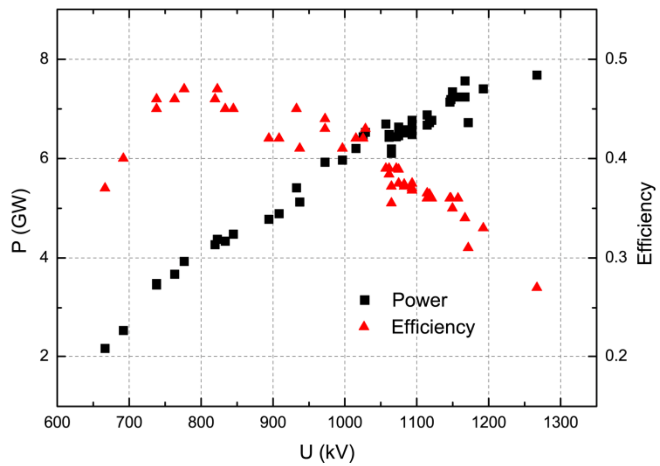
双预调制腔
60-70%

二. 速调型RBWO

- C波段实验：**>6.5GW, 最高效率47%**

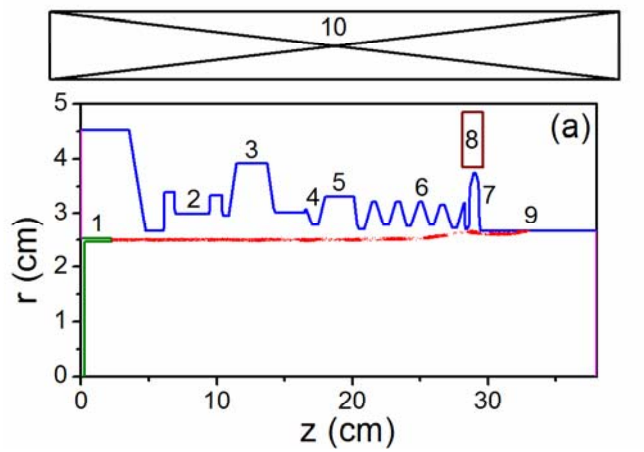


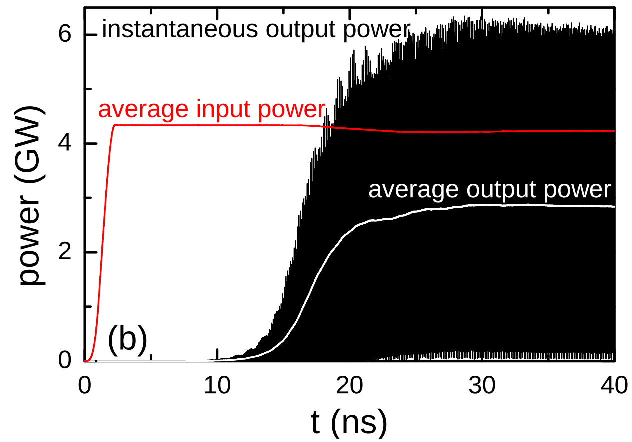


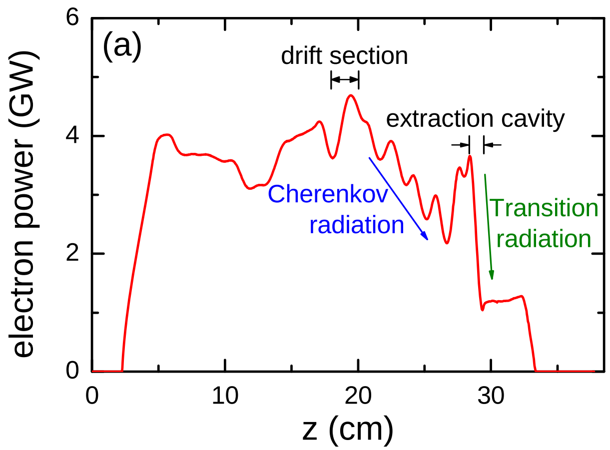


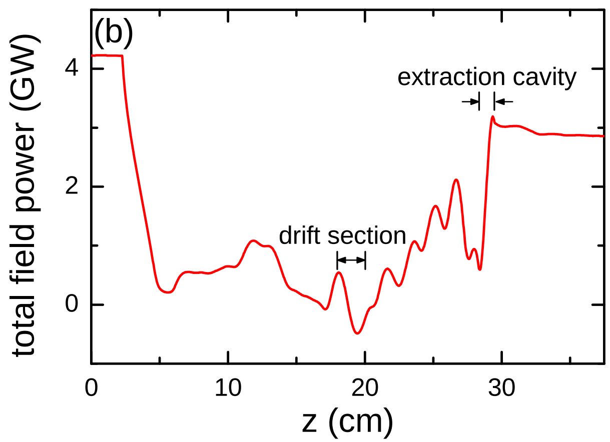
二. 速调型RBWO

- X波段超速调型RBWO：通过电子束后加速将切伦科夫辐射转化成渡越辐射。





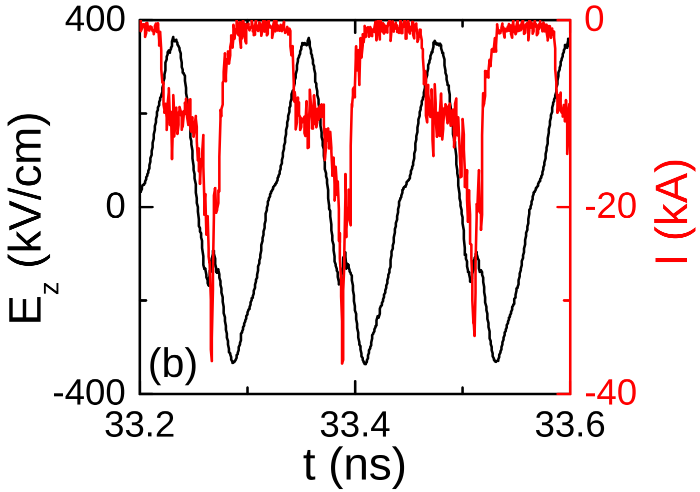




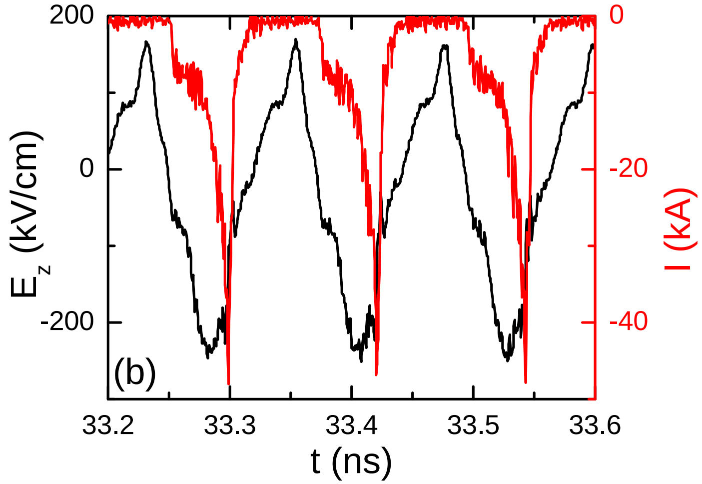
二. 速调型RBWO

- 轴向电场和瞬时电流分布

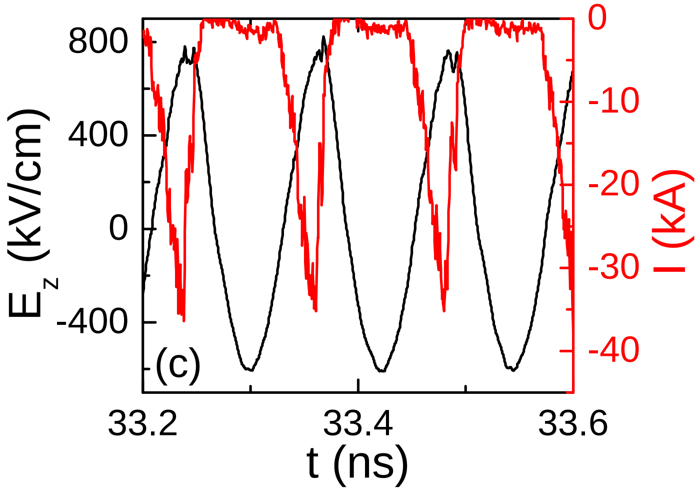
C点

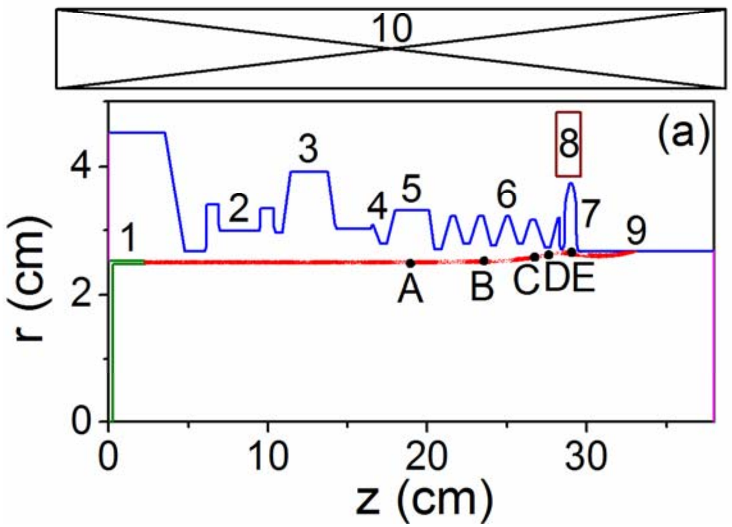


D点



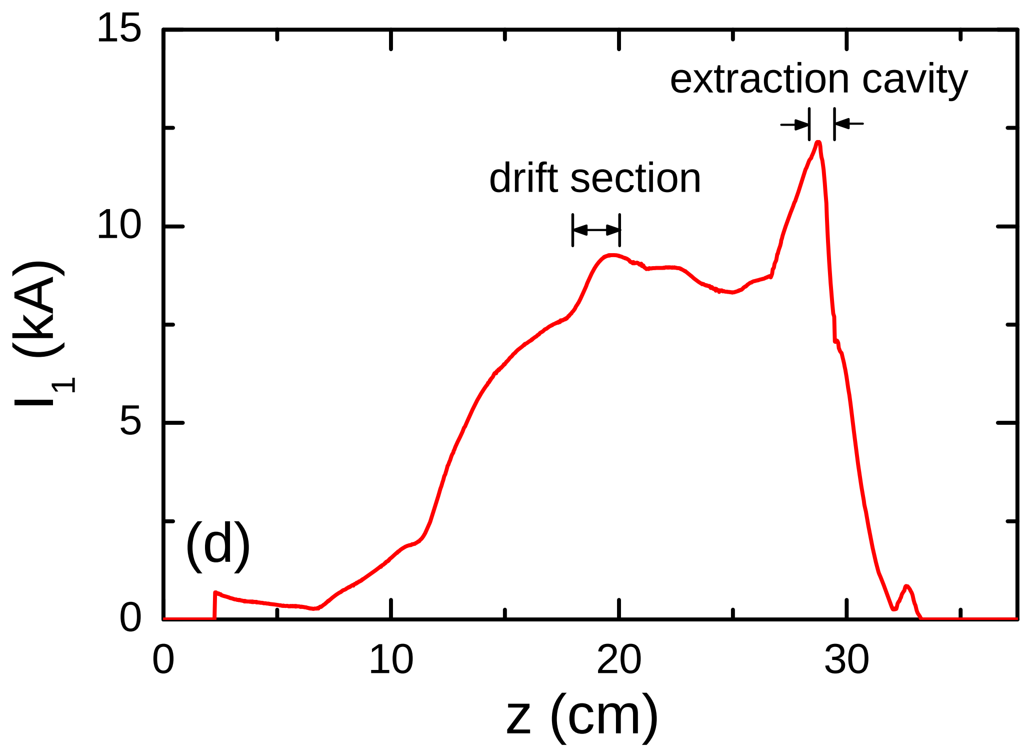
E点





二. 速调型RBWO

- 谐波电流分布



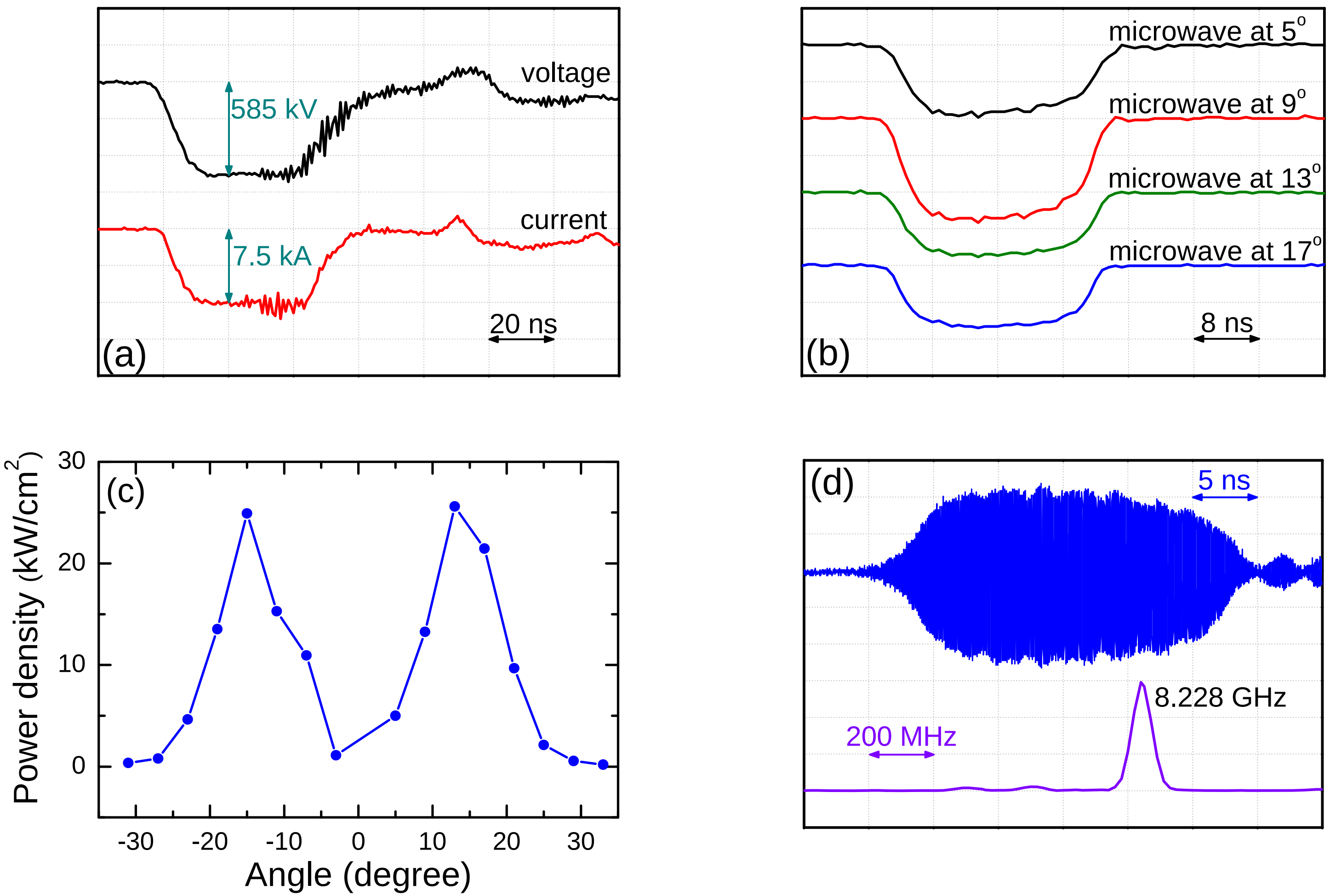
在最后一个慢波结构处快速上升，在提取腔处达到最大

二. 速调型RBWO

- X波段超速调型RBWO

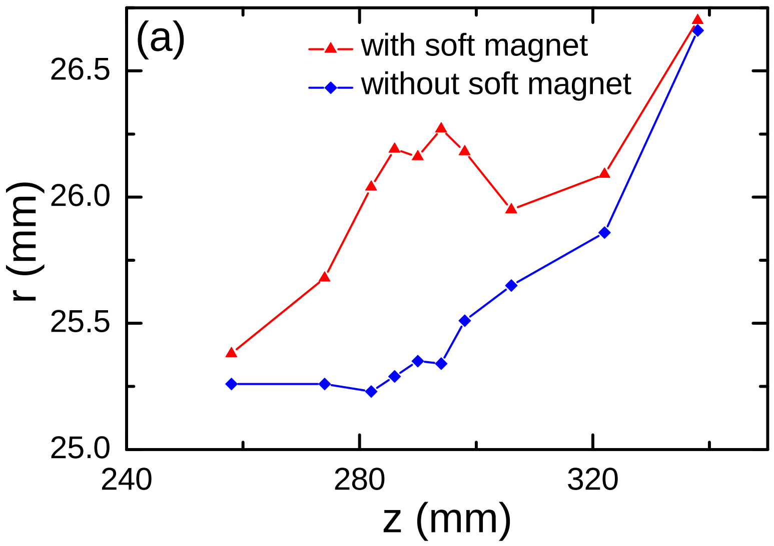
二. 速调型RBWO

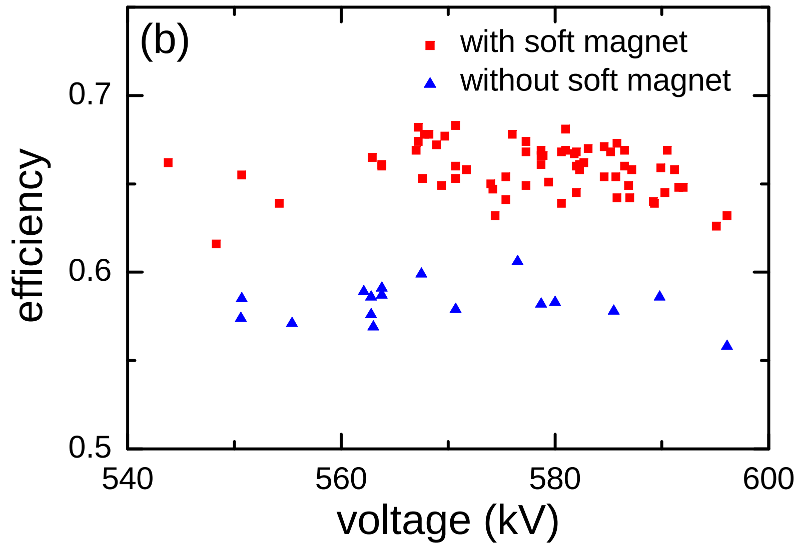
- 585kV, 7.5kA, 2.9GW, 22ns, 66%, 8.228GHz.



二. 速调型RBWO

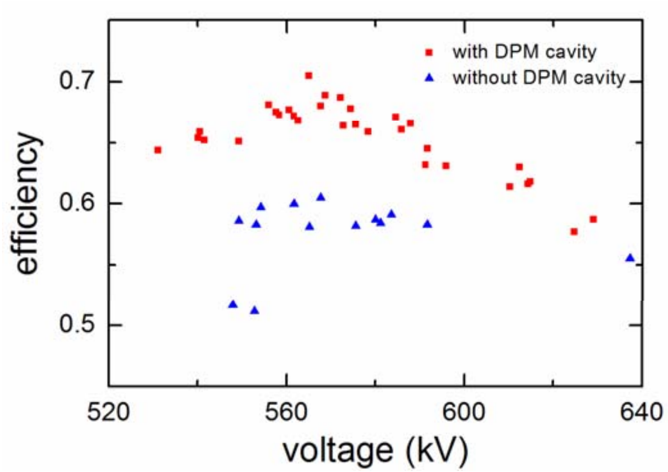
- 有无软磁体时的电子束位置和束波转换效率

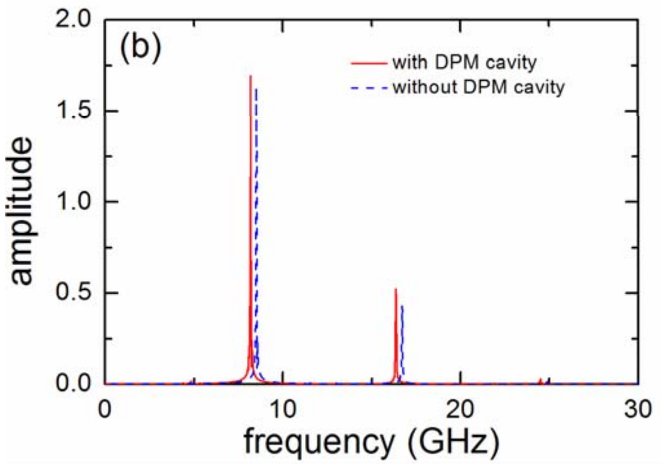


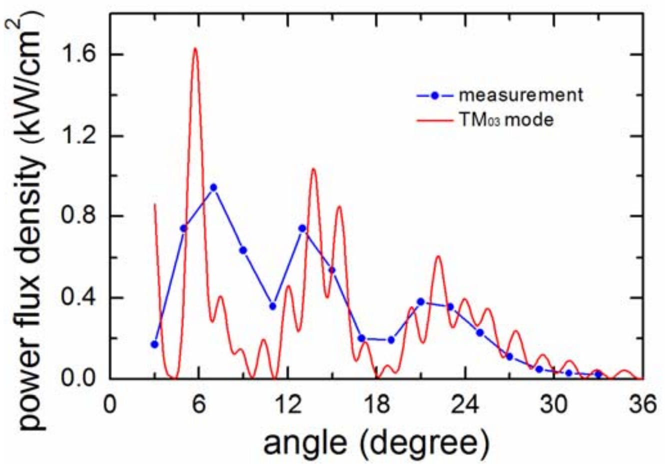


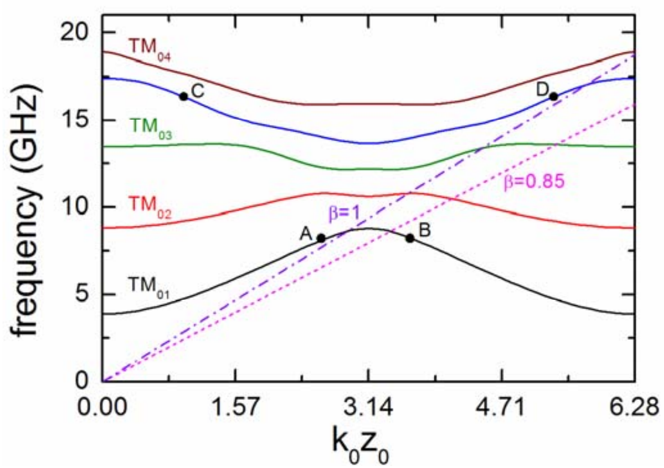
二. 速调型RBWO

- 有无双调制腔时的束波转换效率



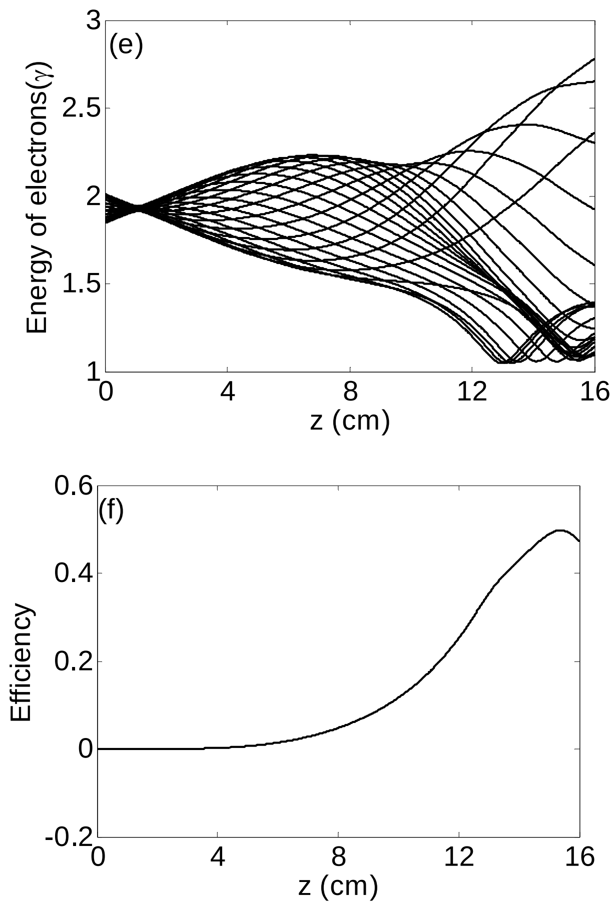




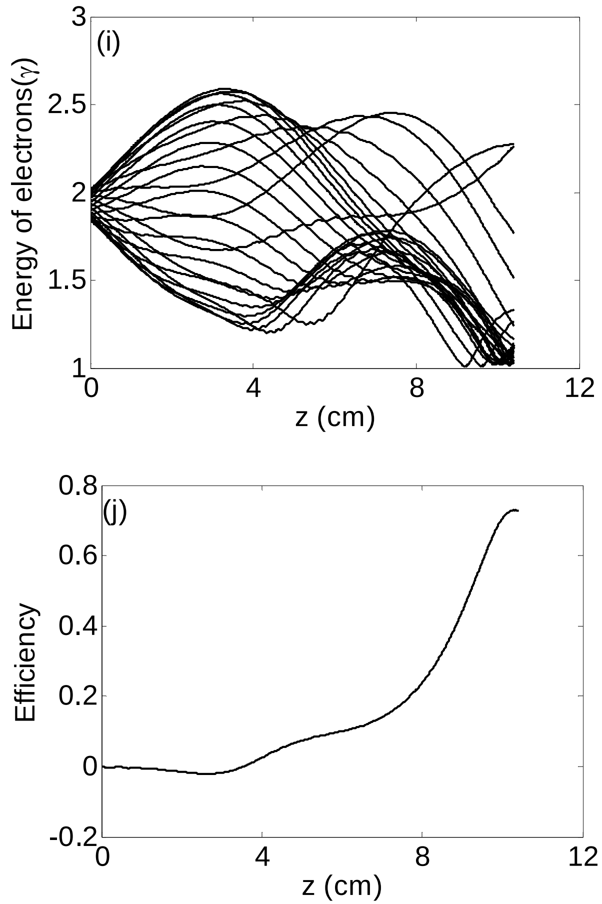


二. 速调型RBWO

□ 能量和效率变化



仅考虑基波



考虑基波和二次谐波

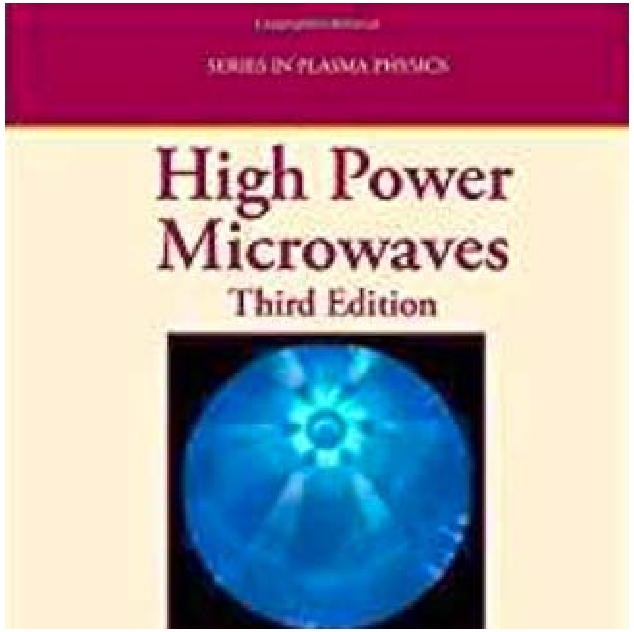
二. 速调型RBWO

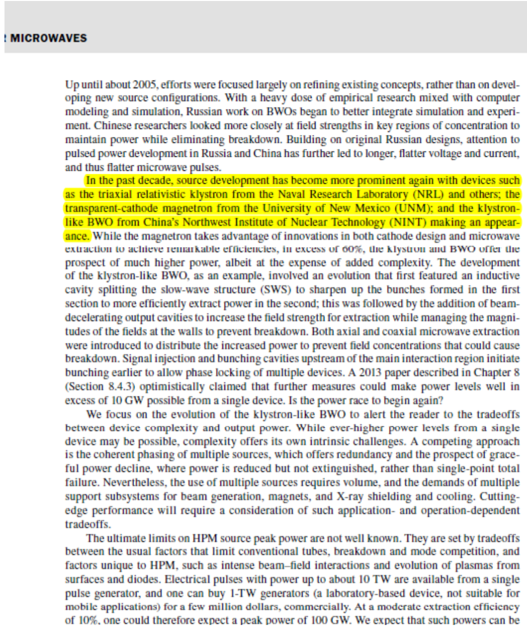
本学科经典著作：

James Benford: IEEE Fellow, EMP Fellow

John A. Swegle: 美国萨凡纳河国家实验室国家安全局高级顾问科学家

Edl Schamiloglu: IEEE Fellow，新墨西哥大学杰





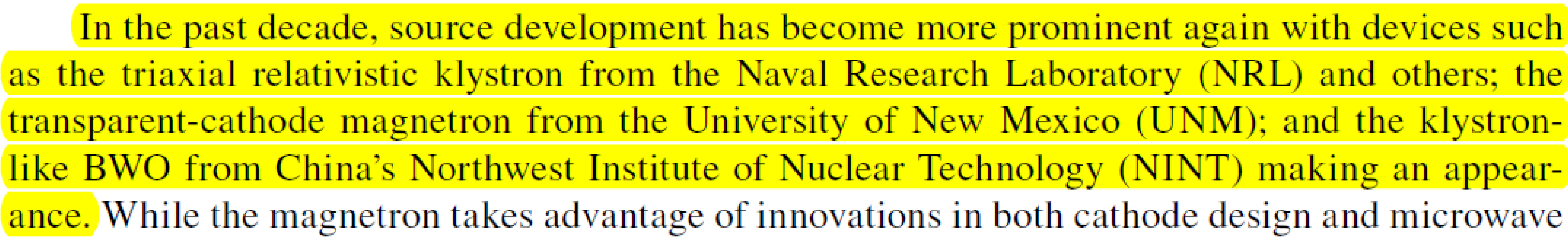
MICROWAVES

Up until about 2005, efforts were focused largely on refining existing concepts, rather than on developing new source configurations. With a heavy dose of empirical research mixed with computer modeling and simulation, Russian work on BWOs began to better integrate simulation and experiment. Chinese researchers looked more closely at field strengths in key regions of concentration to maintain power while eliminating breakdown. Building on original Russian designs, attention to pulsed power development in Russia and China has further led to longer, flatter voltage and current, and thus flatter microwave pulses.

In the past decade, source development has become more prominent again with devices such as the triaxial relativistic klystron from the Naval Research Laboratory (NRL) and others; the transparent-cathode magnetron from the University of New Mexico (UNM); and the klystron-like BWO from China's Northwest Institute of Nuclear Technology (NINT) making an appearance. While the magnetron takes advantage of innovations in both cathode design and microwave extraction to achieve remarkable efficiencies, in excess of 60%, the klystron and BWO offer the prospect of much higher power, albeit at the expense of added complexity. The development of the klystron-like BWO, as an example, involved an evolution that first featured an inductive cavity splitting the slow-wave structure (SWS) to sharpen up the bunches formed in the first section to more efficiently extract power in the second; this was followed by the addition of beam-decelerating output cavities to increase the field strength for extraction while managing the magnitudes of the fields at the walls to prevent breakdown. Both axial and coaxial microwave extraction were introduced to distribute the increased power to prevent field concentrations that could cause breakdown. Signal injection and bunching cavities upstream of the main interaction region initiate bunching earlier to allow phase locking of multiple devices. A 2013 paper described in Chapter 8 (Section 8.4.3) optimistically claimed that further measures could make power levels well in excess of 10 GW possible from a single device. Is the power race to begin again?

We focus on the evolution of the klystron-like BWO to alert the reader to the tradeoffs between device complexity and output power. While ever-higher power levels from a single device may be possible, complexity offers its own intrinsic challenges. A competing approach is the coherent phasing of multiple sources, which offers redundancy and the prospect of graceful power decline, where power is reduced but not extinguished, rather than single-point total failure. Nevertheless, the use of multiple sources requires volume, and the demands of multiple support subsystems for beam generation, magnets, and X-ray shielding and cooling. Cutting-edge performance will require a consideration of such application- and operation-dependent tradeoffs.

The ultimate limits on HPM source peak power are not well known. They are set by tradeoffs between the usual factors that limit conventional tubes, breakdown and mode competition, and factors unique to HPM, such as intense beam–field interactions and evolution of plasmas from surfaces and diodes. Electrical pulses with power up to about 10 TW are available from a single pulse generator, and one can buy 1-TW generators (a laboratory-based device, not suitable for mobile applications) for a few million dollars, commercially. At a moderate extraction efficiency of 10%, one could therefore expect a peak power of 100 GW. We expect that such powers can be



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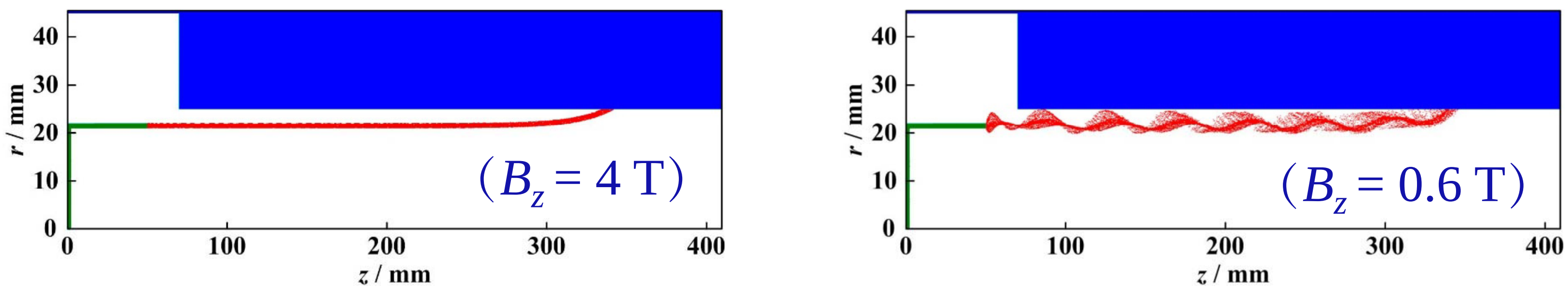
将速调型相对论返波管与美国NRL的三轴相对论速调管和UNM的透明阴极磁控管并列为过去十年出现的三大杰出成果。

三. 双模工作RBWO

- 现有X波段RBWO需超过4T的强磁场，磁体系统耗能巨大，同时体积重量庞大，不利于系统的实际应用。
- 降低引导磁场具有迫切需求。但近20年来低磁场HPM源功率和效率偏低，已成为瓶颈问题。
- 传统观念：低磁场下电子束包络增大，不利于束波作用。传统思路：提高电子束品质。效果：不显著。



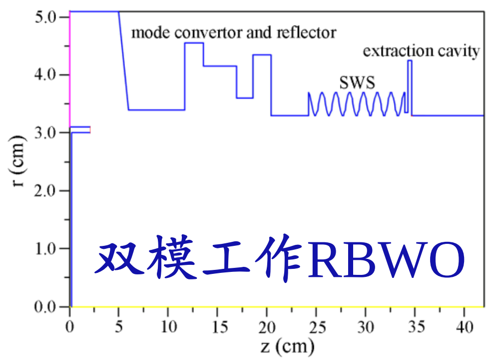
新思路：能否利用包络大的特点？

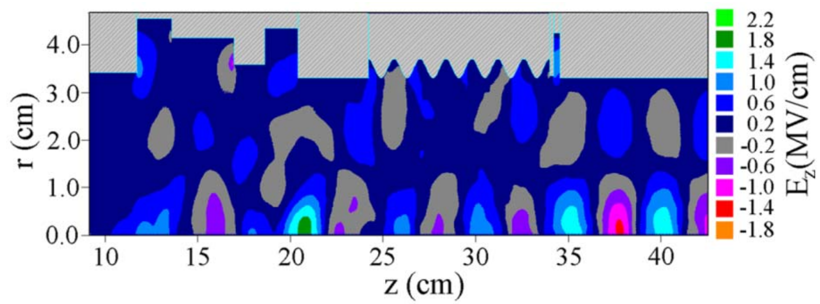
三. 双模工作RBWO

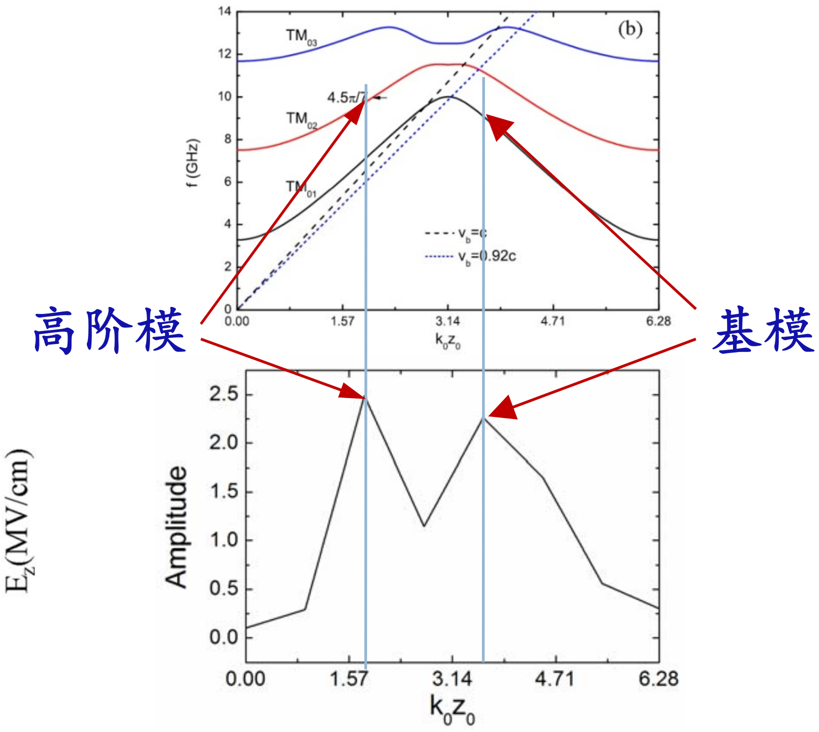
- 提出了*双模工作新机制*：电子束与基模和高阶模同时相互作用。

基模：表面波，与大半径电子作用；高阶模：体波，与小半径电子作用。

- 与单纯基模的过模器件相比，效率提高了60%，
- 高阶模的体波特性，功率容量提高了50%。

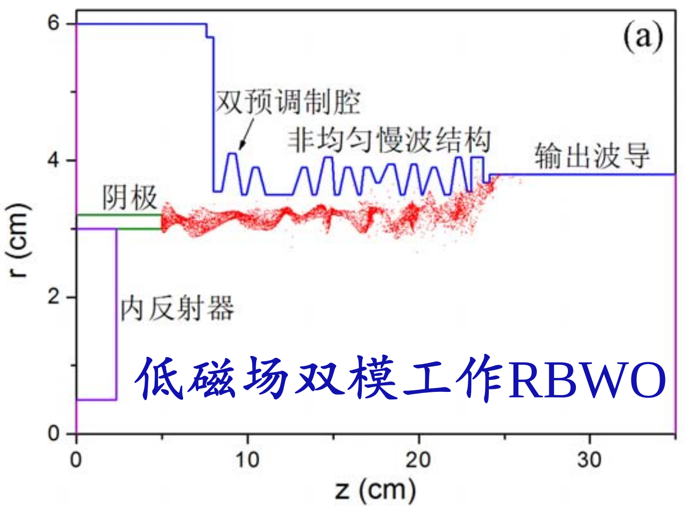


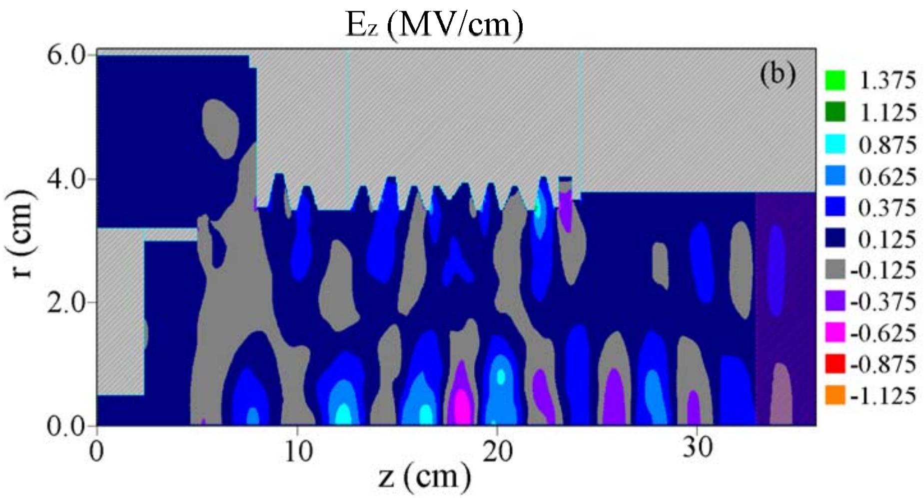




三. 双模工作RBWO

- 转变三大传统观念（单模工作、纯模输出、反射器隔离二极管和慢波结构），给出低磁场HPM源设计的新思想（双模工作、混合模输出、内反射器不隔离二极管和慢波结构）。
- 双模工作: “一心一意”提高效率，“黑匣子”
- 混合模输出：无“后顾之忧”
- 内反射器：器件长度缩短近一半





三. 双模工作RBWO

- 建立低磁场下过模结构双模工作非线性理论

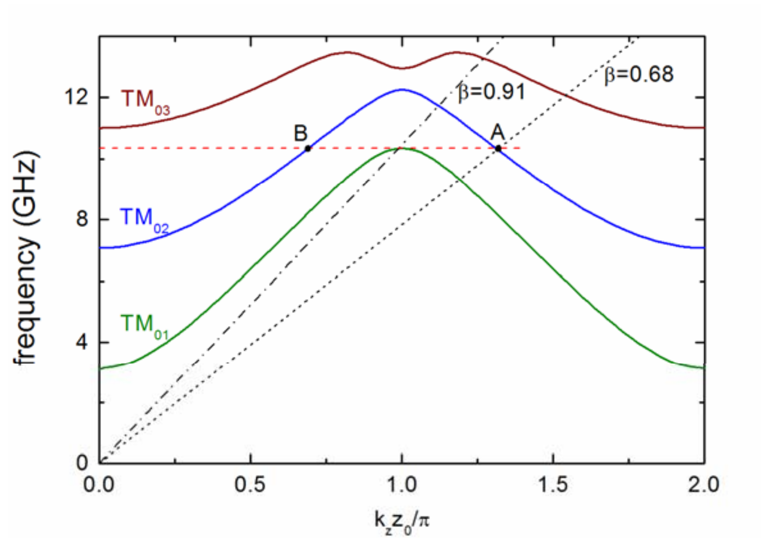
$$\frac{dp_r}{dt} = e\left[\left(E_{r1} + E_{r2}\right) + v_\varphi B_{ext} - v_z\left(B_{\varphi 1} + B_{\varphi 2}\right)\right] + \frac{\gamma m v_\varphi^2}{r}$$

$$\frac{1}{r}\frac{d}{dt}\left(\gamma m r v_\varphi\right) = -e v_r B_{ext}$$

$$\frac{dp_z}{dt} = e\left[\left(E_{z1} + E_{z2}\right) + v_r\left(B_{\varphi 1} + B_{\varphi 2}\right)\right]$$

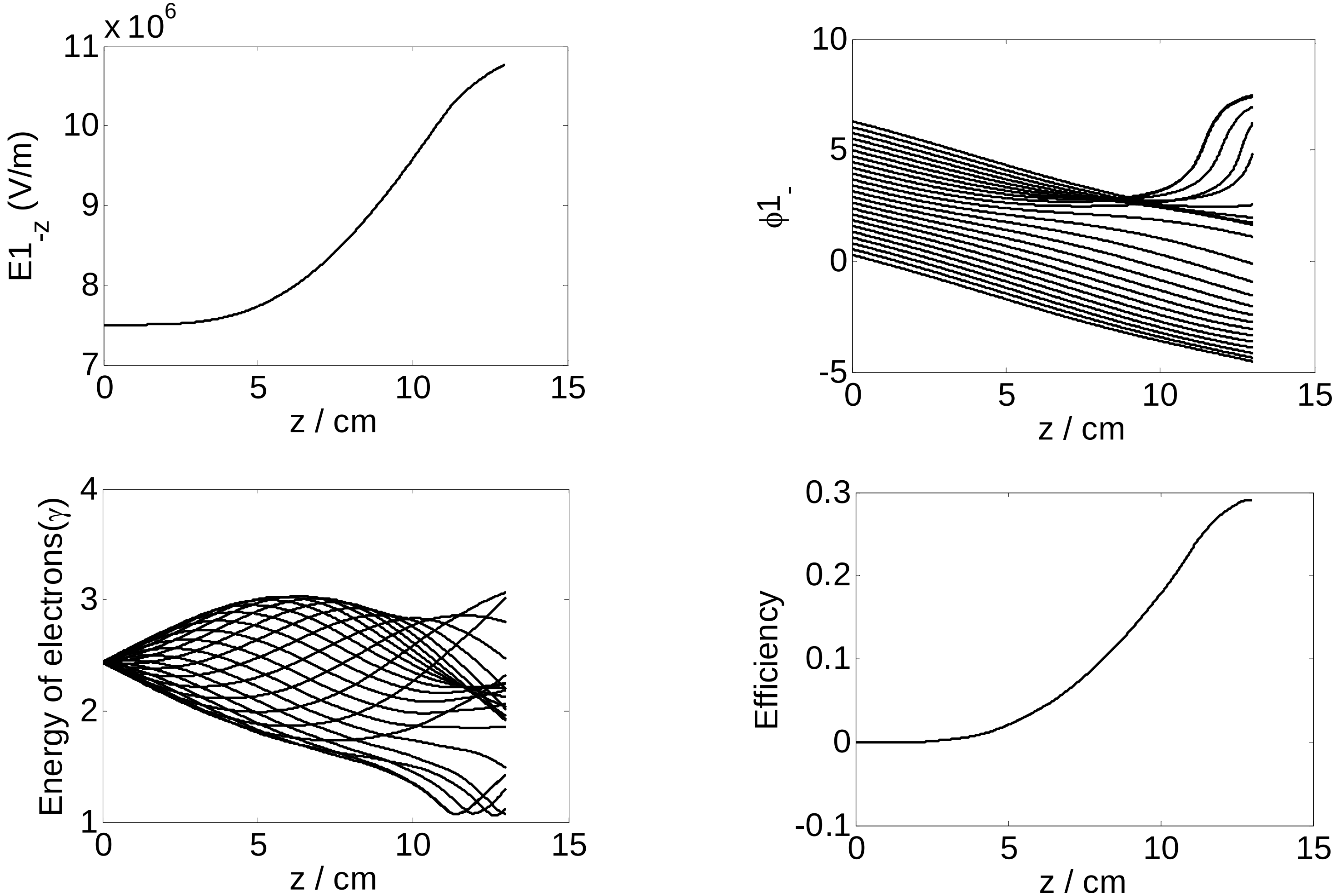
$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \mu_0 \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$



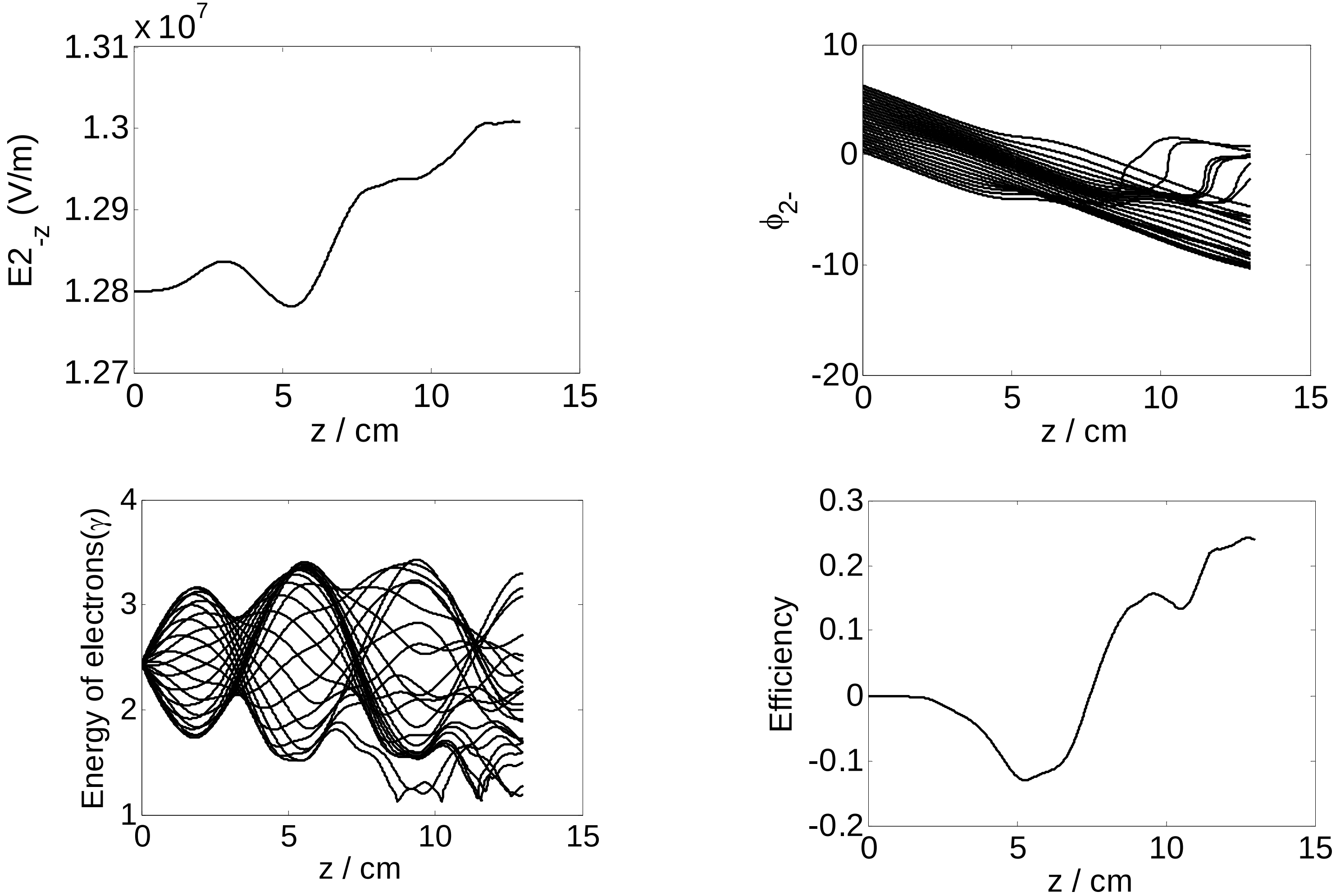
三. 双模工作RBWO

- 仅考虑TM_{01}模式，效率29%



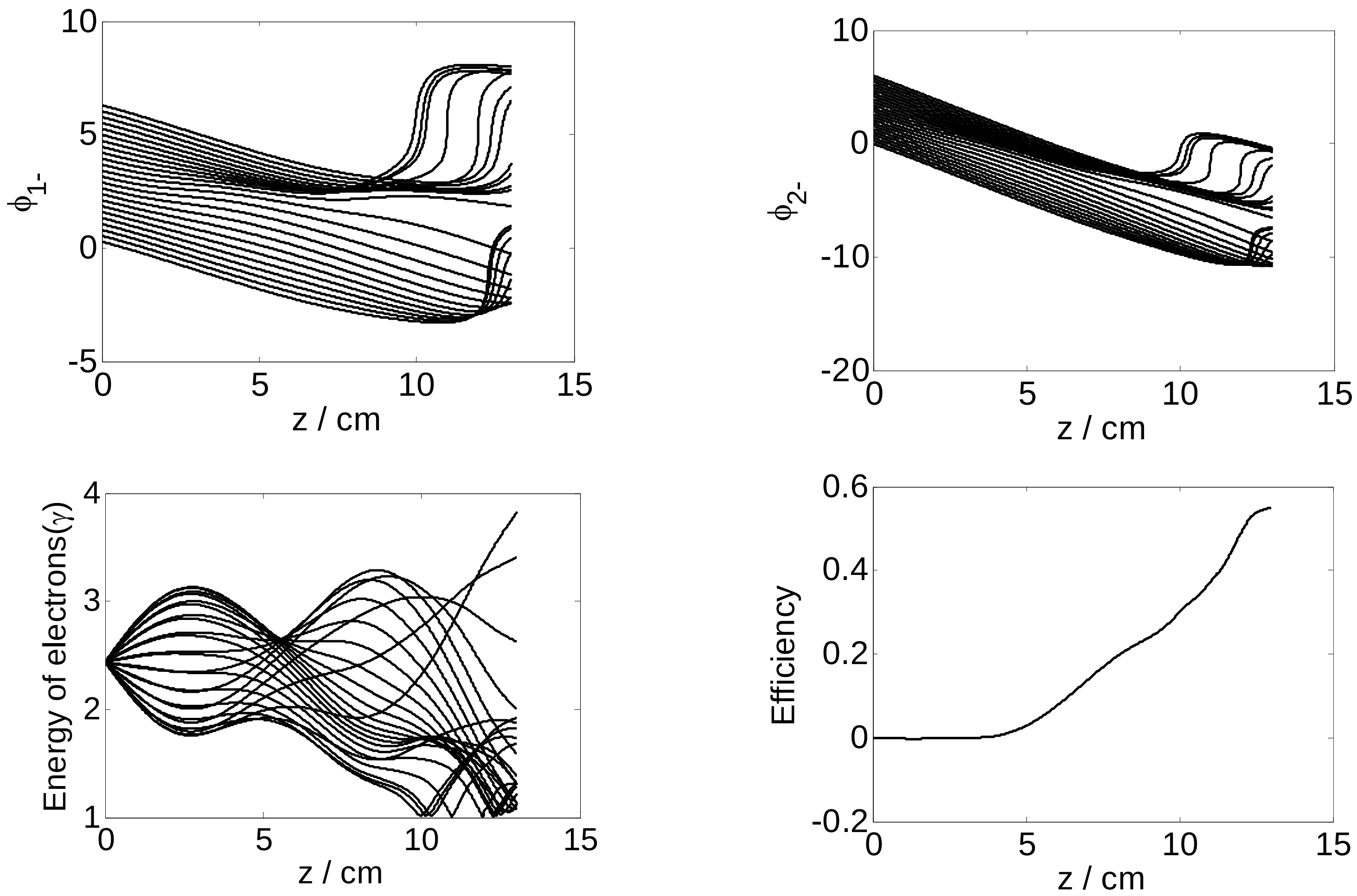
三. 双模工作RBWO

- 仅考虑TM_{02}模式，效率24%



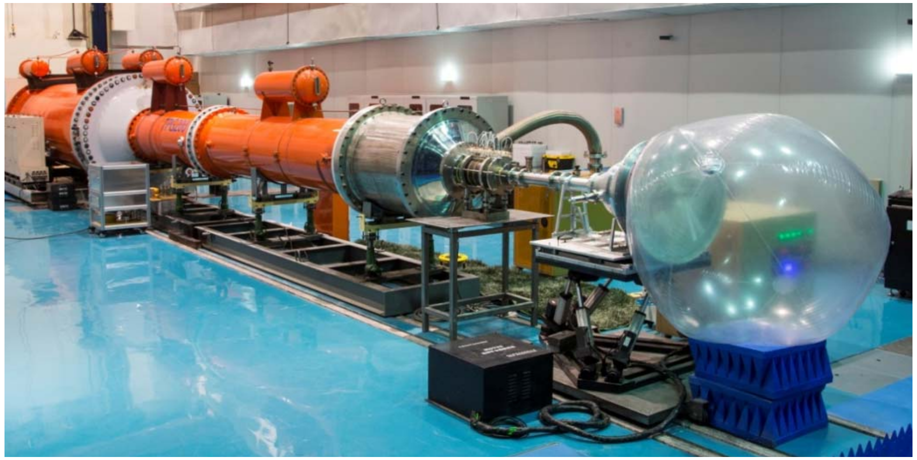
三. 双模工作RBWO

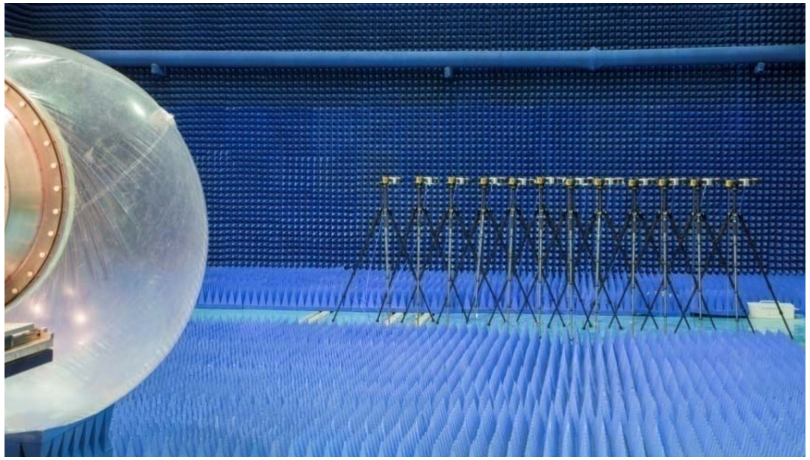
- 同时考虑TM_{01}和TM_{02}模式，效率**55%**

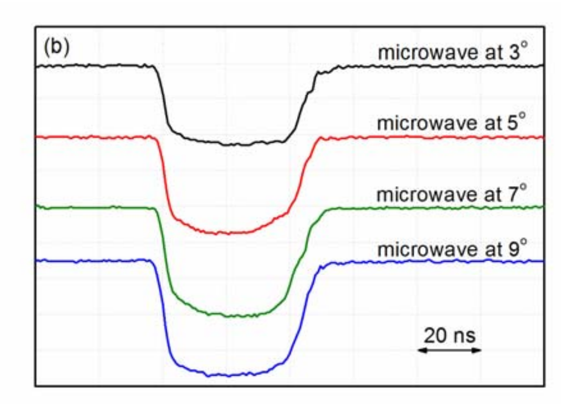


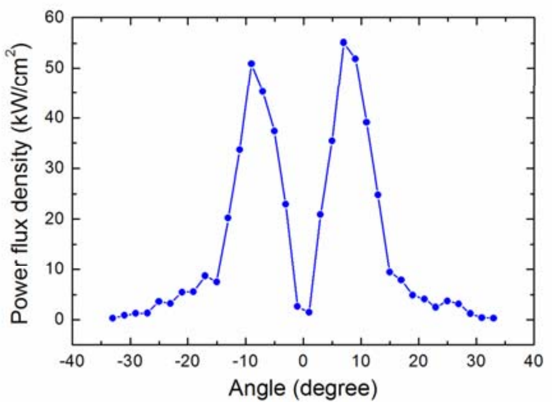
三. 双模工作RBWO

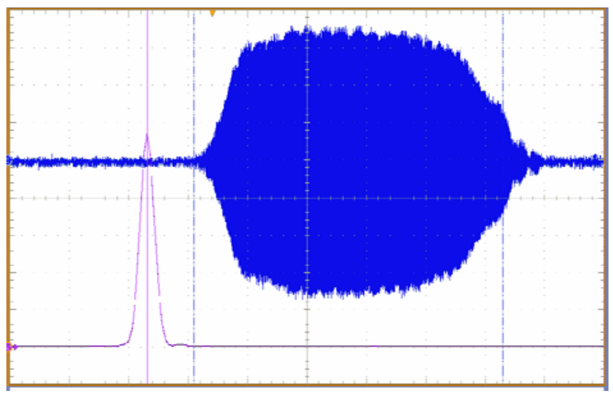
- **实验结果：0.66T**, 9.96GHz, **4.8GW, 42%**；0.76T, **7.6GW**, 32%





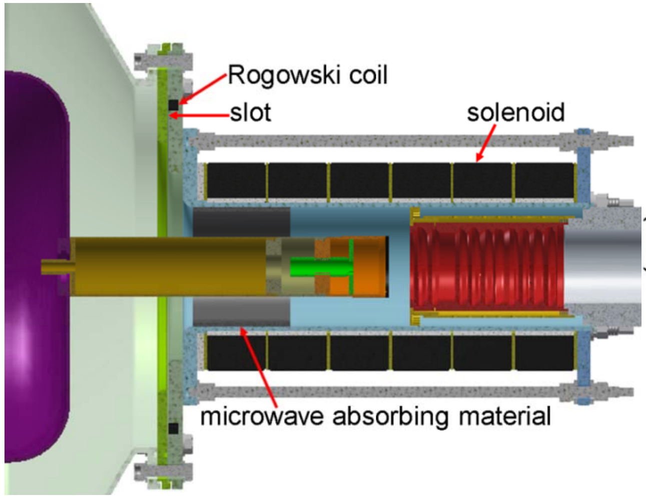


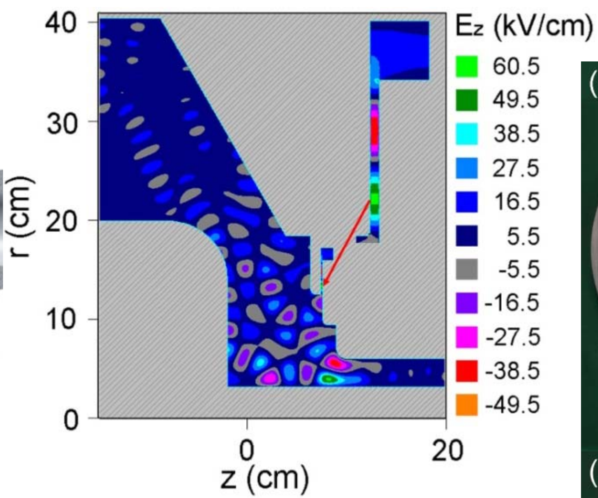


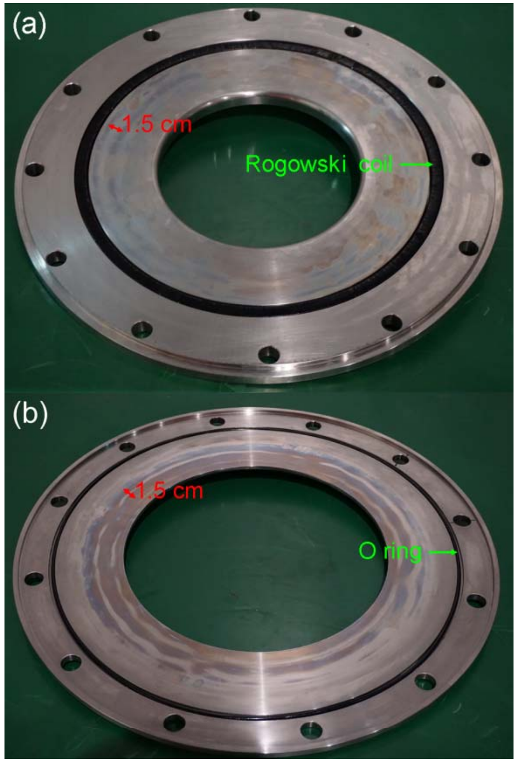


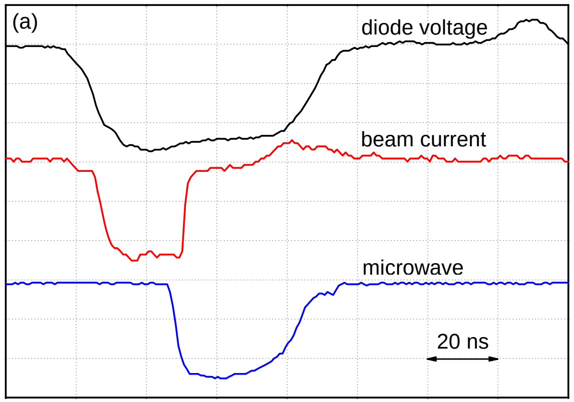
三. 双模工作RBWO

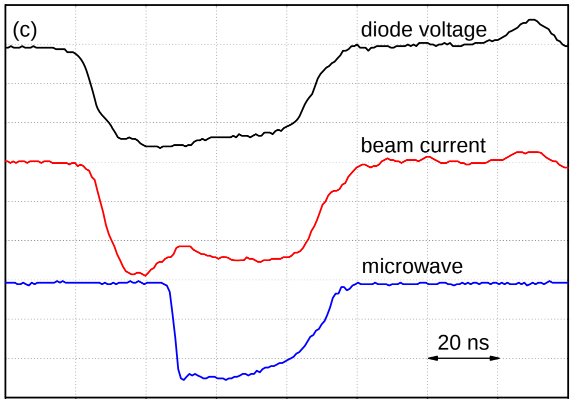
- 在二极管区贴附吸波材料，解决了束流测量截断的问题。





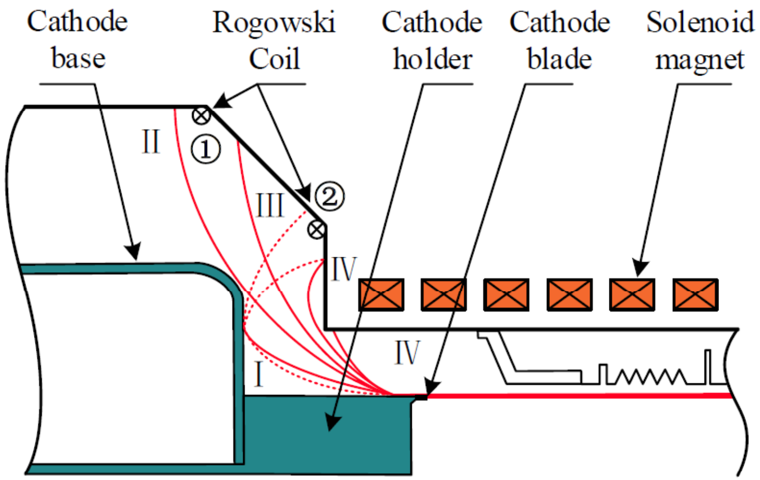


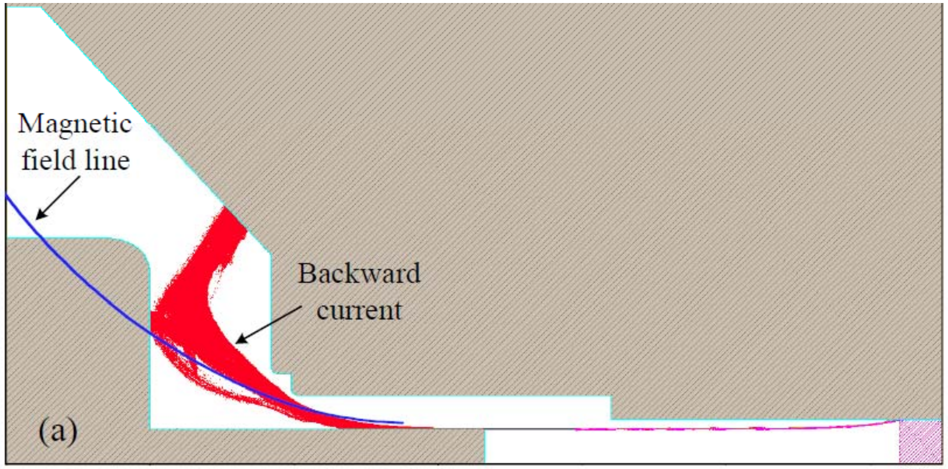


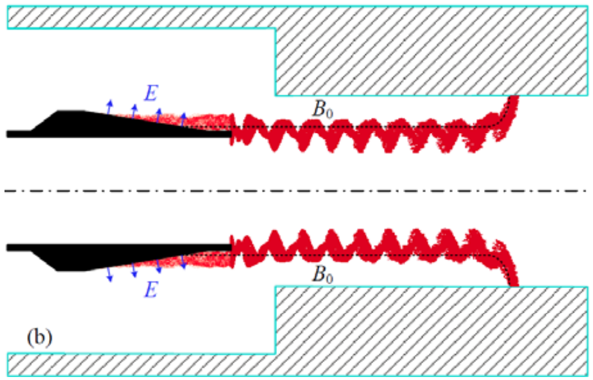


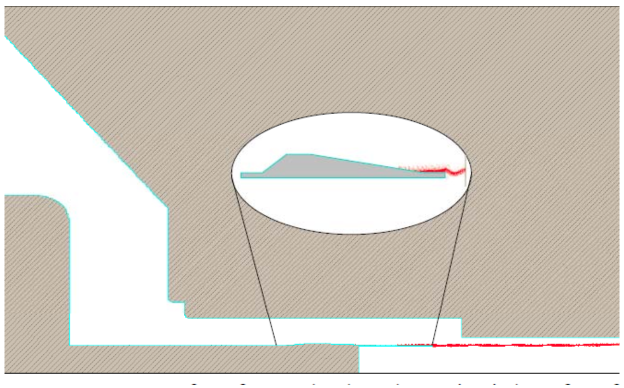
三. 双模工作RBWO

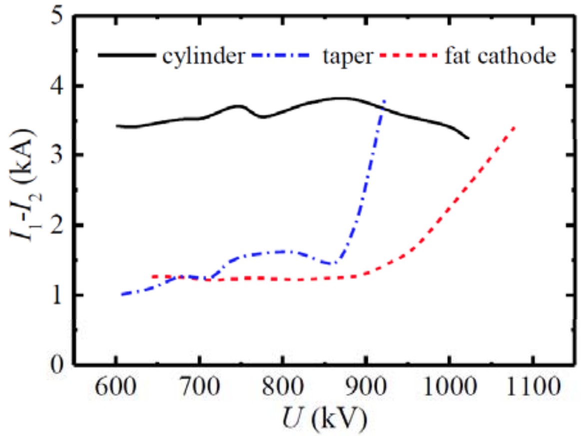
- 采用**斜面阴极**，将回流电流减小2/3





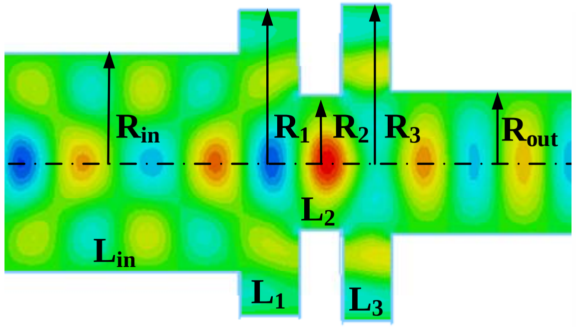


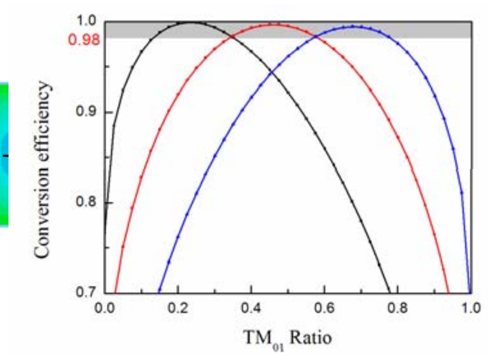


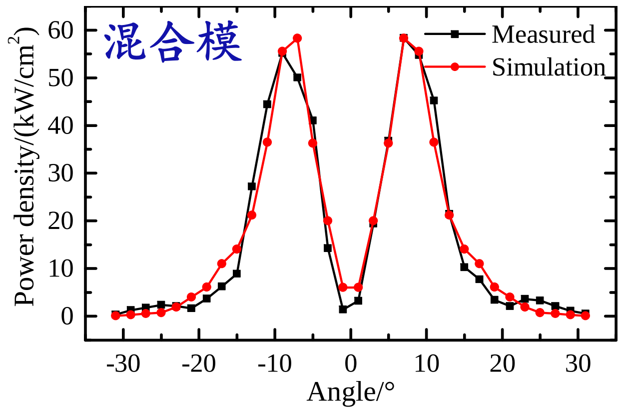


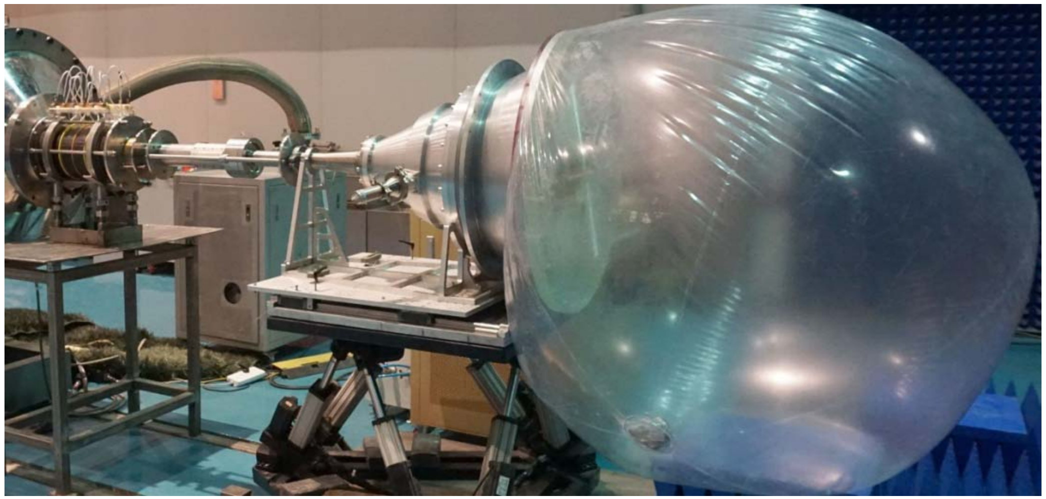
三. 双模工作RBWO

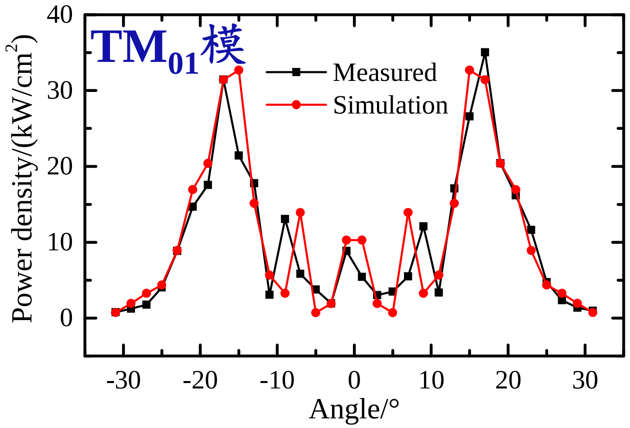
- 采用双腔模式转换器，在不同模式比例和相对相位下实现混合模-TM_{01}模的转换。实验中模转效率大于98%。











三. 双模工作RBWO

本学科经典著作列举了过去十年间中国吉瓦级HPM源的**爆炸式创新**，前三项为：

双模工作相对论返波管，
速调型相对论返波管，
牵引锁相相对论返波管。

into bunching and output sections separated by a drift space of comparable radius so that it was not cut off to the propagation of signal radiation between the two sections. Beginning with large, single-section *surface wave oscillators* (SWOs)[7] and RDGs,[8,9] this group progressed to double-section MWCGs[10] and MWDGs,[11] as well as two-section RDGs. Collectively, these devices produced gigawatt power levels[12–14] at frequencies between 9 and 60 GHz. In the highest power experiment, an X-band MWCG coupled 15 GW into its output waveguide.

The other line of research that began at this early stage, involving a different group at IHCE and IAP, and later collaboration with the University of New Mexico (UNM) and the University of Maryland (UMD), focused on improving the original BWO design. They enhanced the efficiency through either axial variations in the SWS[15] or varying the location of the reflector at the input end of the device,[16,17] reduced[18] or eliminated[19] the magnetic field at which the device operates, and operated in a repetitive mode.[20] Coupled with the SINUS series of repetitive pulsed-power machines, this device has powered gigawatt-class radars.[21,22] This combination could also be the basis for the RANETS-E mobile system that was advertised as a co-development project for parties interested in a 500 MW microwave weapon.[23] In fact, we used it in the SuperSystem concept discussed in Section 2.5.

In the last decade, a burst of innovation has come from China, with gigawatt-level sources coming from the Northwest Institute of Nuclear Technology (NINT) in Xi'an, the Institute of Applied Electronics (IAE) of the China Academy of Engineering Physics (CAEP) in Mianyang, the National University of Defense Technology (NUDT) in Changsha, and the University of Electronic Science and Technology of China (UESTC) in Chengdu. Researchers at NINT are pursuing three new developments:

来自NINT在吉瓦级源中的爆炸式创新。

- A *dual-mode BWO* using a mode-converting reflector at the upstream end of the SWS to convert the TM_{01} backward mode that couples to the beam to a TM_{02} forward-going mode to reduce the field strengths at the wall created by the forward-going mode.[24]

  双模工作相对论返波管

- A KL-BWO with the basic feature of an inductive cavity separating two slow-wave sections, with additional cavities at the input and output ends added over several development cycles to improve beam bunching and reduce fields at the output end to prevent breakdown.[25] Simulations for this device predict 10 GW output and up to 70% efficiency.

  速调型相对论返波管

- Phase locking both of a BWO with priming by a signal injected from the output end at startup,[26] and of a KL-BWO with injection of a locking signal at the beam-injection end of the device.[27]

  牵引锁相相对论返波管

四. 牵引锁相RBWO

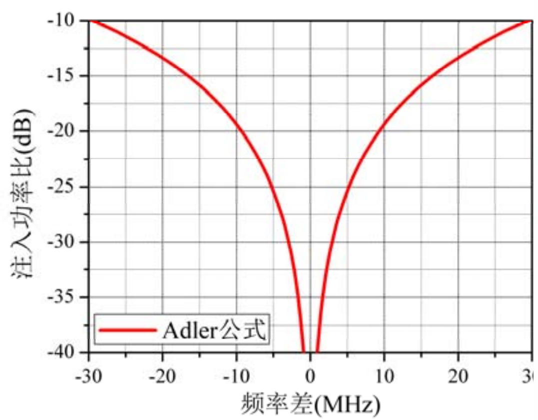
- 单个HPM源输出功率已达3-10GW。强场击穿限制。获得更高功率，必须进行**功率合成**。**核心技术是锁频锁相。**

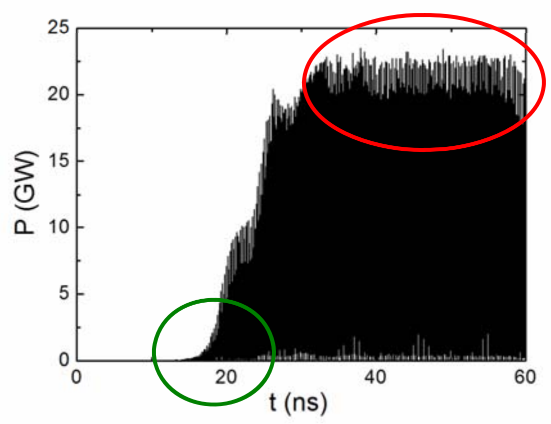
器件类型	频率	相位	传统锁相方法	功率容量	效率
放大器	受控	受控	外加注入信号 100kW量级	较低	较低
振荡器	固有	随机	强耦合法 100MW量级	高	高

四. 牵引锁相RBWO

- 传统的振荡器锁相方法，受经典的Adler条件限制。作用对象：饱和后的微波，功率高，难以调控。

$$\delta\omega \le \frac{\omega_0 \rho}{Q},\ \rho^2 = \frac{P_{in}}{P_{out}}$$





- 创造性地提出在振荡器起振过程外加弱信号对电子束进行预调制从而控制输出微波相位的新方法, 发明了牵引锁相相对论返波管。作用对象：起振阶段的微波，功率低，容易调控。

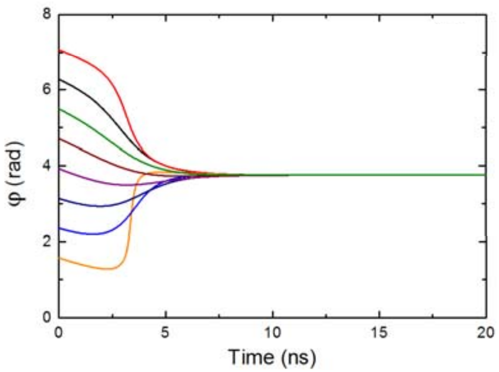
四. 牵引锁相RBWO

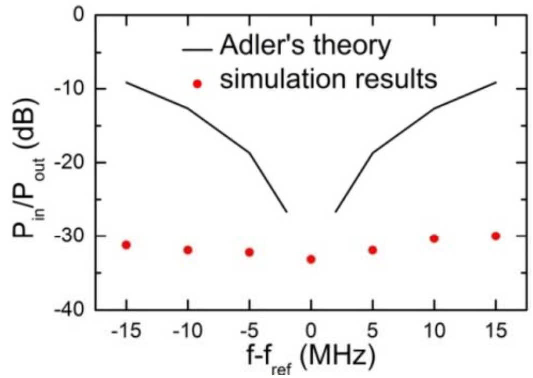
- 建立了理论模型，揭示了牵引锁相机理：外加注入信号的相位决定调制电子束的相位，受调制的电子束诱导处于任意初始相位的微波信号稳定到平衡相位。注入功率与传统法比降低2-3个量级。

$$I_1(t)=2I_0J_1\left(\frac{\omega}{v_0}\alpha_3M_3L_3\right)\sin\left(\theta_0+\frac{\theta_1}{2}+\frac{\omega}{v_0}L_1+\frac{\theta_2}{2}+\frac{\omega}{v_0}L_2+\frac{\theta_3}{2}+\frac{\omega}{v_0}L_3\right)$$

$$\frac{dA'}{d\tau}+A'=\mathrm{Re}\left\{-\frac{Qe}{m_0\omega^3}\frac{1}{\varepsilon_0e^{i\varphi}}\frac{I_0}{2\pi}\int_0^{2\pi}\left[\int_0^L e^{-i\theta}E_{sz}(r_b,z)dz'\right]d\theta_0\right\}$$

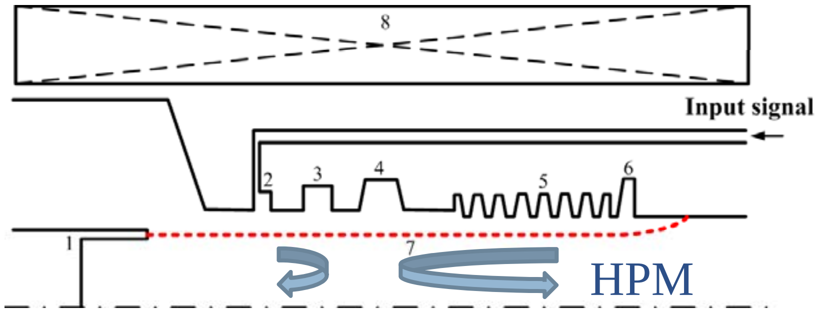
$$\frac{d\varphi}{d\tau}+\delta=\frac{1}{A'}\mathrm{Im}\left\{-\frac{Qe}{m_0\omega^3}\frac{1}{\varepsilon_0e^{i\varphi}}\frac{I_0}{2\pi}\int_0^{2\pi}\left[\int_0^L e^{-i\theta}E_{sz}(r_b,z)dz'\right]d\theta_0\right\}$$

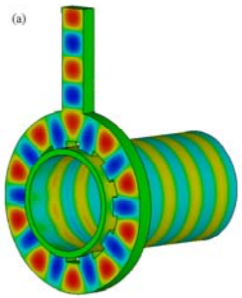


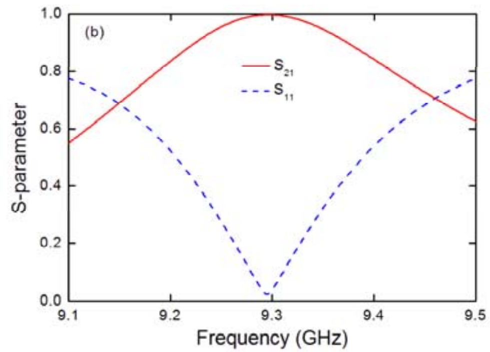


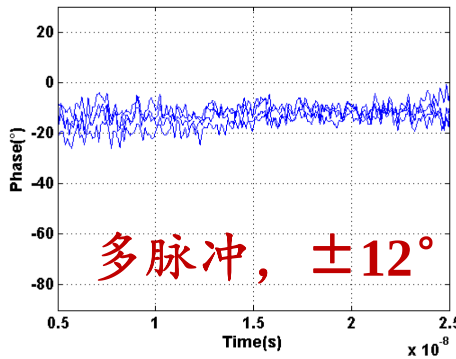
四. 牵引锁相RBWO

- **前端注入法：** 低功率注入通道与HPM产生通道的空间隔离。
- **模式转换器：** 解决了注入信号角向均匀高效注入的技术难题。
- 实现了单路RBWO的牵引锁相：注入功率92kW，与传统强耦合法相比降低了3个量级。



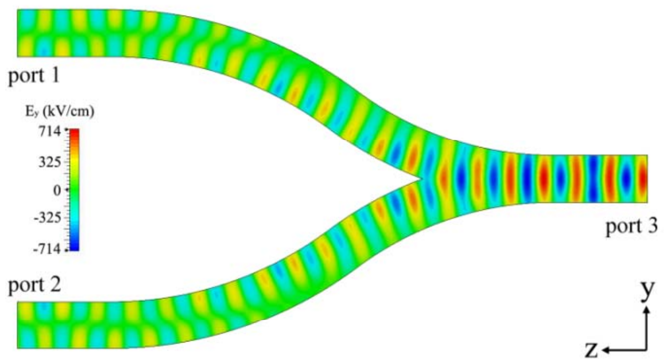


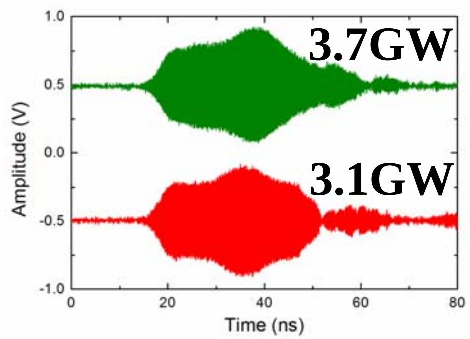


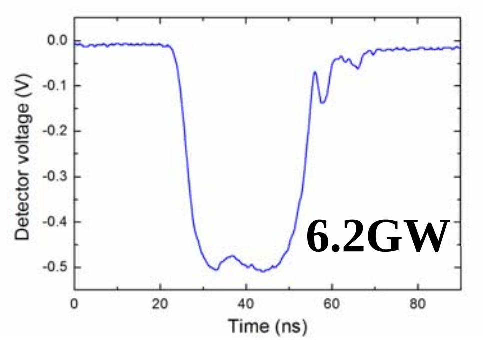


四. 牵引锁相RBWO

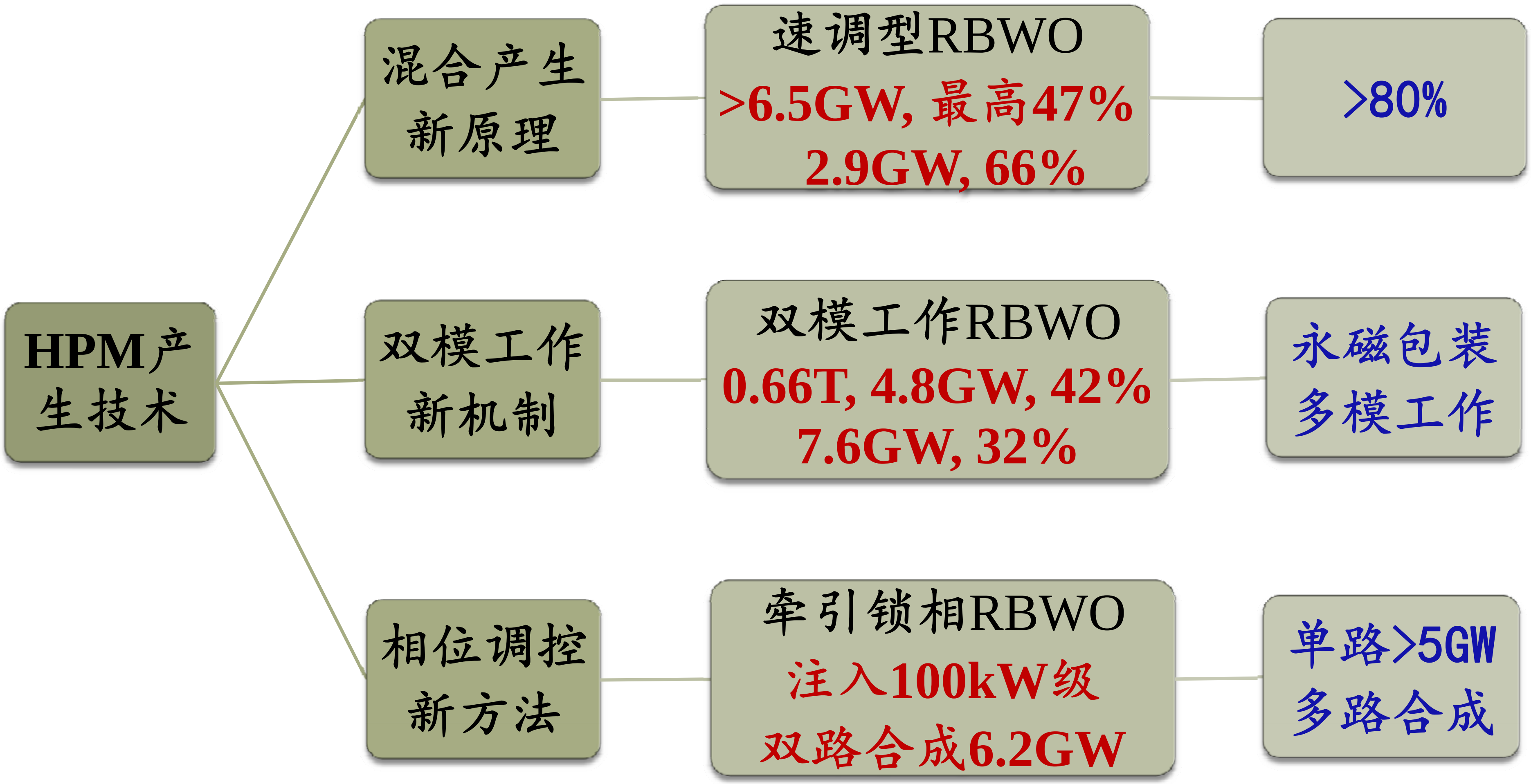
- 转换合成法：研制了高功率容量的合成器。
- 实现了两路牵引锁相RBWO功率合成，合成功率达6.2GW，合成效率大于90%。







五. 总结展望


HPM产生技术
混合产生新原理
速调型RBWO
>6.5GW, 最高47%
2.9GW, 66%
>80%
双模工作新机制
双模工作RBWO
0.66T, 4.8GW, 42%
7.6GW, 32%
永磁包装多模工作
相位调控新方法
牵引锁相RBWO
注入100kW级
双路合成6.2GW
单路>5GW
多路合成

五. 总结展望

1. R. Z. Xiao, Y. C. Shi, H. D. Wang, et al. Efficient generation of multi-gigawatt power by an X-band dual-mode relativistic backward wave oscillator operating at low magnetic field, Phys. Plasmas 27, 043102 (2020)
2. R. Z. Xiao, Y. Y. Gui, G. S. Zhang, et al. Microwave breakdown in a dual-mode relativistic backward wave oscillator operating at low magnetic field, Plasma Research Express 3, 025001 (2021)
3. G. S. Zhang, J. Sun, R. Z. Xiao, et al. Suppression of backward current in a low-magnetic-field foilless diode, Phys. Plasmas 28, 033106 (2021)
4. Y. Y. Gui, R. Z. Xiao, J. W. Li, et al. Mixed-modes conversion method for dual-mode relativistic backward-wave oscillators, IEEE Microwave and Wireless Components Letters, 2021 (Early Access)
5. R. Z. Xiao, H. D. Wang, K. Chen, et al. Role of second harmonic in the optimization of microwave conversion efficiency from an intense relativistic electron beam, IEEE Transactions on Microwave Theory and Techniques, 2021 (Early Access)

五. 总结展望

6. R. Z. Xiao, Y. C. Shi, K. Chen, et al. Conversion of Cherenkov radiation to transition radiation by electron bunch post-acceleration for extremely efficient beam-wave interaction. (under review)
7. R. Z. Xiao, K. Chen, H. D. Wang, et al. Theoretical calculation and particle-in-cell simulation of a multi-mode relativistic backward wave oscillator operating at low magnetic field. (under review)
8. R. Z. Xiao, K. Chen, T. Z. Miao, et al. On truncated electrons in a radial three-cavity transit-time oscillator with efficiency of 53% in the absence of magnetic field. (under review)
9. T. Z. Miao, R. Z. Xiao, Y. C. Shi, et al. Efficiency improvement by manipulating electron beam in a relativistic backward wave oscillator at low magnetic field. (under review)

衷心感谢！

敬请批评指正！