

光阴极本征发射度离线测量装置研制

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摘要 光阴极本征发射度是光阴极电子源装置所能获得的发射度下限,对自由电子激光、超快电子衍射等装置发展具有重要意义。常用的光阴极本征发射度测量方法依赖大型加速器装置,不利于实验室环境下光阴极制备工艺的快速优化。本文基于自由空间漂移原理设计并搭建了一套光阴极离线本征发射度测量装置。该装置通过转移室实现与光阴极制备装置的兼容连接,采用5 mm阴阳极间隙、270 mm漂移距离和微通道板(Micro-channel Plate, MCP)探测系统,对采用Te断续、Cs持续沉积工艺制备的碲化铯(Cs_2Te)光阴极进行量子效率及本征发射度测量。测量结果表明,光阴极表面量子效率均大于5%,最大值达12.5%(266 nm波长);碲化铯光阴极本征发射度为 $0.592 \text{ mm}\cdot\text{mrad}\cdot\text{mm}^{-1}$ (5 kV偏压),不同偏压下的测量结果与理论值吻合良好,验证了装置的可靠性。该离线测量系统为光阴极工艺参数优化提供了便捷高效的解决方案,测量精度通过理论对比和文献验证得到确认。

关键词 光阴极, 本征发射度, 电子源

中图分类号 TL53

DOI: 10.3724/j.0253-3219.2026.hjs.49.250042

CSTR: 32193.14.hjs.CN31-1342/TL.2026.49.250042

An offline system for measurement of the intrinsic emittance of photocathode

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Abstract [Background] Photocathode intrinsic emittance represents the lower limit of emittance achievable by photocathode electron sources and is critical for advancing applications such as free-electron lasers and ultrafast electron diffraction. Conventional measurement methods rely on large-scale accelerator facilities, which are unsuitable for rapid laboratory-based optimization of photocathode fabrication processes. [Purpose] This study aims

国家自然科学基金面上项目(No.12275339, No.12075302)、上海市自然科学基金(No.22ZR1470300)、中国科学院青年创新促进会(No.2023300)资助

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收稿日期: 2025-01-25, 修回日期: 2025-05-05

Supported by National Natural Science Foundation of China (No.12275339, No.12075302), Science and Technology Innovation Plan of Shanghai (No.22ZR1470300), Youth Innovation Promotion Association of Chinese Academy of Sciences (No.2023300)

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Received date: 2025-01-25, revised date: 2025-05-05

to develop an offline intrinsic emittance measurement system for photocathodes that enables rapid characterization and optimization of fabrication parameters in laboratory environments. **[Methods]** An offline intrinsic emittance measurement system was designed and constructed based on the free-space drift principle. Firstly, the system was made compatible with the photocathode preparation facility through a transfer chamber that enabled vacuum transport of photocathodes between preparation and measurement devices under ultra-high vacuum conditions ($\sim 10^{-8}$ Pa). Then, the measurement principle utilizing cathode-anode acceleration followed by field-free drift detection was implemented with a 5 mm cathode-anode gap, 270 mm drift distance, and a micro-channel plate (MCP) detector system with 10^6 gain factor. Finally, cesium telluride (Cs_2Te) photocathodes prepared using intermittent Te and continuous Cs deposition processes were transferred to the measurement chamber and characterized for both quantum efficiency distribution and intrinsic emittance using a 266 nm ultraviolet laser with ~ 100 μm spot size. **[Results]** The measurement results of quantum efficiency show values exceeding 5% across the photocathode surface, with the maximum efficiency reaching 12.5% at 266 nm wavelength. The measured intrinsic emittance of the Cs_2Te photocathode is $0.592 \text{ mm}\cdot\text{mrad}\cdot\text{mm}^{-1}$ under 5 kV bias voltage, aligning well with internationally reported values of $0.50\sim 1.0 \text{ mm}\cdot\text{mrad}\cdot\text{mm}^{-1}$ for similar materials. Measurements under different bias voltages demonstrate good agreement with theoretical predictions. The system exhibits no space charge effects across different laser power levels, confirming the reliability of the measurement results. **[Conclusions]** The offline measurement system proposed in this study successfully enables rapid and reliable characterization of photocathode intrinsic emittance, providing a practical and efficient solution for photocathode fabrication process optimization in laboratory environments without requiring large accelerator facilities. The measurement accuracy validated through theoretical comparison and consistency with literature values demonstrates that this approach significantly reduces the optimization cycle time for high-quality photocathode development, making it a valuable tool for advancing high-brightness electron source technology.

Key words Photocathode, Intrinsic emittance, Electron source

对于光阴极注入器,光阴极是电子束产生的核心部件,其性能与电子束品质直接相关^[1-3]。光阴极本征发射度是描述光阴极性能的重要物理量^[4-6],它是光电子逸出光阴极表面后残余动能产生的,与光阴极光电特性、工作参数、光阴极表面粗糙度息息相关^[7-9]。不同于空间电荷效应等因素对束流发射度的贡献,光阴极本征发射度对束流发射度的贡献无法通过下游束流元件补偿消除。因此,光阴极本征发射度是直线加速器装置中电子束所能获得的发射度下限^[10]。对光阴极本征发射度开展测量及优化对提升束流品质具有重要意义。

目前,国际上已发展多种测量方法,如动量空间成像法、螺线管扫描法、“胡椒屏”法等光阴极本征发射度测量方法^[11-14],这些方法大多依赖于大型的加速器装置,设备复杂,不利于光阴极制备工艺迭代优化,且测量过程中易受空间电荷效应和束流光学的影响^[10]。此外,高量子效率半导体光阴极化学活性较高,对 H_2O 、 O_2 、 CO_2 等气体组分比较敏感^[15-16]。这些方法通常需要通过额外制造转移装置和装载装置,以实现样品在制备装置和加速器装置间传输^[17],不利于光阴极制备过程中的快速测量和分析。

本文基于自由空间漂移原理^[18],设计并搭建了

一套适用于实验室环境的光阴极本征发射度测量装置。该装置具备光阴极转移接口,通过转移室,可在真空环境下实现光阴极在制备装置和测量装置之间传输,开展光阴极本征发射度离线快速测量,对指导光阴极工艺优化,降低本征发射度提供了高效便捷的解决方案。

1 测量原理

光阴极本征发射度测量系统布局如图1所示。光电子从阴极发射出来,在阴极-阳极间电压加速后穿过阳极栅网区,经长度为 d 的无场区漂移后被探测器接收。整个装置电路采取阴极接负电压,阳极、探测器和腔体接地。当光电子从阴极发射出来后,在阴极-阳极间加速电压作用下到达阳极栅网,在这一过程中电子作抛物线运动,位置随时间的函数可由牛顿力学给出,如式(1)所示:

$$z = v_z t + \frac{eVt^2}{2mg} \quad (1)$$

式中: V 是阴极-阳极电压; g 是阴极-阳极间隙; v_z 是沿纵向 z 方向的初始速度; e 是电子电荷; m 是电子的质量; t 是时间。根据式(1)可得光电子在阴极-阳极间飞行时间如下:

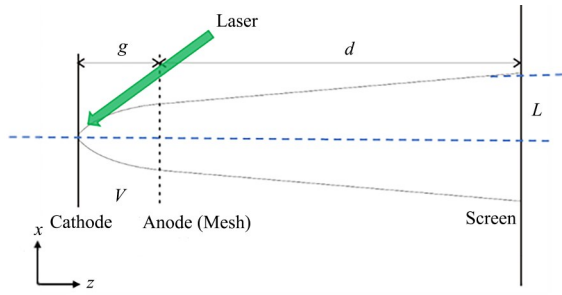


图1 光阴极本征发射度测量物理原理示意图
Fig.1 Schematic diagram of the physical principle of photocathode intrinsic emittance measurement

$$t = \frac{g}{eV} \sqrt{2m} \left(\sqrt{\varepsilon_z + eV} - \sqrt{\varepsilon_z} \right) \quad (2)$$

式中: ε_z 是纵向 z 方向的初始电子动能。在光阴极电子源应用中,初始电子能量通常小于1 eV,而测量中阴极-阳极电压 V 通常为kV量级。因此,式(2)可简化为:

$$t = g \sqrt{\frac{2m}{eV}} \quad (3)$$

由于沿 x 方向没有横向电场,电子的横向动量可由式(4)给出:

$$p_x = \frac{x}{g} \sqrt{\frac{emV}{2}} \quad (4)$$

式中: x 是电子运动到阳极栅网时的横向位移。光电子在栅网处沿 z 方向和沿 x 方向的夹角可由式(5)给出:

$$\theta = \frac{p_x}{p_z} = \sqrt{\frac{\varepsilon_x}{eV}} \quad (5)$$

式中: ε_x 是电子沿 x 方向的初始动能。结合式(3),电子在阳极栅网处的横向位移 x 可表示为:

$$x = 2g \sqrt{\frac{\varepsilon_x}{eV}} \quad (6)$$

电子从阴极运动至探测器处产生的横向位移 L 可由式(7)给出:

$$L = x + \theta d \quad (7)$$

根据光阴极本征发射度定义(式(8)),结合式(5)~(7)可根据测量的横向位移和装置参数给出光阴极本征发射度结果,如式(9)所示:

$$\frac{\varepsilon_{\text{cathode}}}{\sigma_{x,y}} = \frac{\sqrt{\langle p_{x,y}^2 \rangle}}{mc} \quad (8)$$

$$\varepsilon_{\text{int}} = \frac{\varepsilon_{\text{cathode}}}{\sigma_x} = \frac{p_x}{mc} = \frac{L}{2g + d} \sqrt{\frac{2eV}{mc^2}} \quad (9)$$

式中: ε_{int} 为测量到的光阴极本征发射度。

2 装置设计

2.1 装置整体布局

因高量子效率半导体光阴极化学活性较高,对 H_2O 、 O_2 、 CO_2 等气体组分比较敏感,光阴极制备及本征发射度测量均需要在极高真空下进行($10^{-8} \sim 10^{-10}$ Pa)。为实现光阴极无损传输及测量,光阴极本征发射度测量装置与光阴极制备装置之间采用兼容安装接口。整个光阴极本征发射度离线测量装置布局如图2所示,其主要由测量室、转移室和过渡段组成。测量室主要用于光阴极本征发射度测量。转移室用于光阴极在制备装置和本征发射度测量装置之间转移。过渡段用于确保转移室与测量室之间的真空连接。通过磁力杆和阴极舟可实现光阴极在转移室和测量室之间传送。

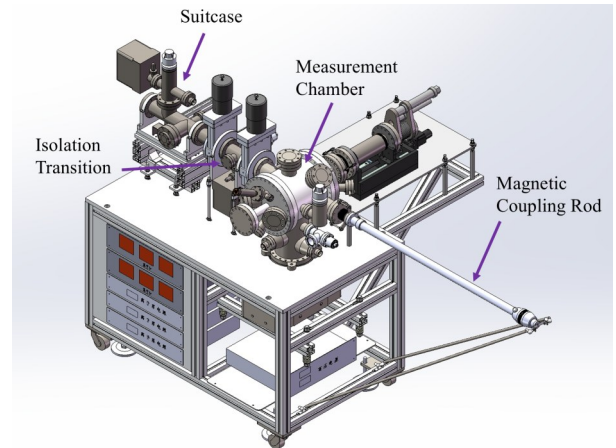


图2 光阴极本征发射度测量装置三维图
Fig.2 Three-dimensional diagram of the photocathode intrinsic emittance measurement device

2.2 测量室设计

光阴极本征发射度测量室包含驱动光路入射/反射窗、光阴极取放组件、阴阳极组件及测量组件等(图3)。驱动光路入射/反射窗用于驱动光入射及反射光监测。取放组件具备阴极样品在阴极舟上的取放、安装就位、阴极基底加热和降温、施加负偏压的功能。该部分机械结构设计光阴极制备装置中取放组件设计一致,确保两台装置之间实现样品转移。阴阳极组件产生垂直于光阴极表面方向的电场,提供光电子加速。阴阳极间采用30 mm陶瓷绝缘,可实现大于10 kV耐压。阴阳极最小间隙为5 mm。阴极板留有阴极孔,工作时可将阴极样品插入阴极孔中进行测量。为确保阴阳极间场均匀性,且驱动光可以入射至阴极表面,阳极采用1 mm厚石英片,表面镀金膜实现导电及透光。阳极中央开3 mm直径通孔,安装阳极栅网,使得电子束可以穿过。

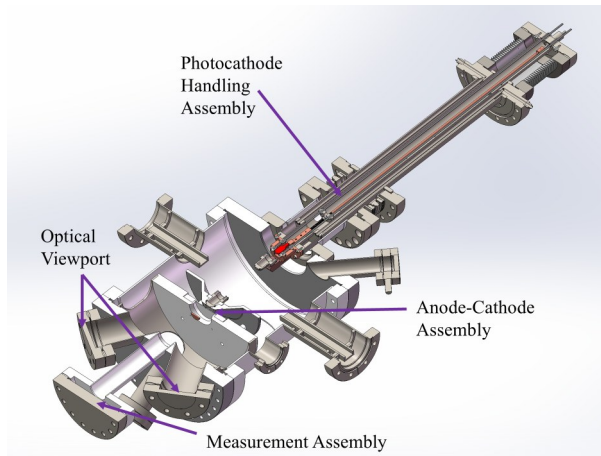


图3 光阴极本征发射度测量装置测量室示意图(俯视图)
Fig.3 Measurement chamber diagram of the photocathode intrinsic emittance measurement device (top view)

为降低空间电荷力引入的测量误差,采用较低能量的驱动光产生光电子束进行测量。测量组件用于实现低电荷量工况下束斑分布测量,其采用微通道板阵列(Micro-channel Plate, MCP)与荧光靶组合

的方式。光电子漂移至探测器时,首先入射至微通道板阵列中进行放大后到达荧光靶,荧光靶产生的荧光经耦合系统进入到电荷耦合器件(Charge-Coupled Device, CCD)进行成像。装置采用的MCP最大增益系数为 10^6 。采用的荧光靶电光转换效率约 60% ($20 \text{ ph} \cdot \text{e}^{-1} \cdot \text{kV}^{-1}$, @3 kV)。

2.3 驱动光路设计

因碲化铯光阴极工作波长为紫外波段,测量光源采用266 nm半导体激光器。驱动光路布局如图4所示。激光器出口安装紫外衰减片,用于调节激光出射的激光功率。为降低驱动光斑尺寸引入的测量误差,要求阴极上的光斑尺寸小于 $100 \mu\text{m}$ 。光路中采用小孔整形与相传递相结合的方案实现。采用 $100 \mu\text{m}$ 小孔对光斑横向进行整形,之后采用单透镜成像(相传递)方案将小孔处光斑等比例传递至光阴极表面。

为实时测量光阴极上驱动光斑尺寸,在测量腔入射窗前分光搭建虚阴极光路。图5为CCD测量得到的虚阴极上的光斑分布,可以得出光斑尺寸的

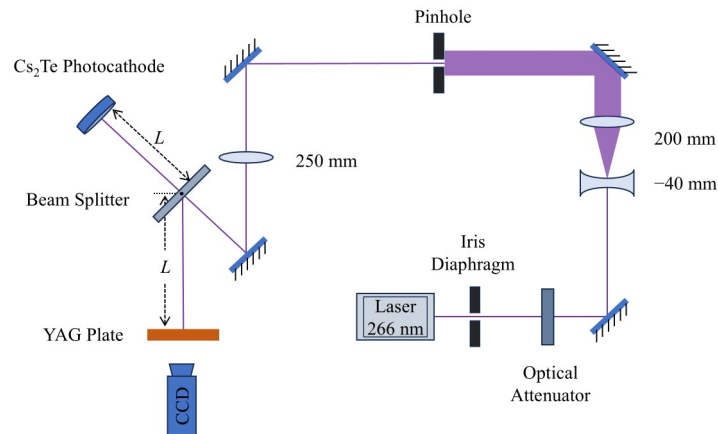


图4 驱动光路布局图
Fig.4 The layout of the driving laser system

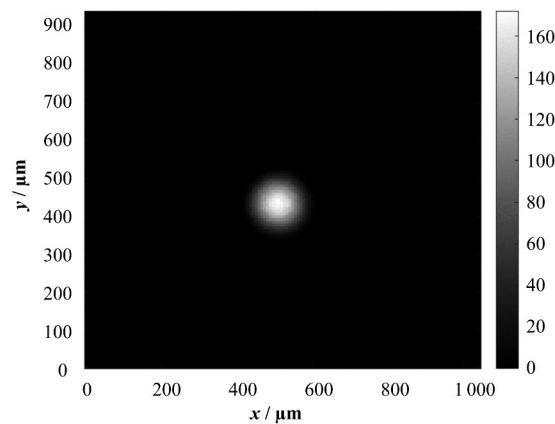


图5 虚阴极测量到的光斑尺寸
Fig.5 The spot size measured at the virtual cathode

半高全宽(Full Width at Half Maximum, FWHM)约100 μm ,与采用的光阑孔径一致。

3 碲化铯光阴极性能测量及分析

实验中的光阴极采用Te断续、Cs持续沉积工艺制备^[19],该工艺制备的光阴极已应用至硬X射线自由电子激光装置、强流电子枪测试平台装置中^[20-21]。光阴极量子效率和本征发射度是评估光阴极性能的两项重要指标,在光阴极本征发射度离线测量装置中分别对实验室制备的碲化铯(Cs_2Te)光阴极量子效率和本征发射度进行了测量和评估。

3.1 光阴极量子效率测量

光阴极转移室安装有石英窗和电极接口,可进行光阴极量子效率测量。光阴极在传送到测量室之前,可先在转移室内进行光阴极量子效率分布测量。测量光路采用与本征发射度测量相同的驱动光路(图4),阴极上激光光斑尺寸(FWHM)约100 μm ,通过电动镜架对光阴极表面不同位置处量子效率进行测量,以绘制光阴极量子效率分布。图6为光阴极量子效率分布测量结果,入射光波长为266 nm。光阴极直径约7 mm,测得光阴极不同位置量子效率均大于5%,最大处可至~12.5%,满足高量子效率光阴极应用需求。

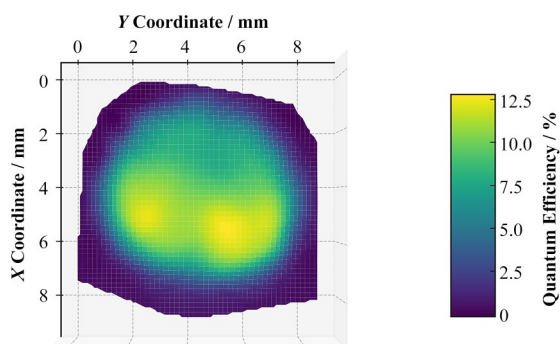


图6 光阴极量子效率分布(彩图见网络版)

Fig.6 Quantum efficiency distribution of the photocathode (color online)

3.2 光阴极本征发射度测量

完成量子效率测量后,光阴极被传送至测量室进行本征发射度测量。图7为装置CCD上测量到的电子束束斑分布。测量实验中,采用的驱动激光功率约为100 nW,阴阳极偏压为5 kV,装置阴阳极间隙 g 为5 mm,漂移距离 d 为270 mm。经测量,电子束束斑尺寸(RMS)为1.2 mm,根据式(9)可得出光阴极本征发射度为 $0.592 \text{ mm} \cdot \text{mrad} \cdot \text{mm}^{-1}$ 。为了验证测量结果的准确性,对不同阴阳极偏压下探测器上

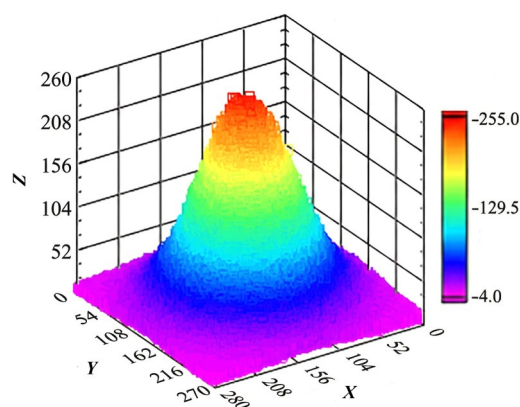


图7 测量腔探测器上测得的电子束束斑分布(彩图见网络版)

Fig.7 Spot distribution of the electron beam measured on the detector of the measurement chamber (color online)

电子束束斑尺寸进行测量,并与理论值进行对比。图8表明光阴极本征发射度测量结果与理论值能够较好吻合,验证了测量结果的可靠性。此外,经对国际上碲化铯光阴极本征发射度测量结果调研,碲化铯光阴极本征发射度通常在 $0.50 \sim 1.0 \text{ mm} \cdot \text{mrad} \cdot \text{mm}^{-1}$ (与采用的驱动激光波长、阴极梯度、制备工艺有关^[22-25]),这也在一定程度上说明本装置测量结果的准确性。

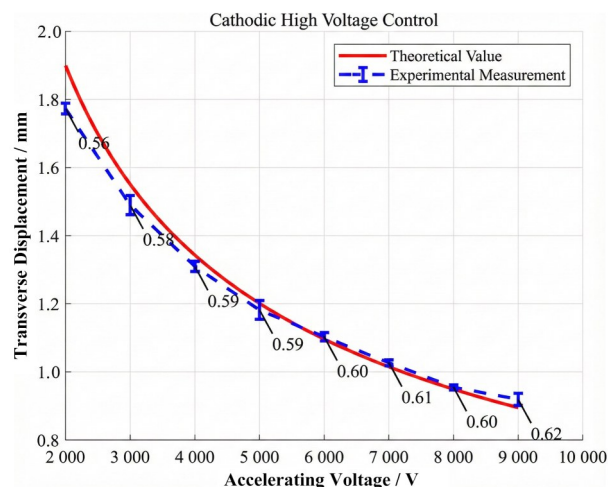


图8 不同阴阳极偏压下电子束束斑尺寸(彩图见网络版)

Fig.8 Electron beam spot size measured under different bias voltages (color online)

为了验证空间电荷效应对光阴极本征发射度测量结果无影响,对不同驱动激光功率下光阴极本征发射度进行了测量,如图9所示。测量结果指出,随激光功率变化,光阴极本征发射度测量结果基本不变,可说明空间电荷效应对实验中测量结果无影响。

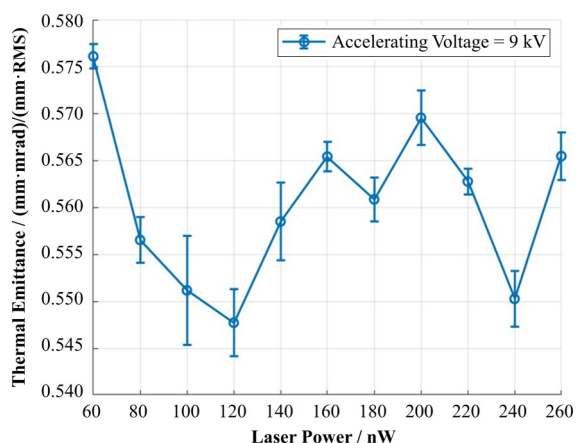


图9 不同驱动激光功率下光阴极本征发射度测量结果
Fig.9 Measurement results of photocathode intrinsic emittance under different driving laser powers

4 结语

光阴极本征发射度在一定程度上决定电子束的最终品质。光阴极本征发射度测量对光阴极工艺参数优化具有重要指导意义。本文基于自由空间漂移原理设计并搭建了一套光阴极离线本征发射度测量装置。该装置可实现光阴极在制备装置与测量装置之间无损传输,支持所制备光阴极量子效率和本征发射度测量。基于该装置对采用Te断续、Cs持续沉积工艺制备的光阴极的量子效率和本征发射度开展了测量。测量结果与理论结果基本吻合,且与国际上报道的碲化铯光阴极测量结果基本一致。未来课题组将基于该装置开展光阴极本征发射度影响因素分析及光阴极制备工艺优化,为获得更低本征发射度光阴极提供支持。

作者贡献声明 冯志文负责光路搭建及调试、本征发射度测量和文章撰写;李旭东负责光阴极制备、转移及传输;孟浩负责本征发射度测量;周琴负责光阴极制备;侯涛负责实验数据的收集;姜增公负责本征发射度装置设计、实验设计、装置调试及文章撰写;顾强负责实验设计、指导并协助文章修订。

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