THU

用于VHEE-FLASH多角度放疗的X波段快速高功率旋转移相器研制

李洪雨

2026.10.17



清華大學

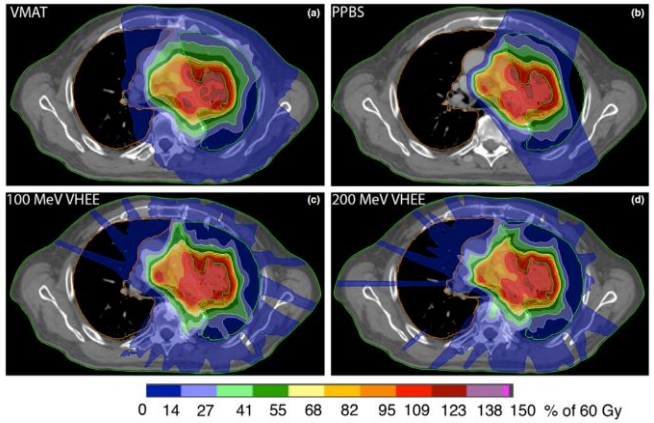
Tsinghua University

内 容 提 要

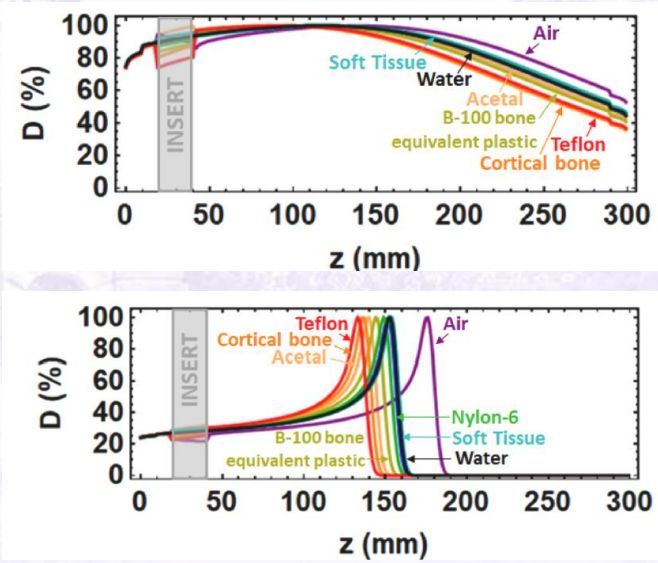
- 研究背景及意义
- 研究内容及方法
- 待进行的工作

VHEE与FLASH放疗

- 三种FLASH放疗模式
  - 光子：容易实现多角度（需要大电流加速器+转换靶）
  - 质子：实现了临床实验（需要快速能量扫描技术）
  - 电子：实验和临床实践更充分（需要VHEE-RT）
- 超高能电子束 (VHEE, 50-250MeV) 的优势
  - 穿透更深，半影更小
  - 受组织不均匀性影响小
  - 更容易扫描和定位



肺癌治疗计划比较：VHEE、PPBS等



插入不同干预介质时的深度百分比剂量分布
上：VHEE，下：质子

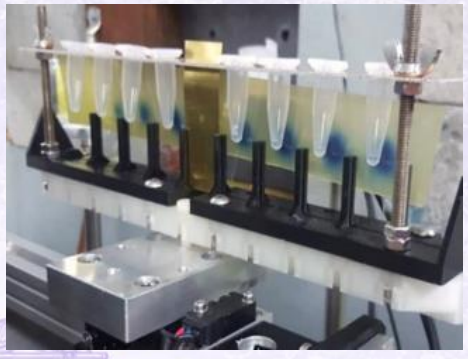
Lagzda, A. et al. (2020). NIMB 482: 70-81.
I. Martínez-Rovira, et al. (2015). Med. Phys. 42(2), 685-693

VHEE的研究现状

VHEE 生物学实验

质粒DNA照射实验 (2021)

- 首次量化超高能电子束对DNA的损伤
- VHEE束对DNA的损伤与常规放疗相似
- 可以推断VHEE的生物效应与常规放疗相似



质粒DNA照射实验图

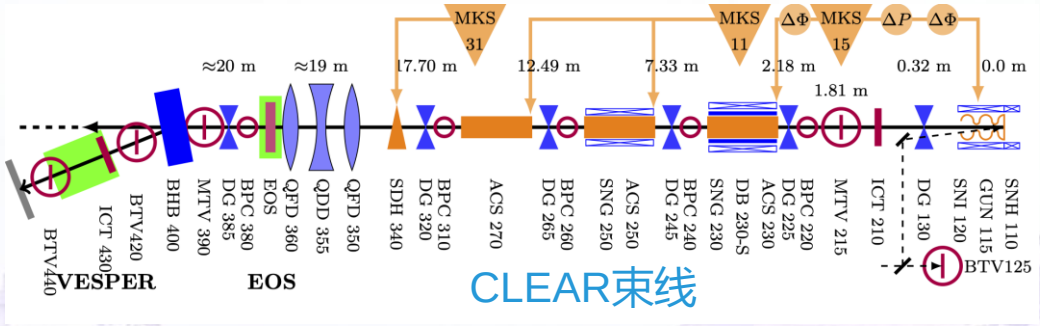
体外癌细胞实验 (2024)

- 首次体外测定超高能电子束对肺癌、前列腺癌细胞的RBE
- 对癌细胞杀伤与常规放疗相似
- VHEE束剂量分布比VMAT更优，适合密度不均匀组织的肿瘤治疗



癌细胞照射实验图

VHEE-FLASH 实验装置



CLEAR束线

Consideration	CLARA	CLEAR	ARES	SAFEST（在建）
宽能量范围	Yes – 100-250 MeV	Yes – 60-220 MeV	Reasonable – 100-155 MeV	No – 80-100 MeV for first phase
辐射参数	Small Gaussian beam (σ < 5mm)	Small Gaussian beam (σ < 5mm) Flat circular field (diameter < 15mm)	Small Gaussian beam (σ < 5mm)	Flat rectangular field (~ 10x10 cm^2)
FLASH 能力	Yes - Above threshold for σ < 4mm and SSD < 45cm across energy range	Yes – Single-shot dose delivery results in dose rate > 10^8 Gy/s	Limited - Above threshold for σ < 2.5mm at SSD up to 15cm and for σ < 2mm at SSD up to 35cm	Yes - > 350 Gy/s for flat field at all simulated SSD

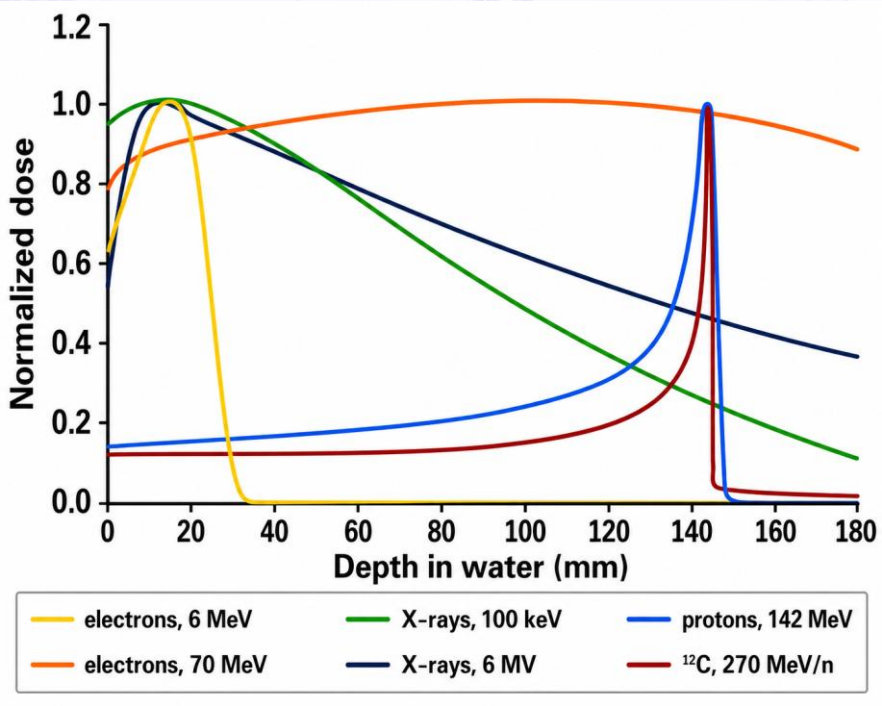
现存欧洲VHEE-FLASH设施

R. M. Jones, et al., Scientific Reports **11** (2021), no. 1
Wanstall, H. C. et al. (2024). Sci. Rep. 14(1): 10957

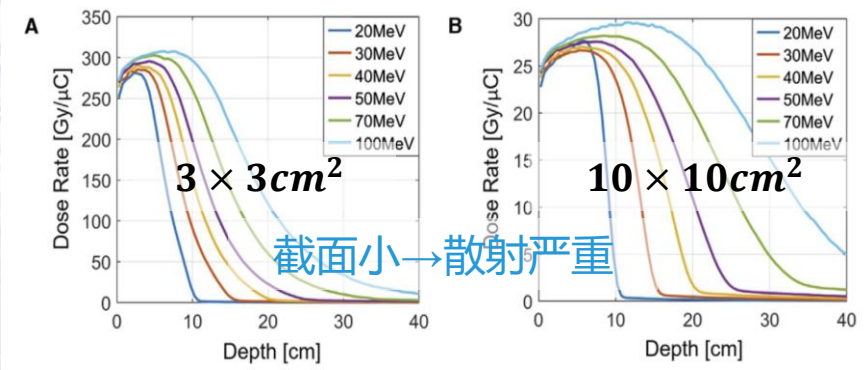
K. Small et al., Beam Interactions with Materials and Atoms, August 2025

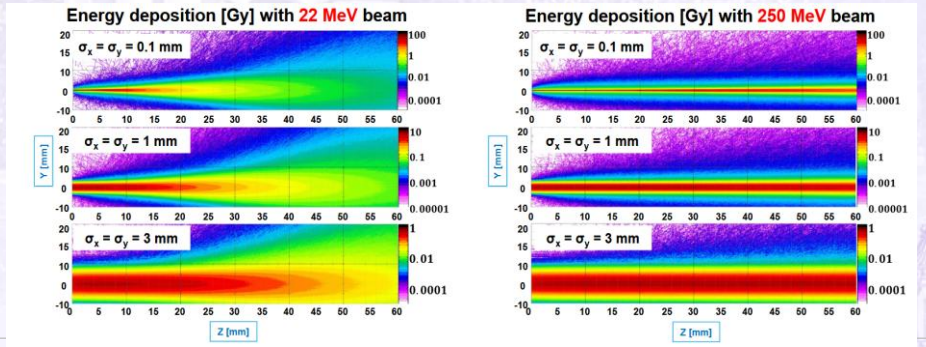
VHEE的剂量递送挑战

- 迈向临床面临的挑战
- VHEE入口剂量问题
  - 剂量沉积较平坦
  - 表面保护较差



- 笔形束扫描的难题
  - 电磁扫描用时需<100ms
  - 子束多→重频高
  - 截面小→散射大
  - 入口剂量

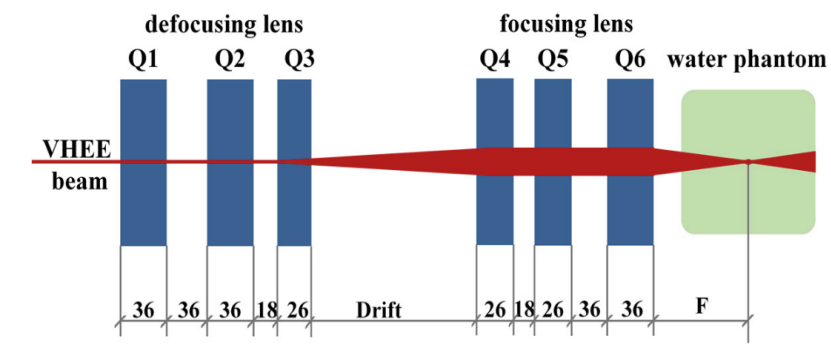




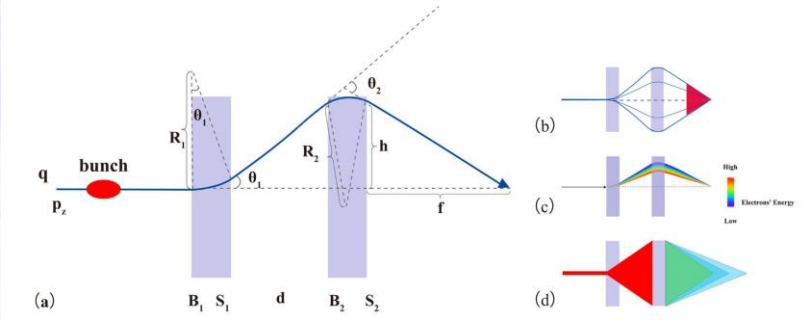
Vozenin, M.-C. et al. (2022). Nat. Rev. Clin. Oncol. 19(12): 791-803
Lin, X. (2023). Tsinghua University (PhD thesis).
Stephan, F. et al. (2022). Phys. Med. 104: 174-187.

VHEE多角度照射方案 研究现状

- 其他方案

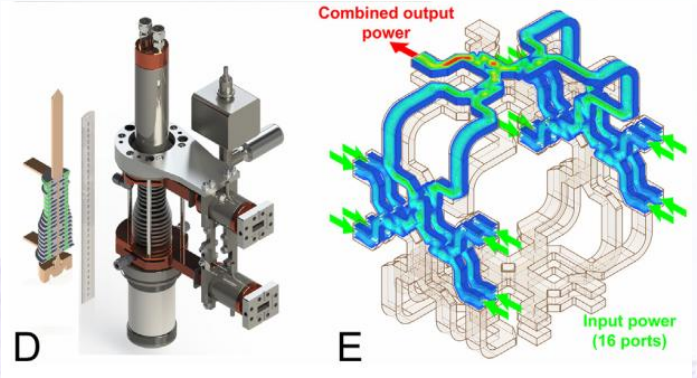


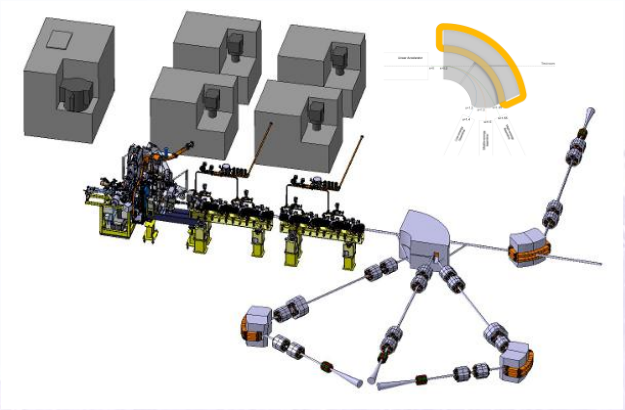
聚焦VHEE



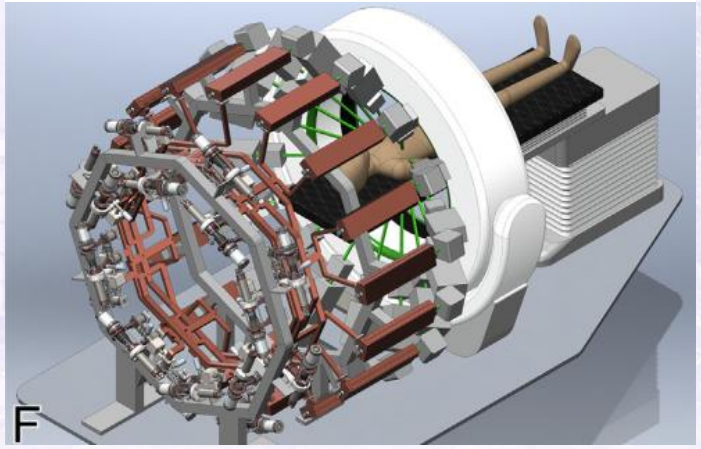
双二极铁扫描

- 多角度照射方案（建设中）
  - 避开危及器官、降低表面剂量

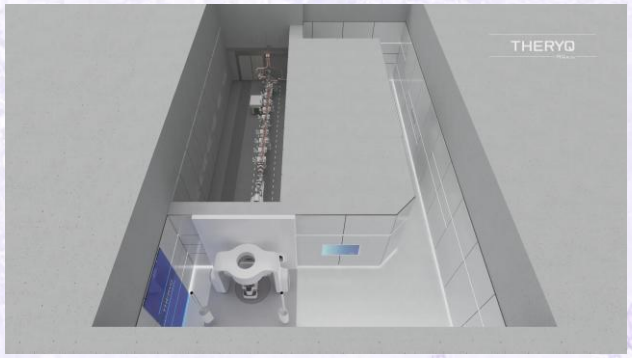




CERN-CHUV合作 磁铁色散偏转DEFT



SLAC 多角度加速器阵列PHASER

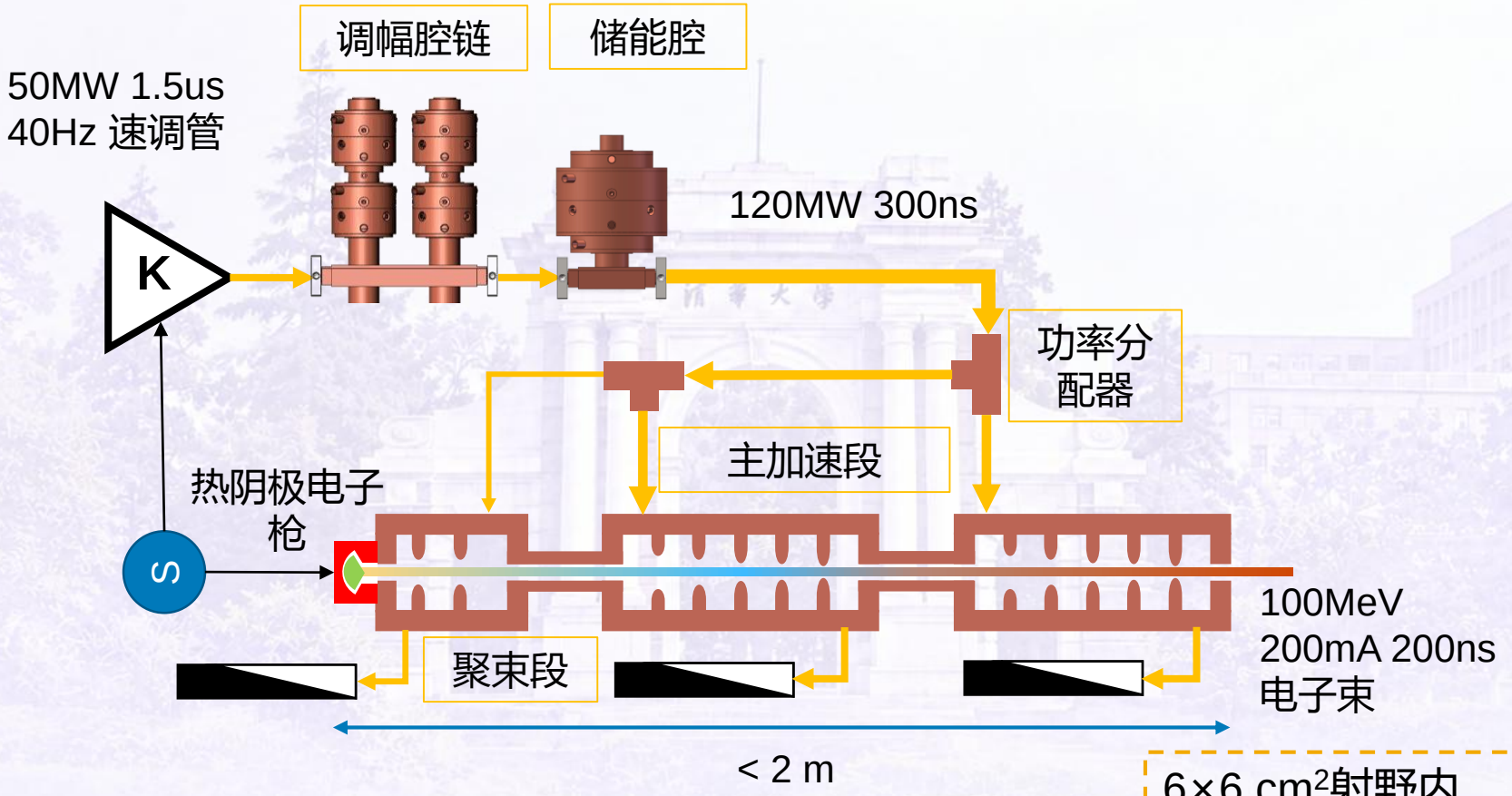


新方案FLASHDEEP 旋转治疗床

Zhou, B. et al. (2024). arXiv: 2401.01557.
Whitmore, L. (2023). University of Manchester (PhD thesis).
Panaino, C. et al. (2025). Cancers 17(2): 181.
Maxim, P.G. et al. (2019). Radiother. Oncol. 139: 28-33.
A. Ganguly. High does rate linacs for FlashRT. VHEE. 2021.
Korchevnyuk, V. (2024). EPFL (PhD thesis).;Rossi, C. et al. (2024). JACoW LINAC 2024
https://www.theryq-alcen.com/flash-radiotherapy-products/flashdeep/

VHEE放疗超快多角度照射系统设计

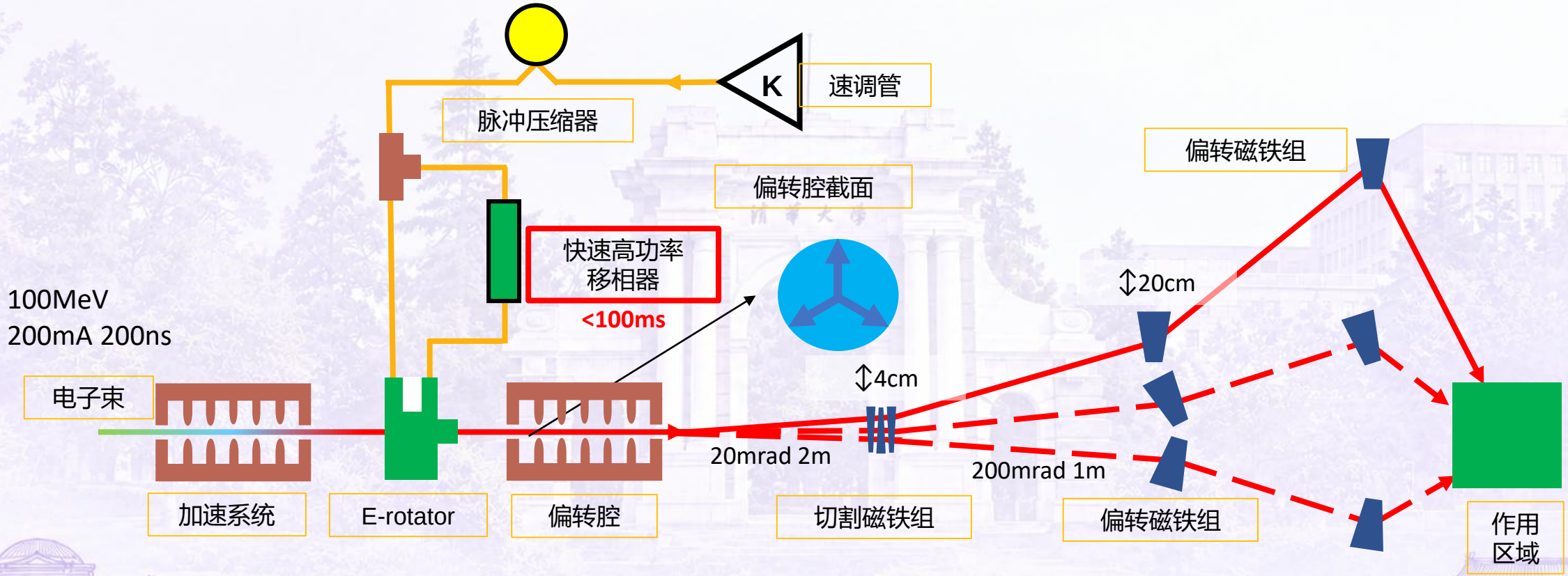
- 清华大学 100MeV 紧凑型VHEE加速系统示意图



Lin, X. (2023). Tsinghua University (PhD thesis).

VHEE放疗超快多角度照射系统设计

- 100MeV VHEE超快多角度照射系统示意图

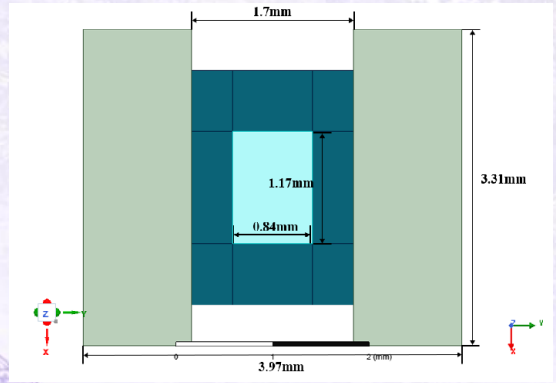


移相器种类

- 快速高功率移相器 方案选择
  - 目标：数十MW级；100ms内移相

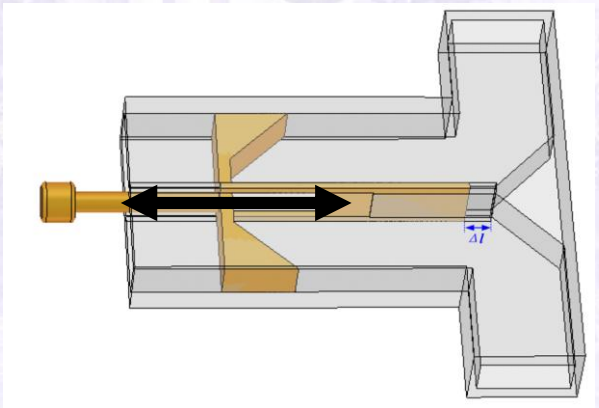
- 铁氧体移相器
  - 励磁电流快速控制
  - 受限于铁氧体非线性效应
    功率容量~100kW

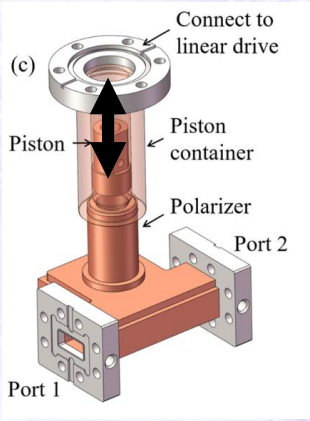
- 机械移相器
  - 移相慢
  - 功率容量大
  - 推挽式/**旋转式**





正脊波导铁氧体移相器



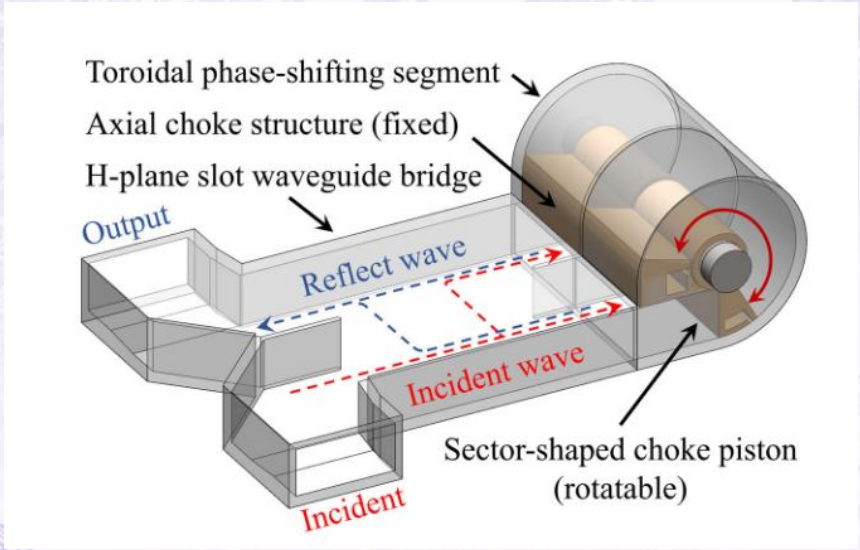


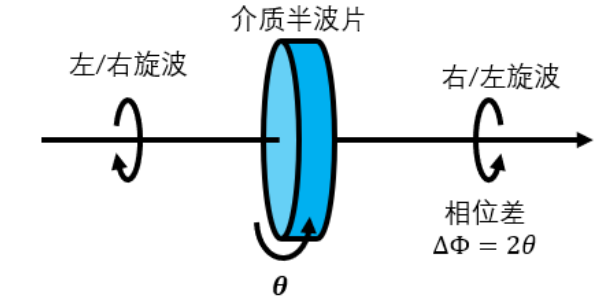
推挽式机械移相器 往复平移

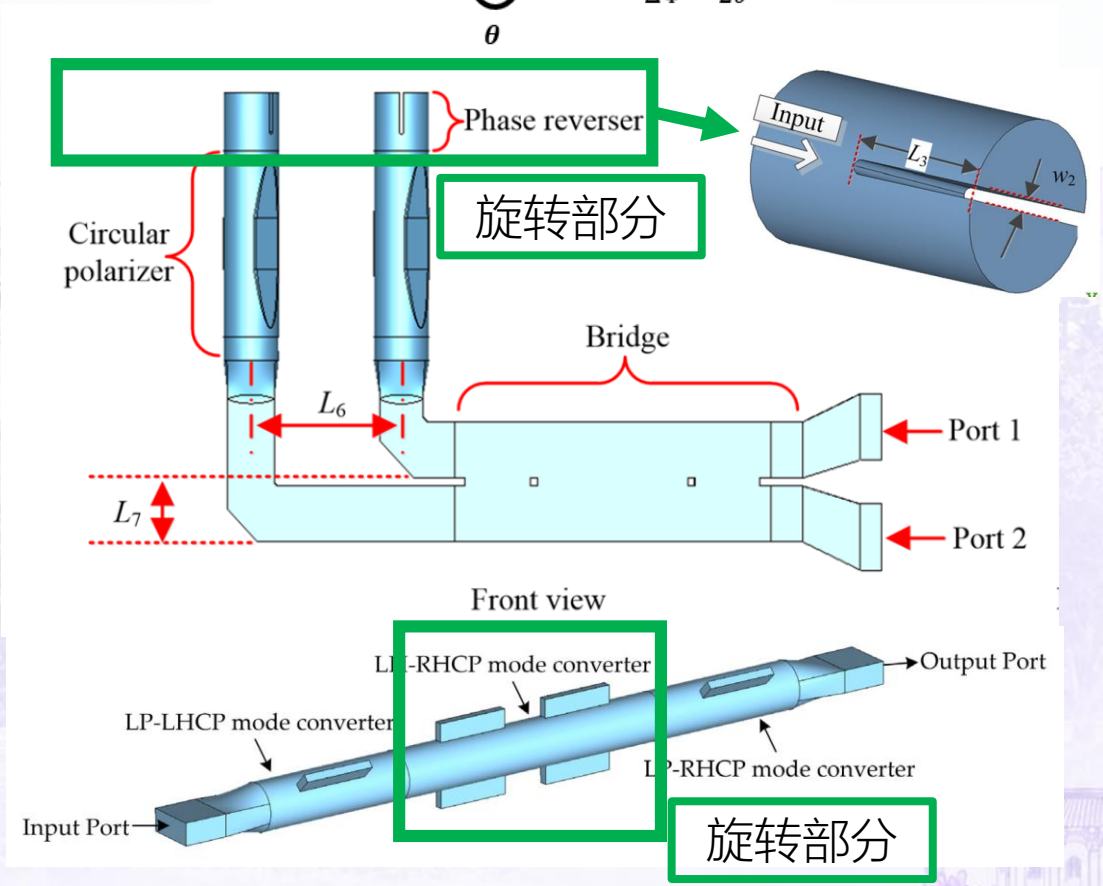
马骥.Ka波段高功率铁氧体波导移相器.电子科技大学,2024
Zhuang, Q. et al. (2023). Rev. Sci. Instrum. 94(3).
Hu, F. et al. (2024). Rev. Sci. Instrum. 95(9).

移相器种类

- 旋转式机械移相器
- 基本原理
  - 2θ效应
- 或 直接旋转短路面







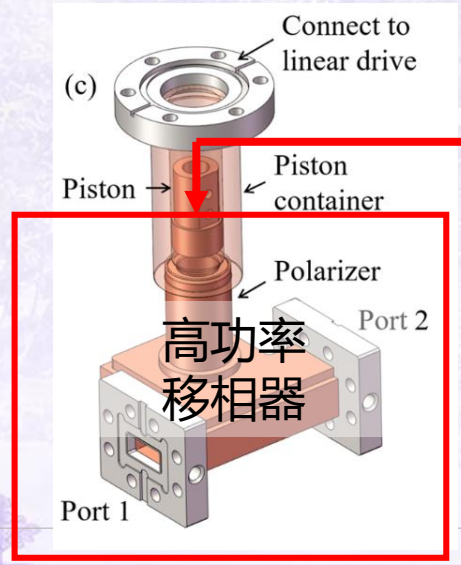
Yuan, C.-W. et al. (2020). Rev. Sci. Instrum. 91(11).
Zhuang, Q. et al. (2023). Electronics 12(13): 2963.
Cai, J. et al. (2024). IEEE Microw. Wirel. Technol. Lett. 34(4): 383-386.

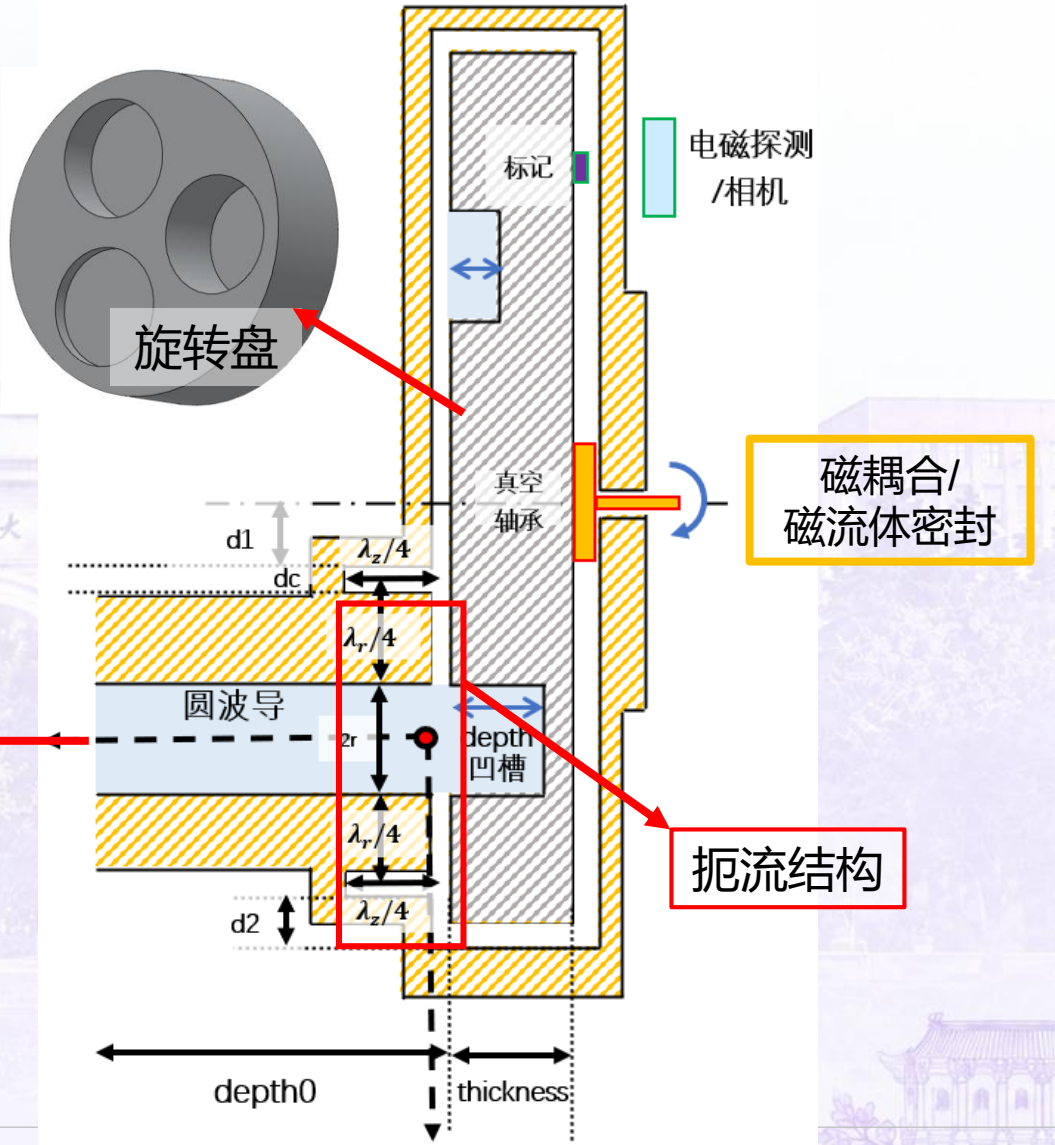
内 容 提 要

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移相器方案

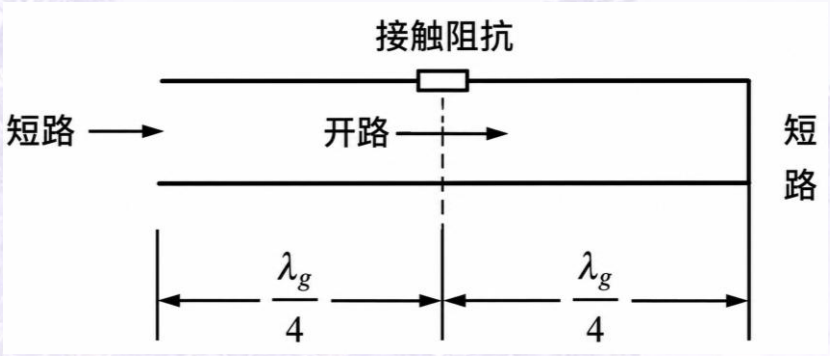
- 设计方案
  - 短路面 连续旋转
  - 照射100ms 宏脉冲200ns
- 剂量估算
  - 目标~40Gy/s剂量率
  - 3束线均分 圆盘~800rpm

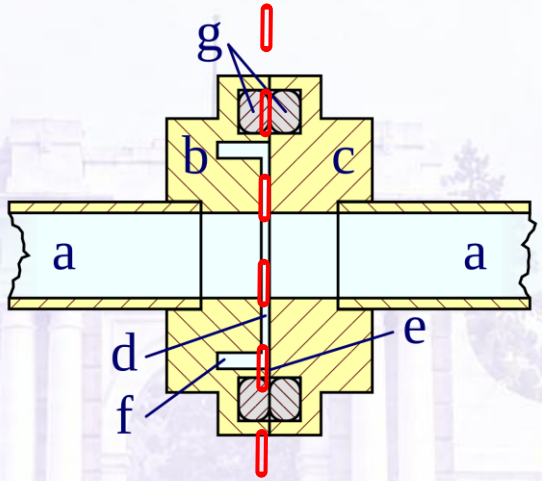


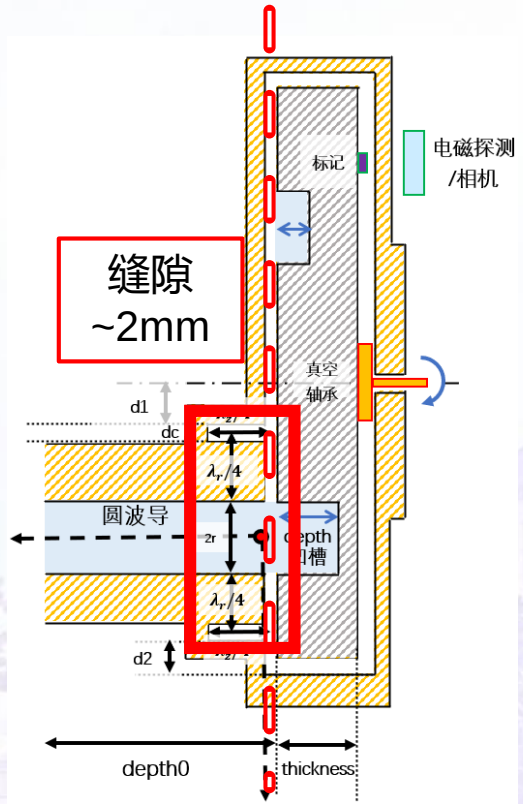


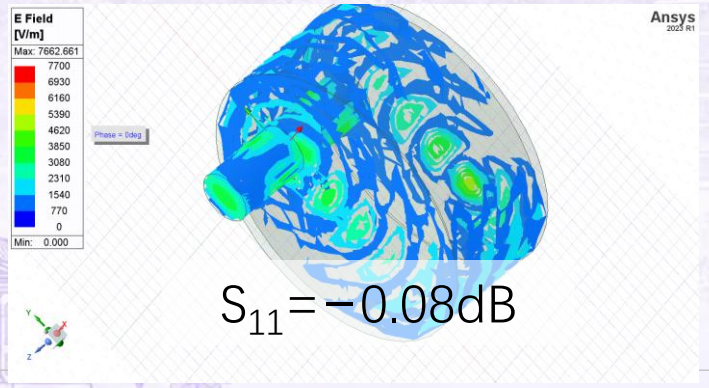
微波泄漏的抑制

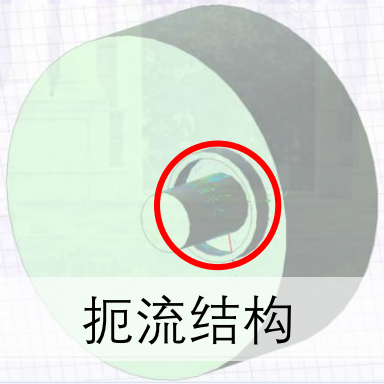
- 扼流原理
  - 传输线 λ/4阻抗变换
  - 高阻抗 抑制微波泄漏

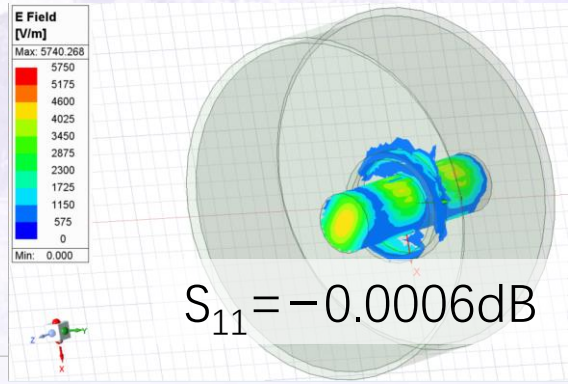






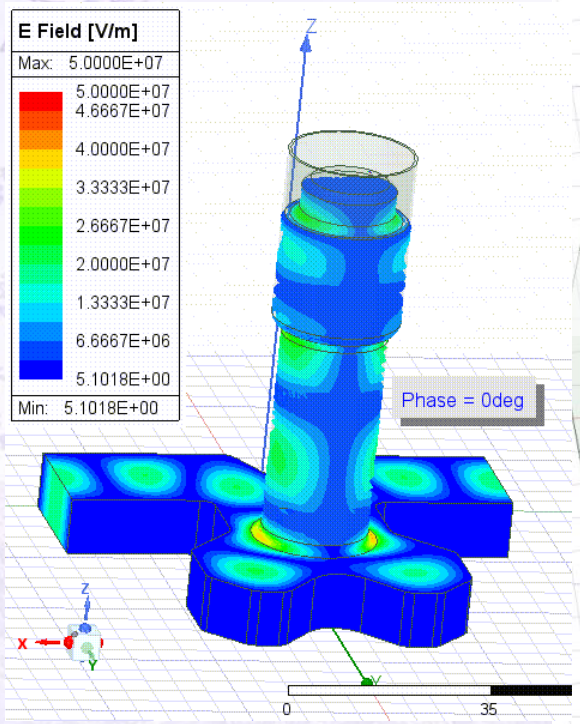


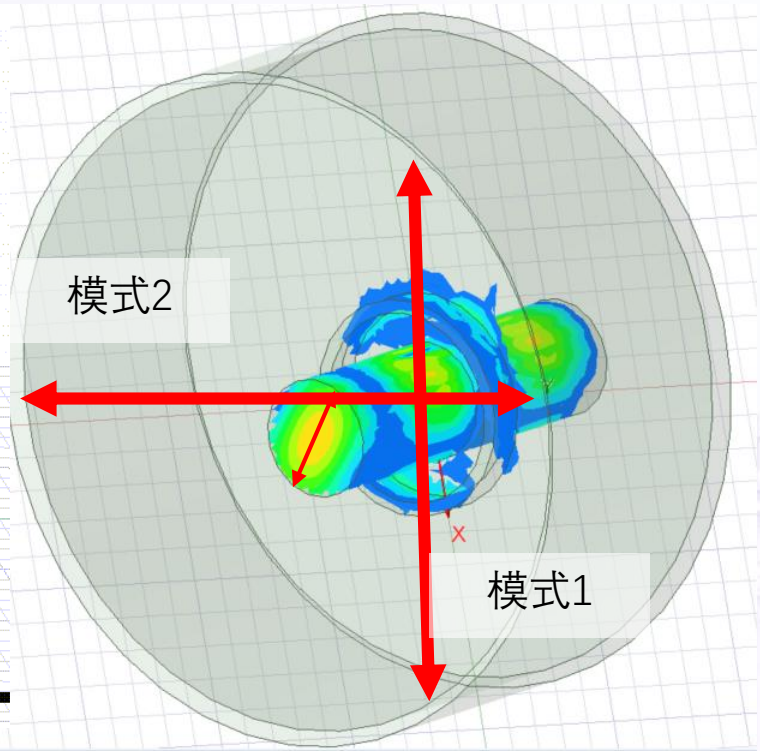




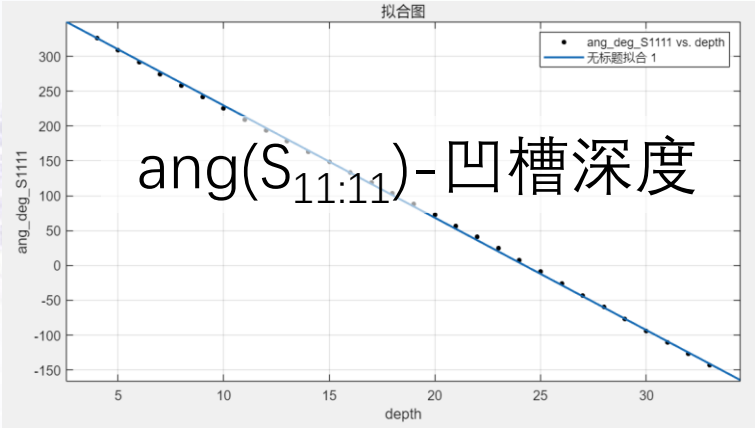
顾茂章/张克潜, 微波技术, 1989

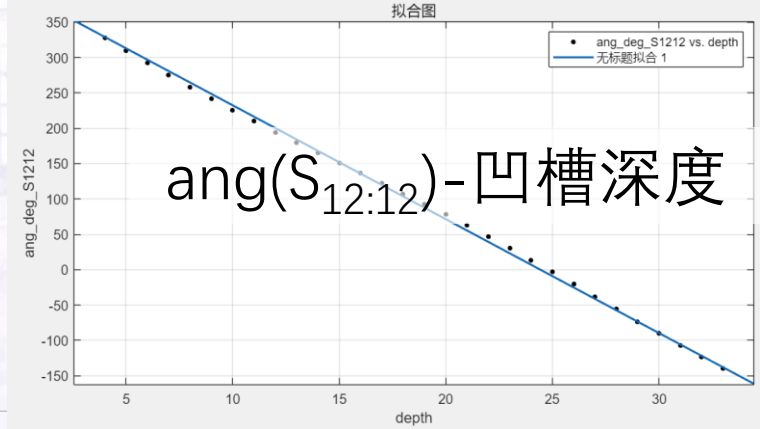
极化模式确认

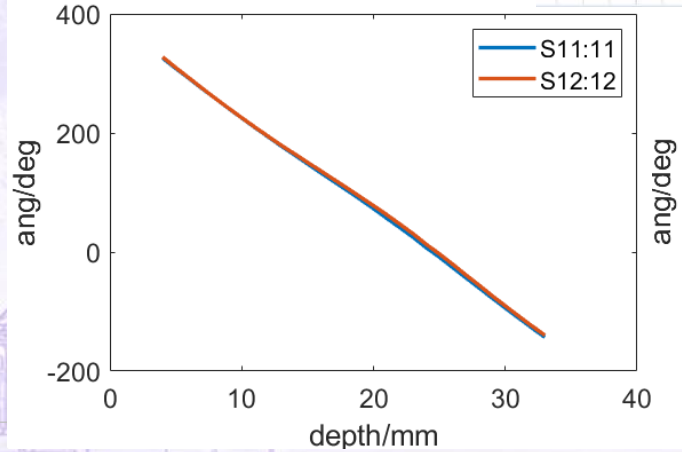


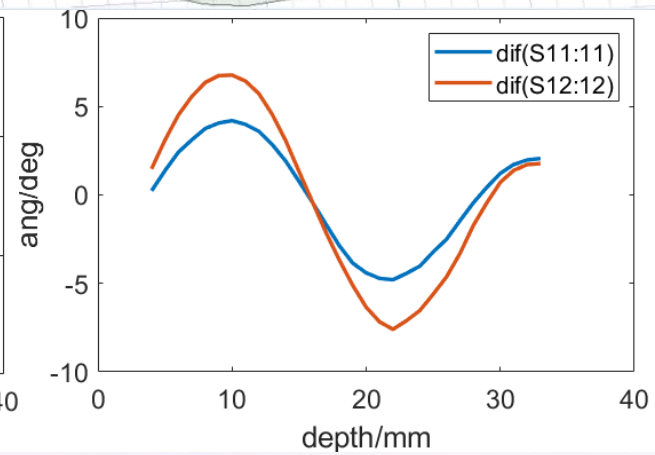


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- $ang(S_{12:12}) = 2\pi\frac{depth}{\lambda_0} + \theta_{12,0} + \boldsymbol{dif(S_{12:12})}$





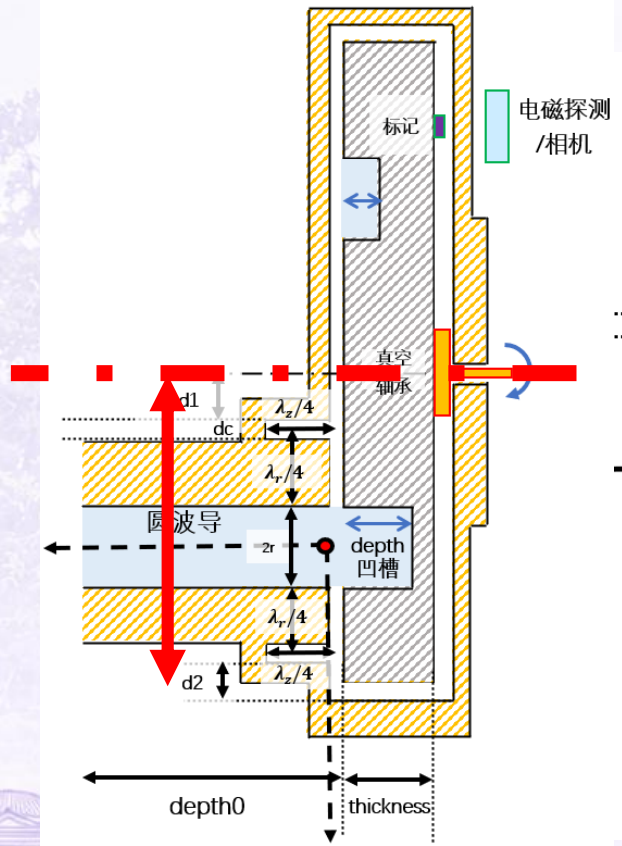




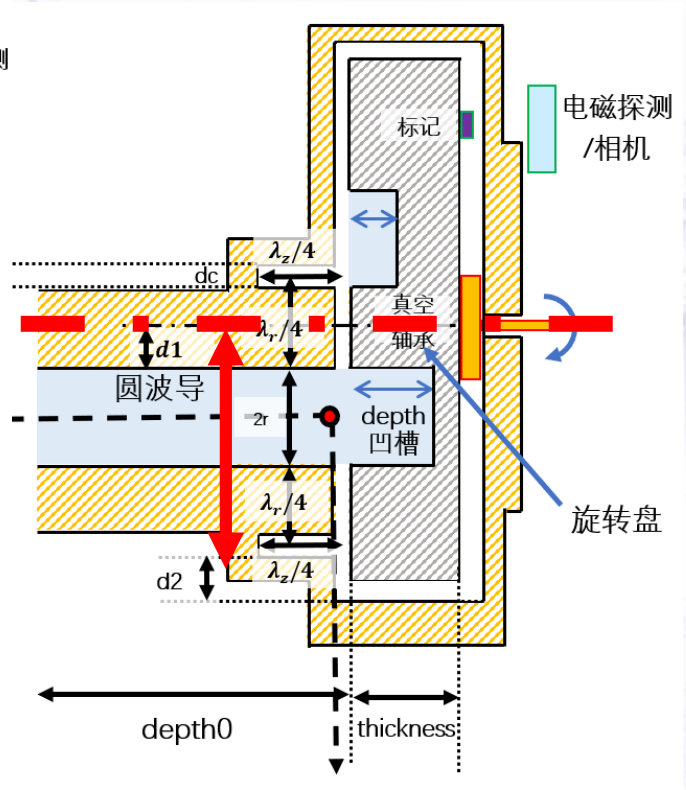
相位差~2°;最大<5°

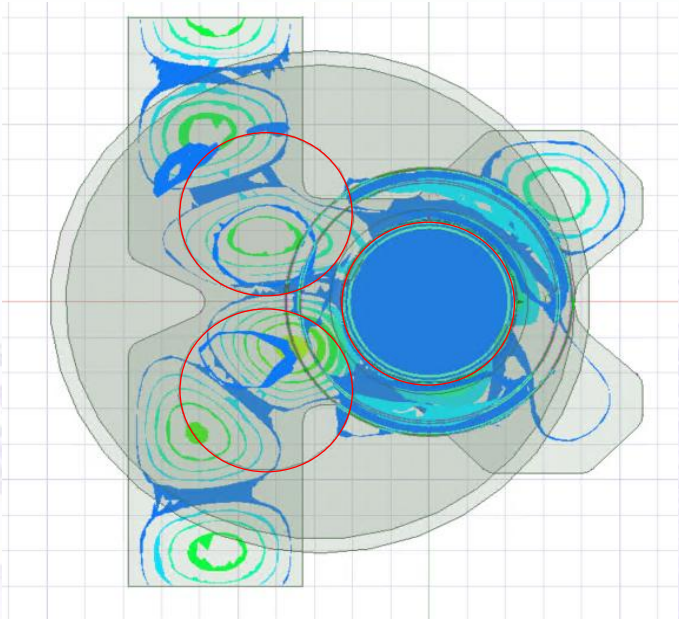
更紧凑的设计

- 初版



- 新版

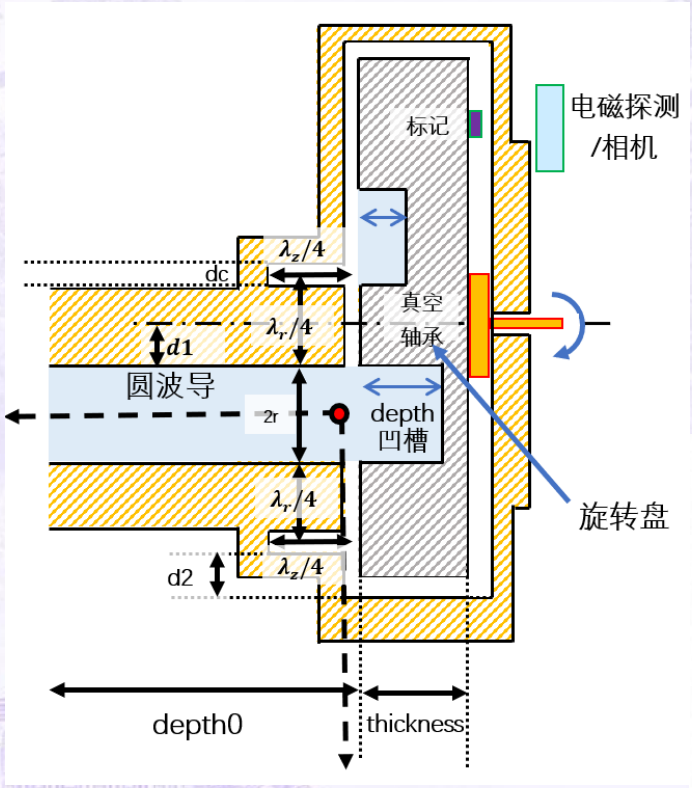




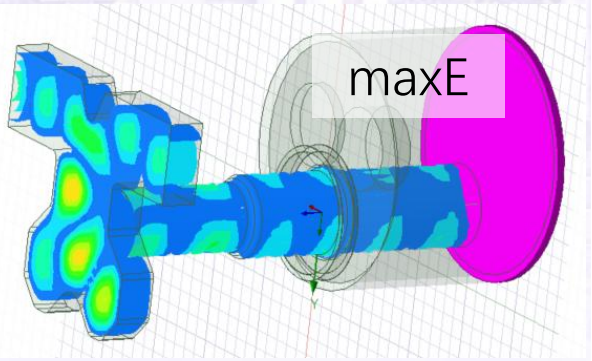
- 盘半径缩小为70%
- 最多5凹槽->3凹槽

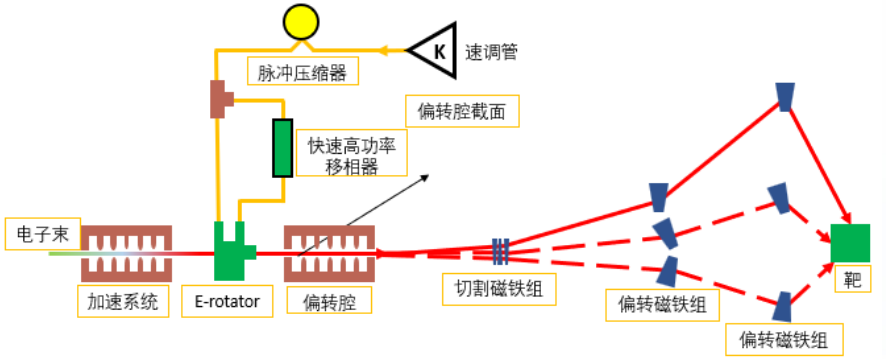
初步优化结果

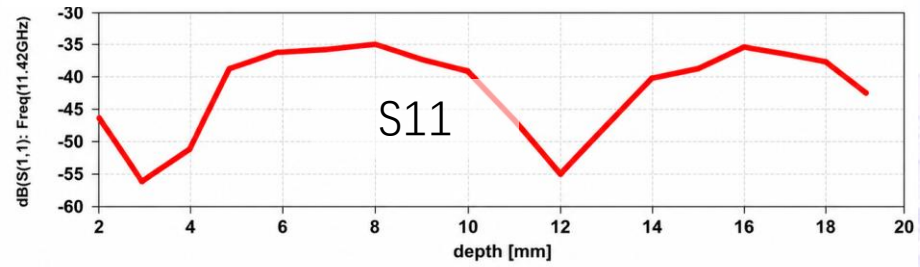
- 导波半波长17.6mm~120°相位差⇔5.88mm
- S21~(-0.055,-0.035)dB; S11<-35dB;
- 能量损失~1.2%； maxE~1400V/m

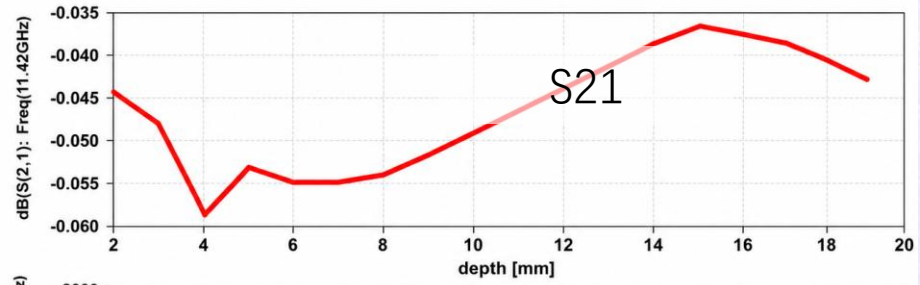


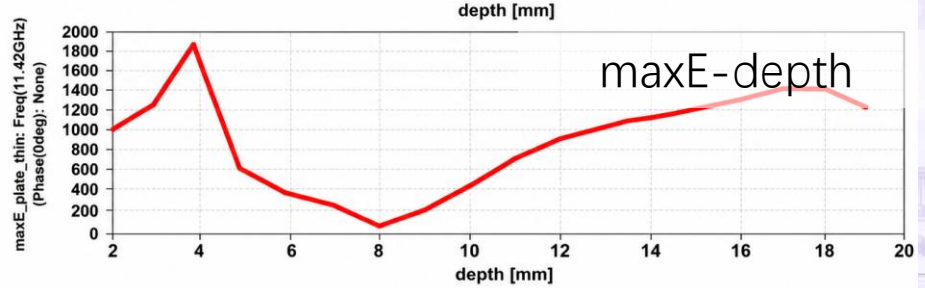








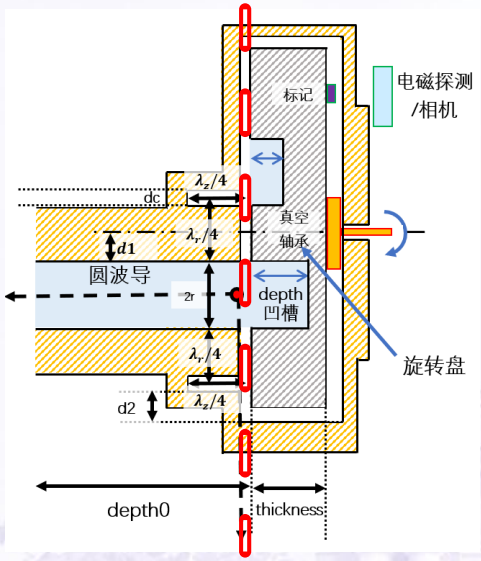


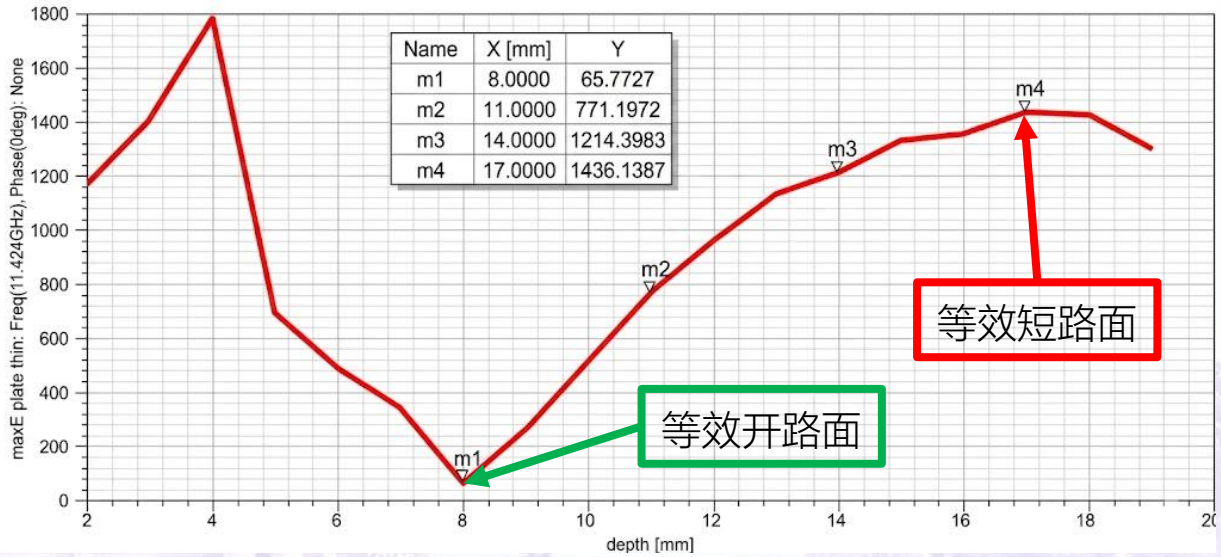


初步优化结果

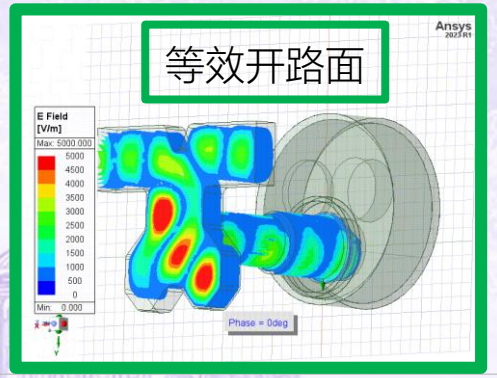
缝隙位置：

- 等效短路面最差
- 等效开路面最好

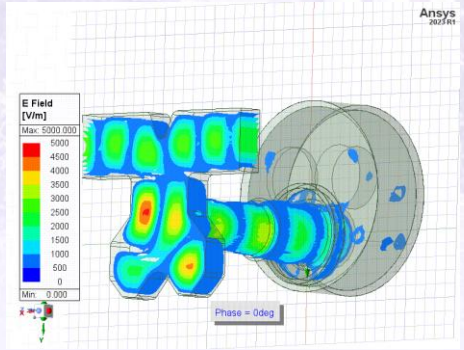




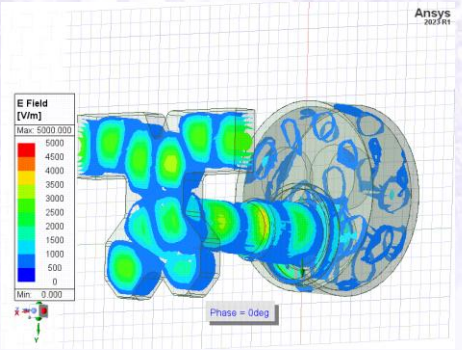
- 深度8mm~0°
- maxE~70



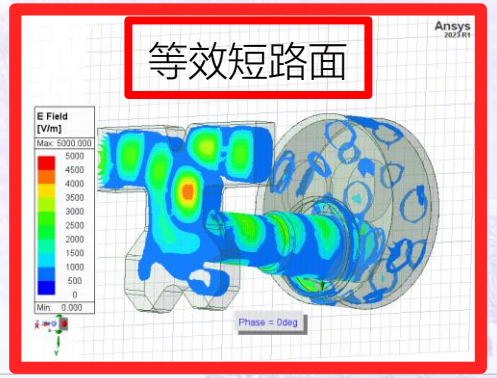
- 深度11mm~±60°
- maxE~770



- 深度14mm~±120°
- maxE~1210

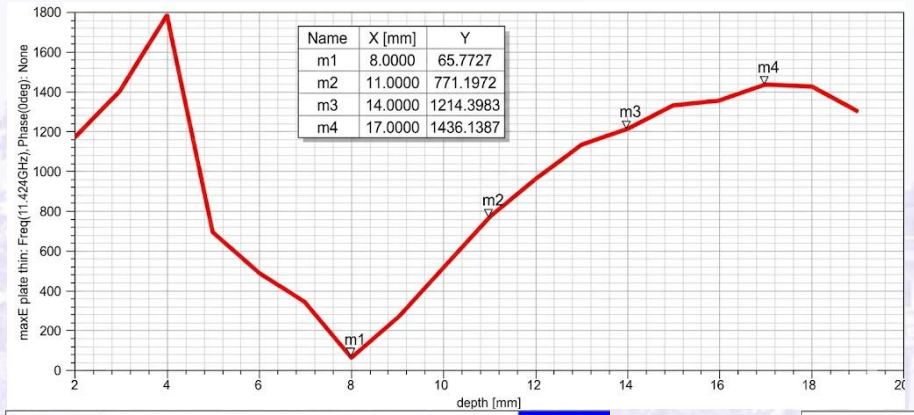


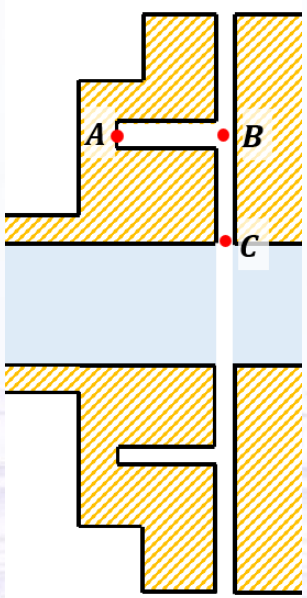
- 深度17mm~±180°
- maxE~1440

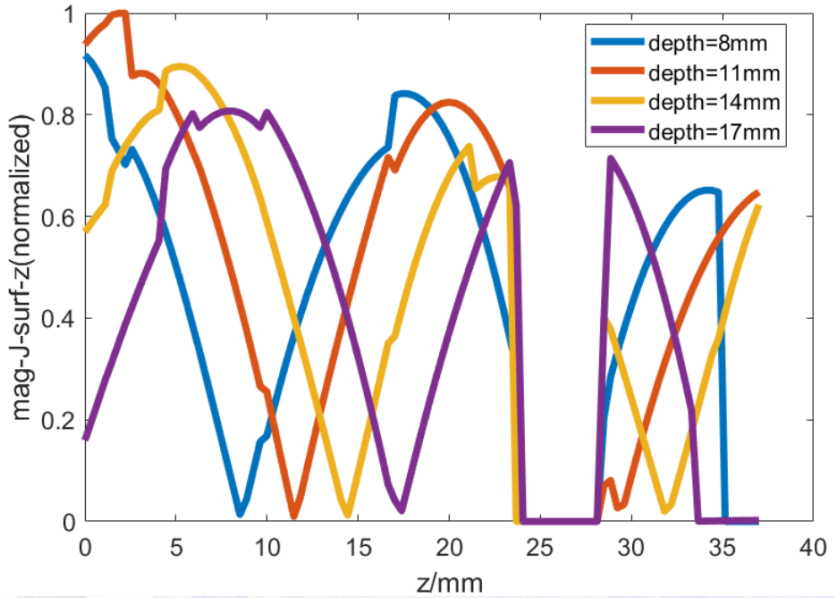


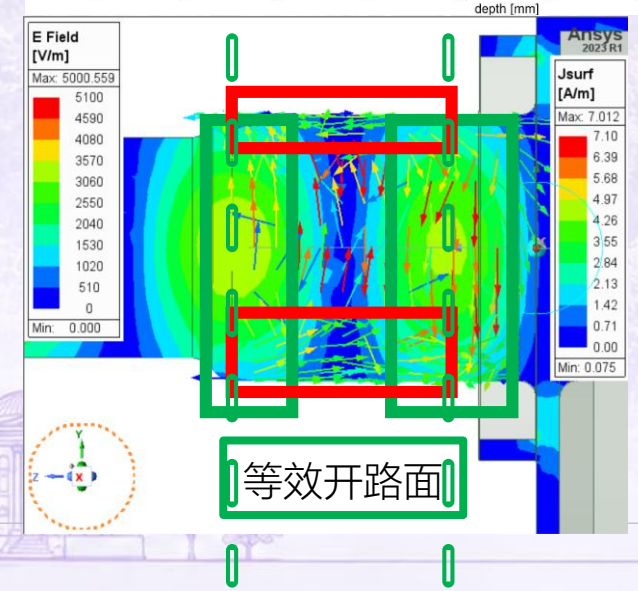
扼流效果的原理

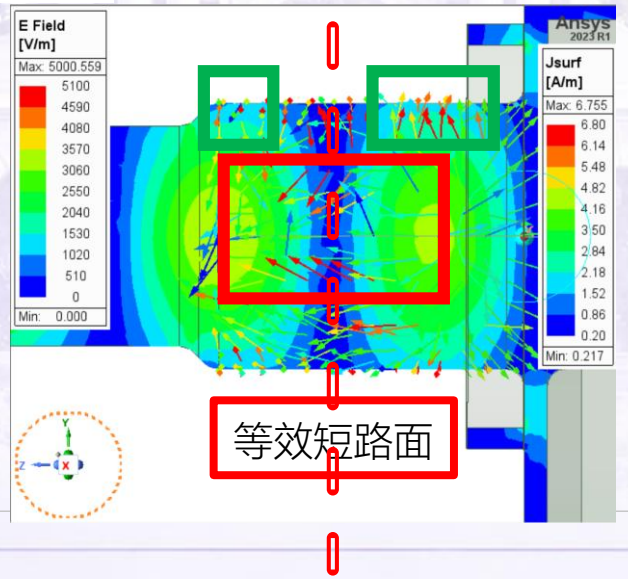
- 短路面扼流最差
- 纵向表面电流J_{surf-z}

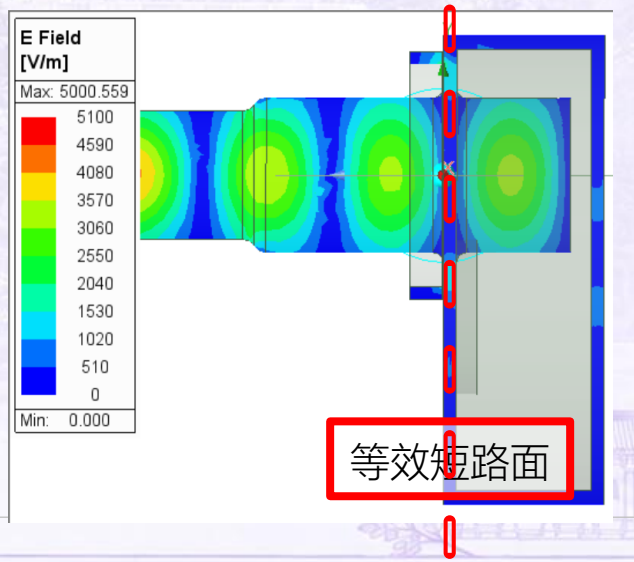






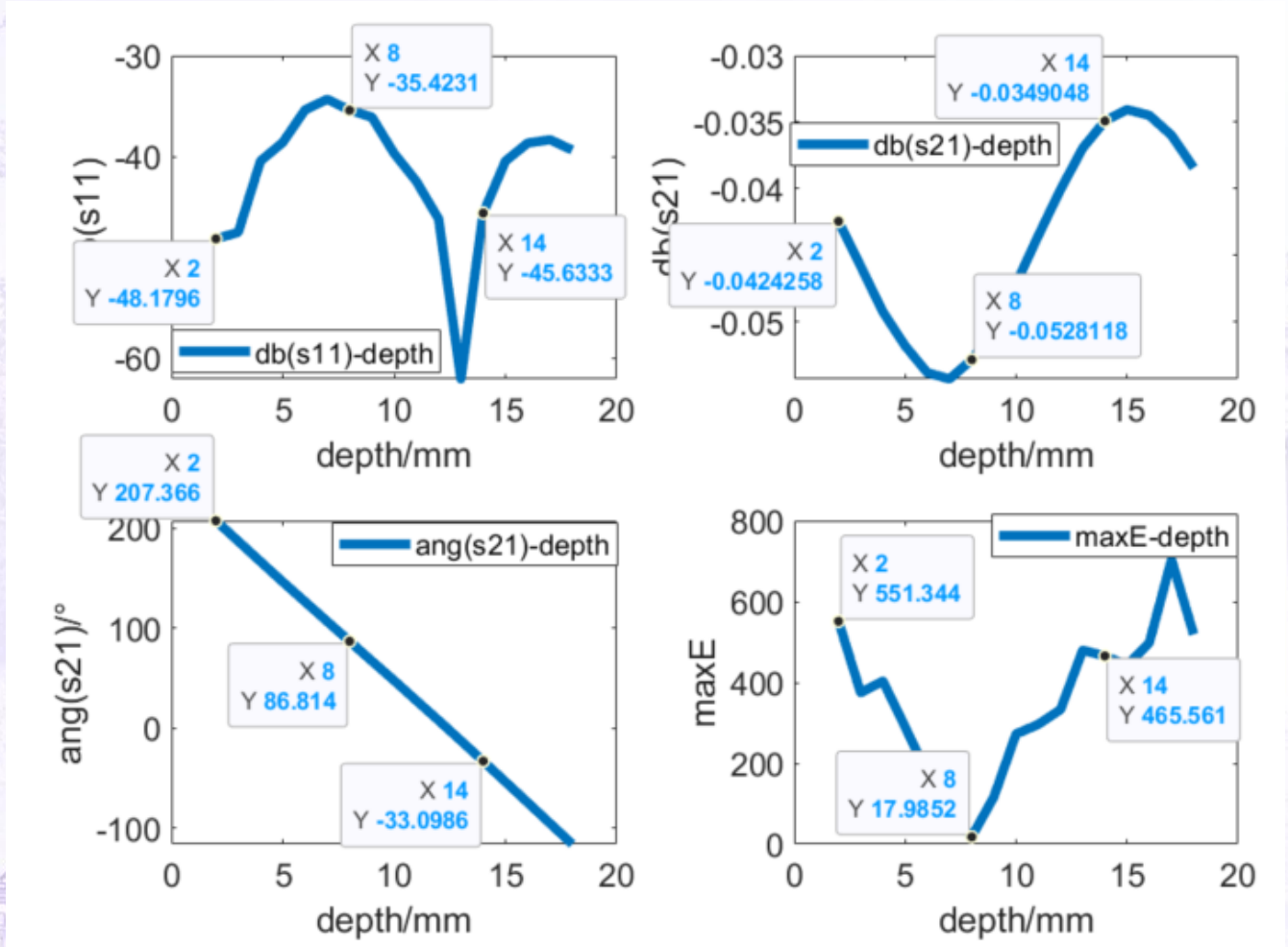


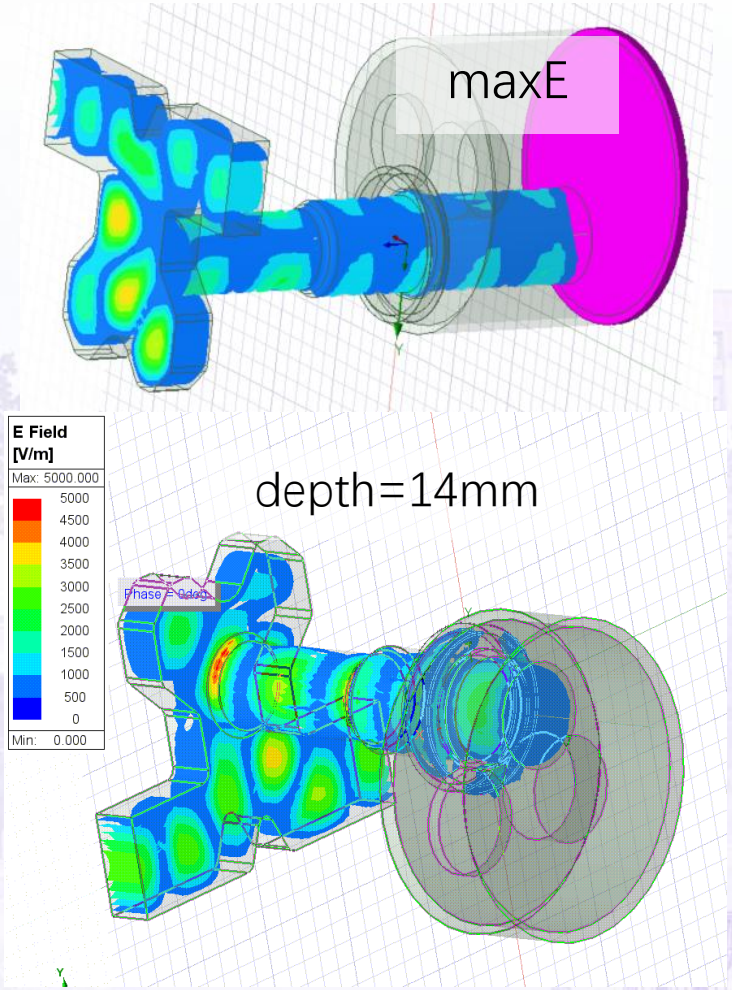




优化结果

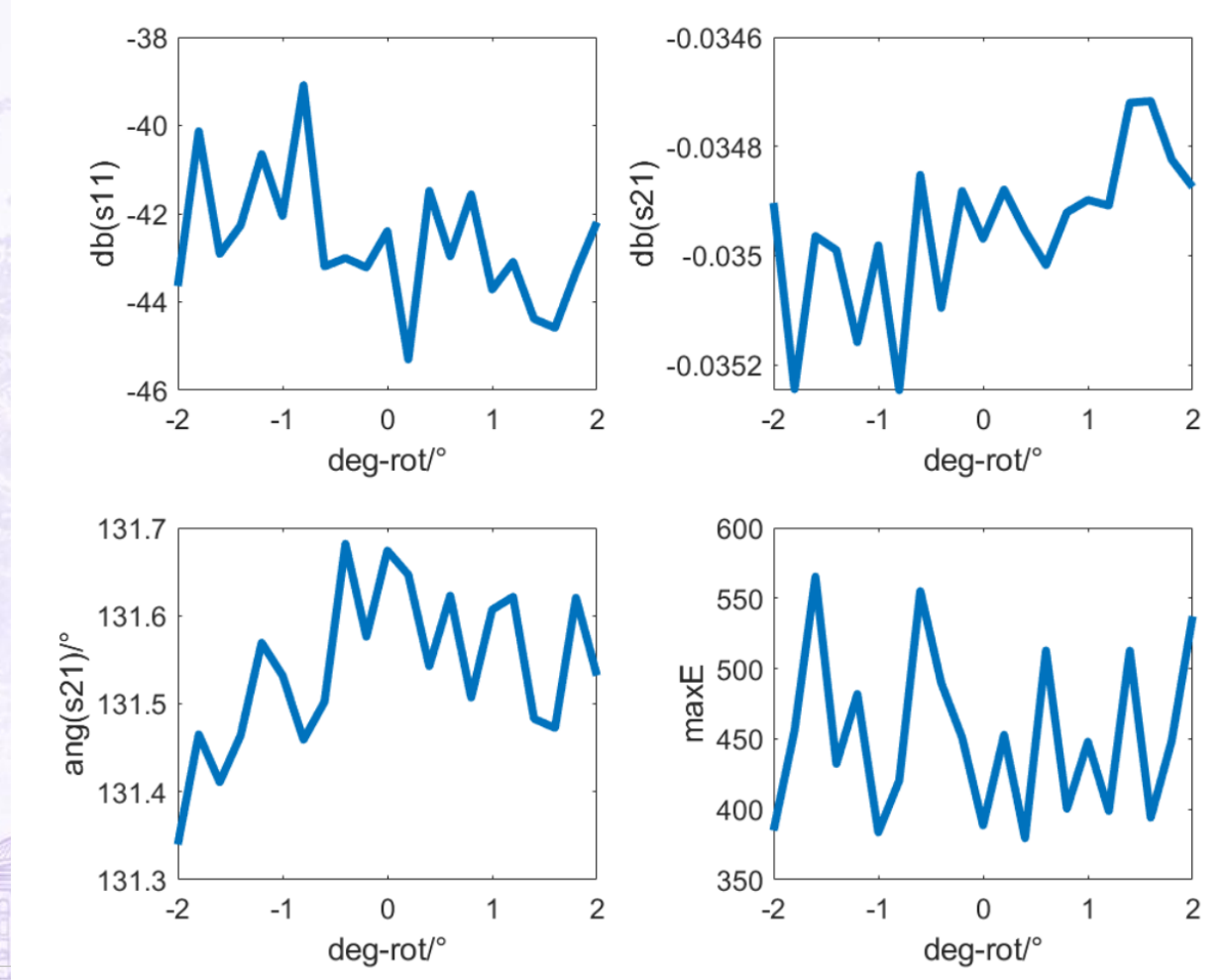
- 选择depth=14mm进行优化

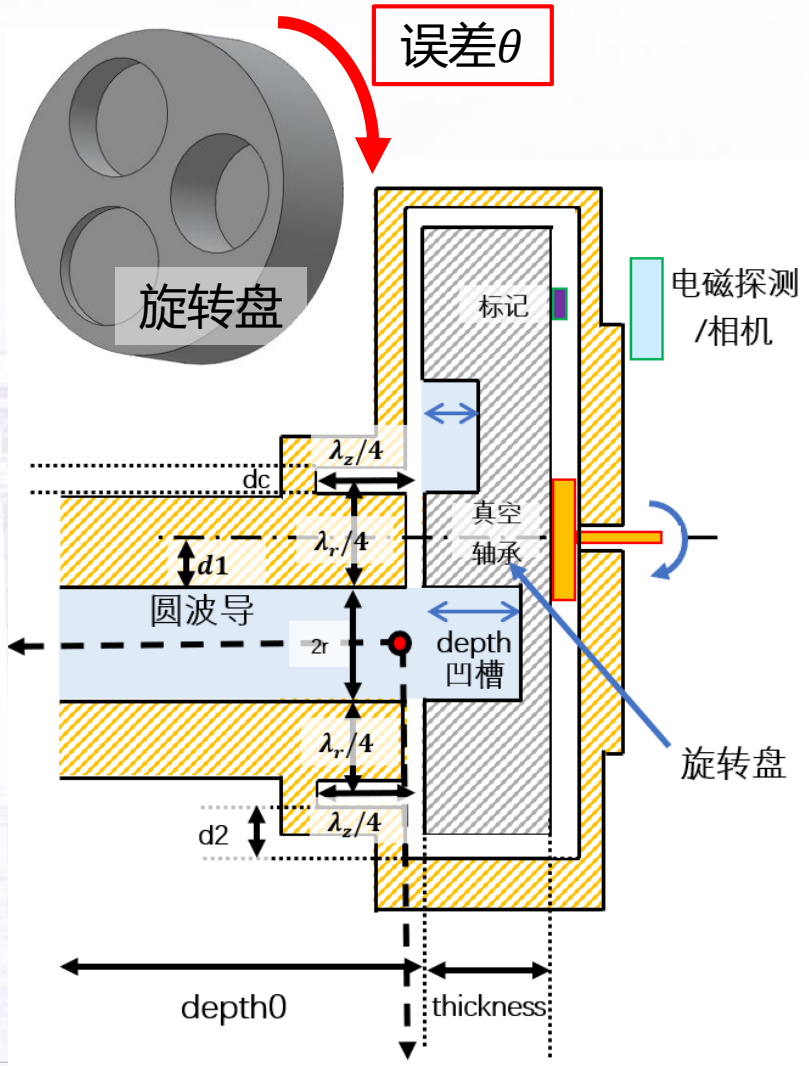




旋转误差估计

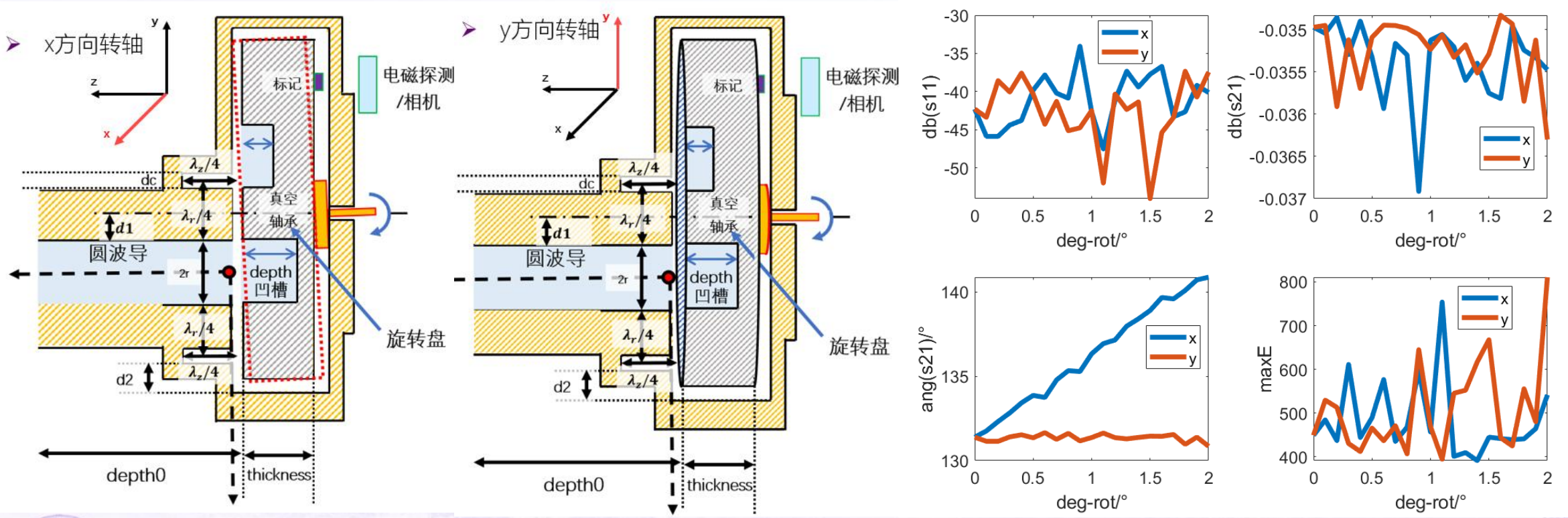
- 圆盘旋转角度误差θ





同轴度误差估计

- 工程上 同轴度误差一般<0.2°
- x轴转0.2°~相位差2°

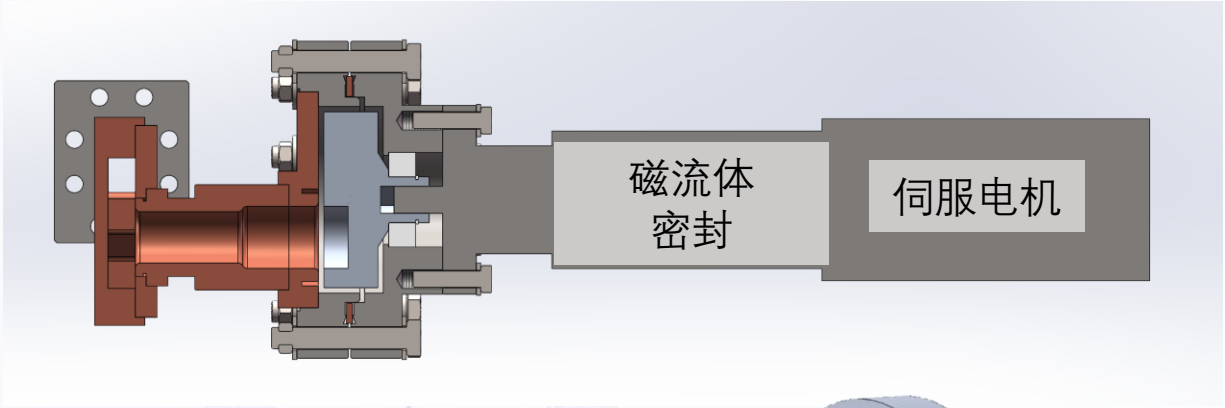


内 容 提 要

- 研究背景及意义
- 研究内容及方法
- 待进行的工作

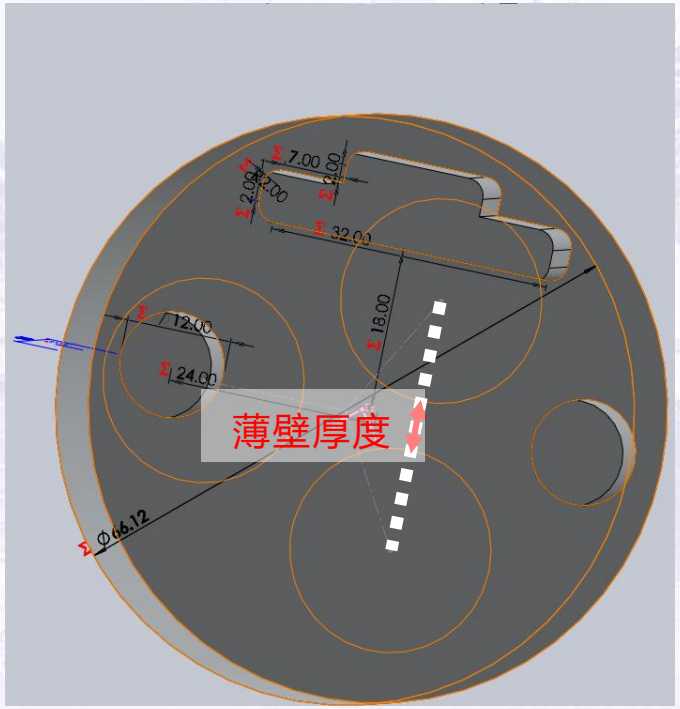
加工前的调整

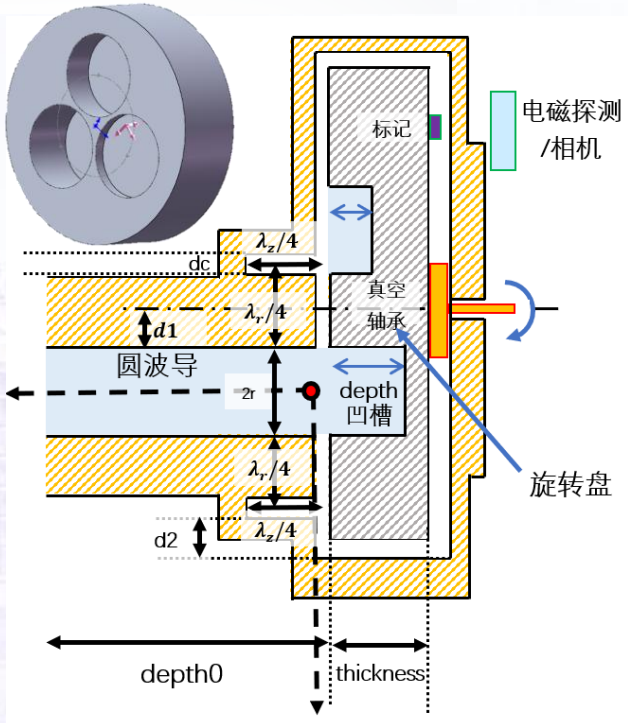
- 增加薄壁厚度
- 初步动平衡



薄壁厚度：2→3mm

参数	值/mm	值/mm
d	2	2
d1	2.94	3.52
d2	2.62	2.58
r	11.5	11.5
depth	1.98/7.95/13.92	
thickness	20	
λ_r	22.23	22.33
λ_z	29.09	29.45
dc	1.88	2.19
薄壁厚度	2	3.015
圆盘半径	33.06	33.78



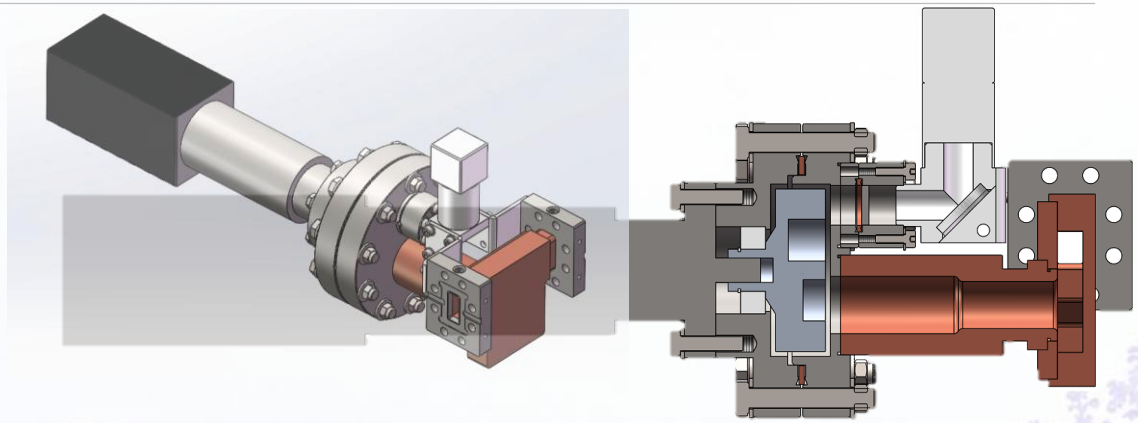


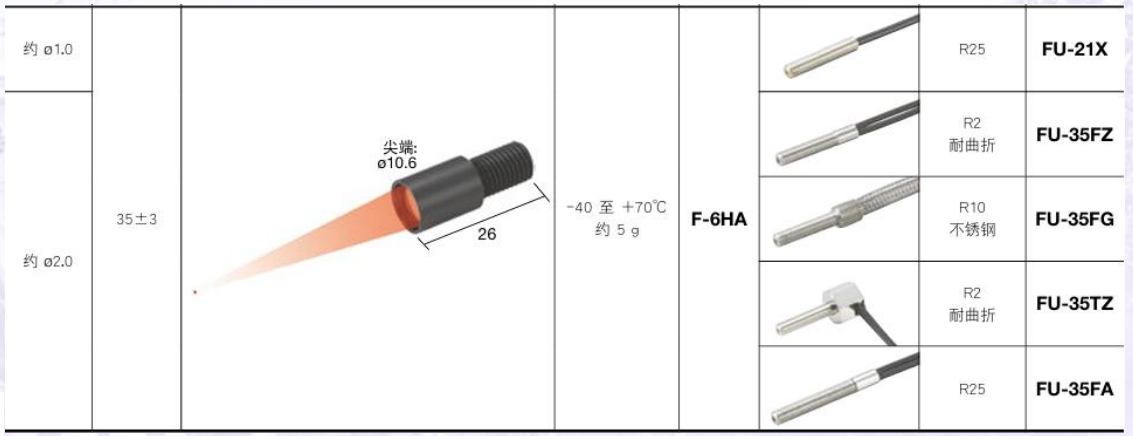
转速探测 方案与测试

- 暂定方案
- Keyence:
  - FS-N41P放大器+FU-35FA同轴反射光纤 +F-6HA长聚焦镜头（焦距~35mm）
- 近两周 制作真空外样机 验证测试
- 后续工作
  - 对接磁流体密封厂家
  - 安装电机
  - 完整测试

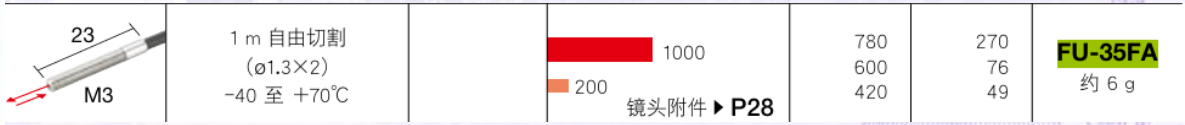


磁流体密封产品





F-6HA 产品手册



FU-35FA产品手册

谢谢观看

敬请各位老师同学批评指正

2026.10.17