



高强度缪子束流的产生 现状与展望

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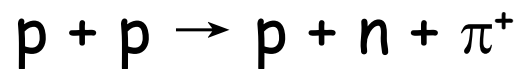
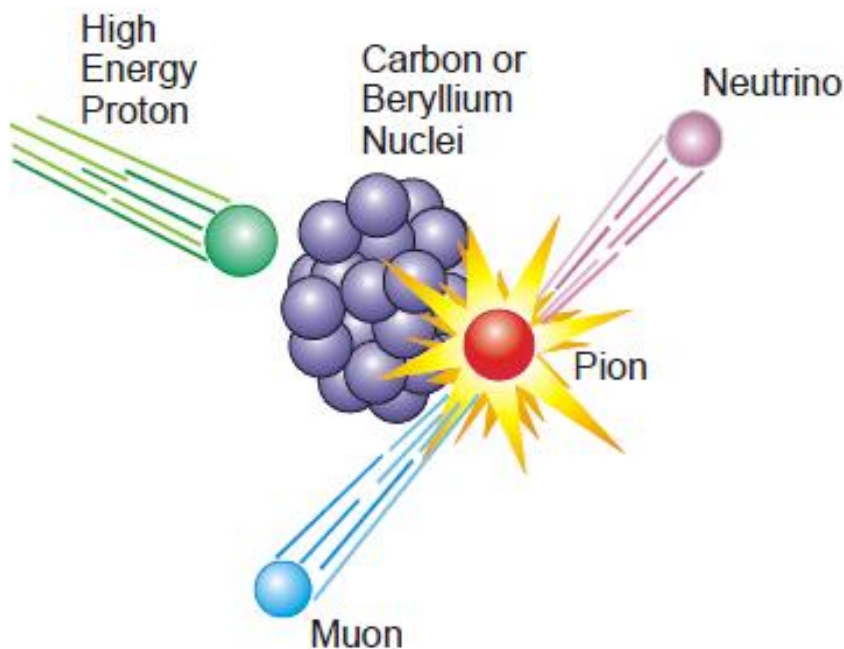
缪子束加速和对撞机技术及其应用
科学与技术前沿论坛

目录

- 缪子束流产生
- 国际上研究
- 国内的研究
- 总结与展望

缪子产生

- 质子轰击靶物质
- 缪子作为三级粒子被产生与俘获

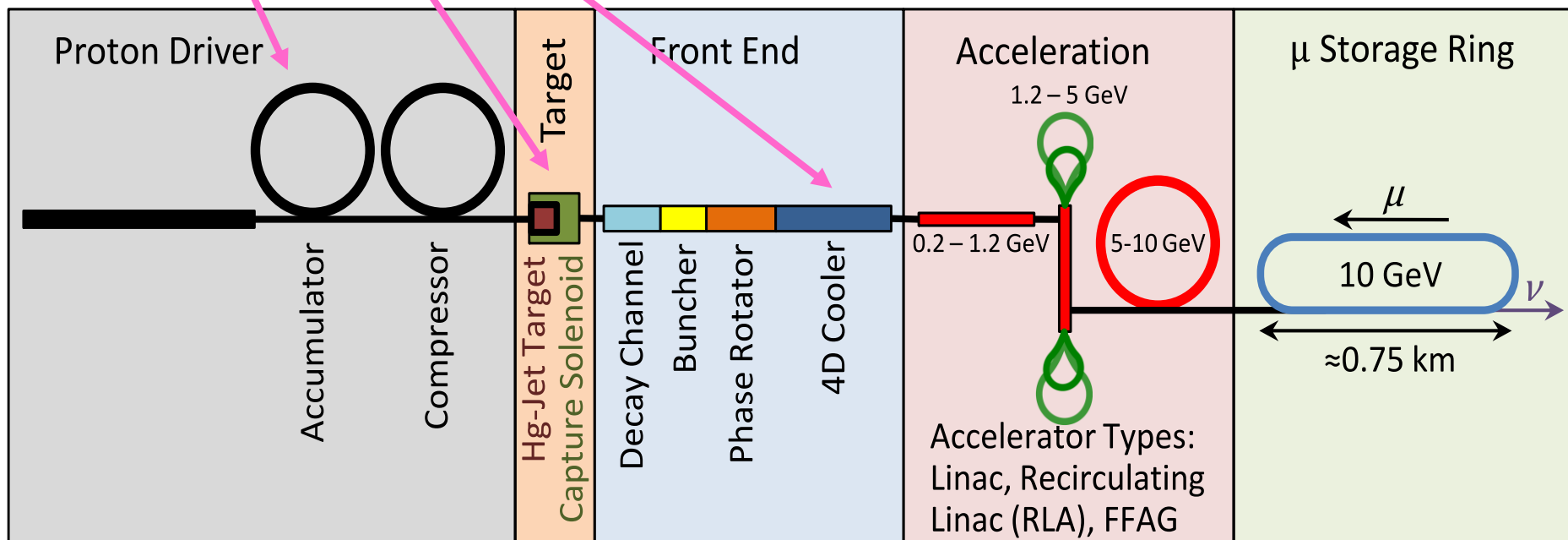


- 高强度缪子束流依赖于高强度质子束流，带来高强度辐射

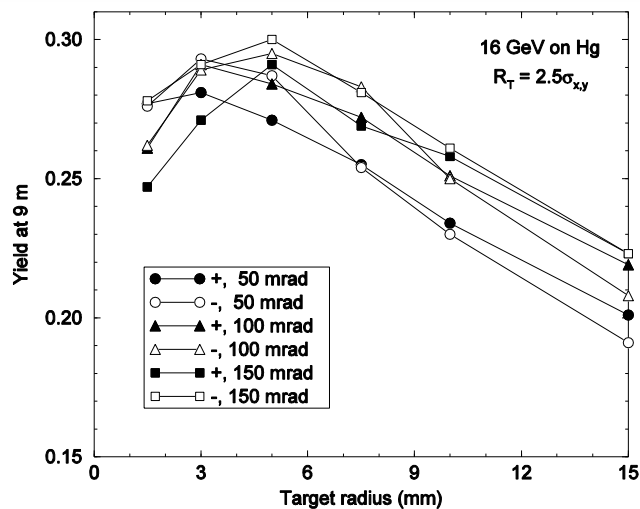
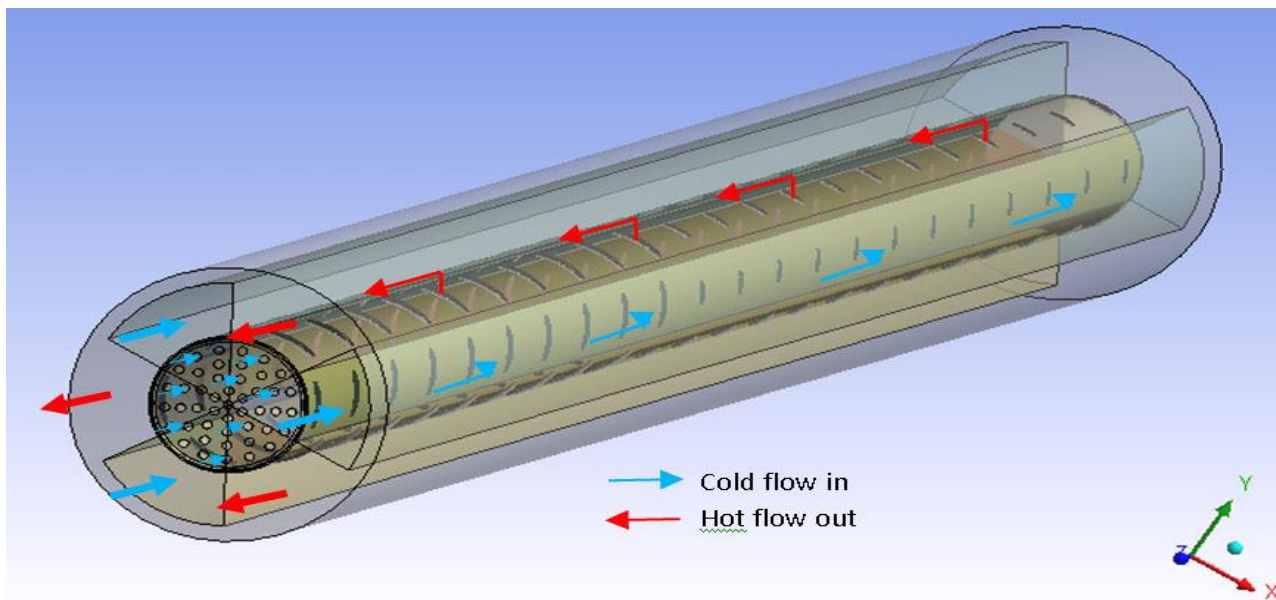
典型装置：中微子工厂

- 3 个主要的技术瓶颈：

- 高功率驱动器 ← 在中国发展迅速
- 靶站 ← 在中国有一些研究
- 缪子冷却 ← 在中国开展很少



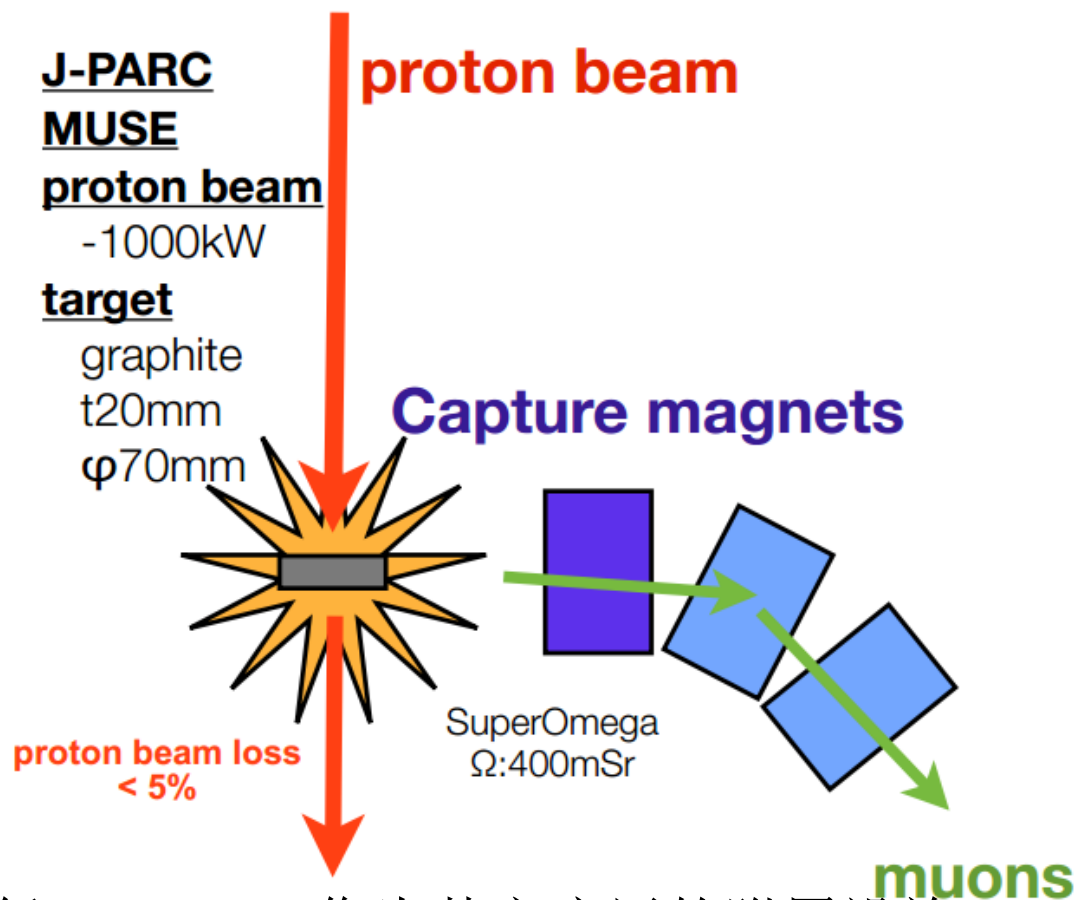
大尺寸的靶体会强烈吸收pion



Pion capture maximized by use of target of ≈ 5 mm radius.

传统缪子束线

- 薄靶
- 侧面收集



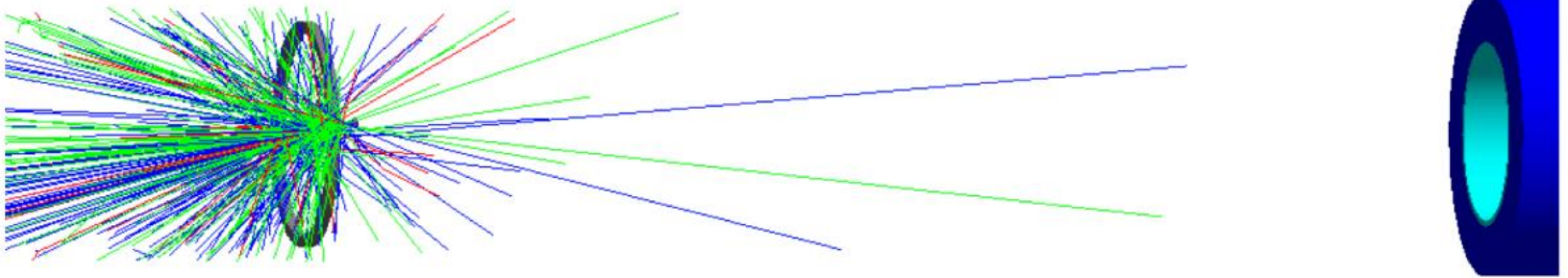
缺点:

- ◆ 束流利用率很低 ← 作为其它应用的附属设施
- ◆ 俘获效率很低
- ◆ 更适合收集低能表面缪子用于多学科研究而不是未来缪子加速器

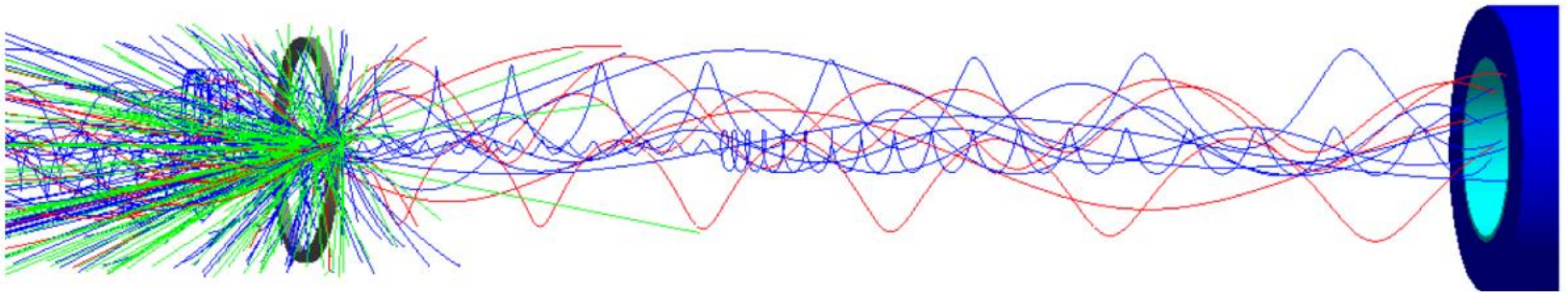
提高俘获效率

R.M. Dzhilkibaev, V.M. Lobashev, Sov.J.Nucl.Phys **49**, 384 (1989)

Instead of this

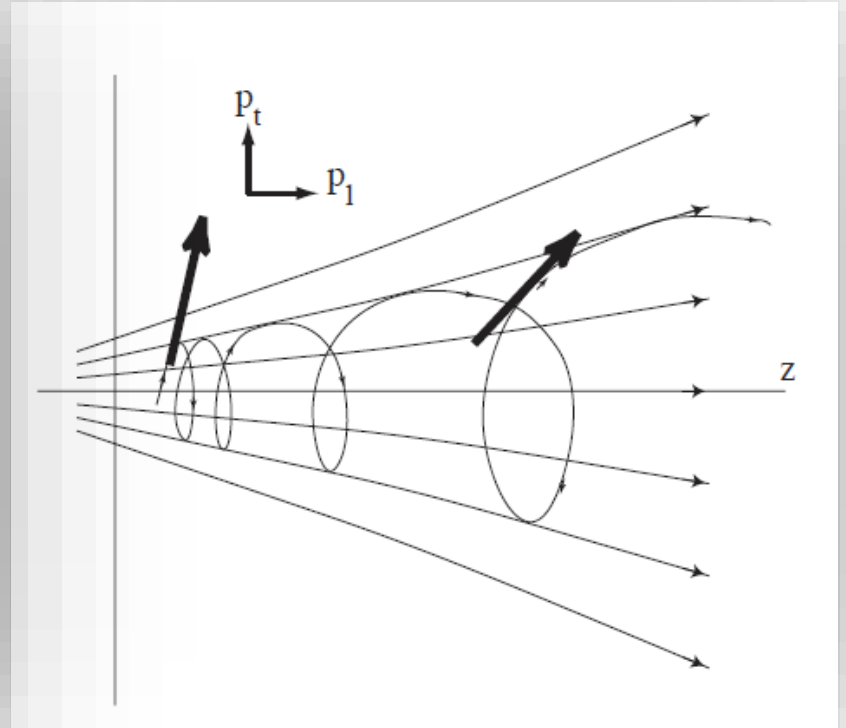
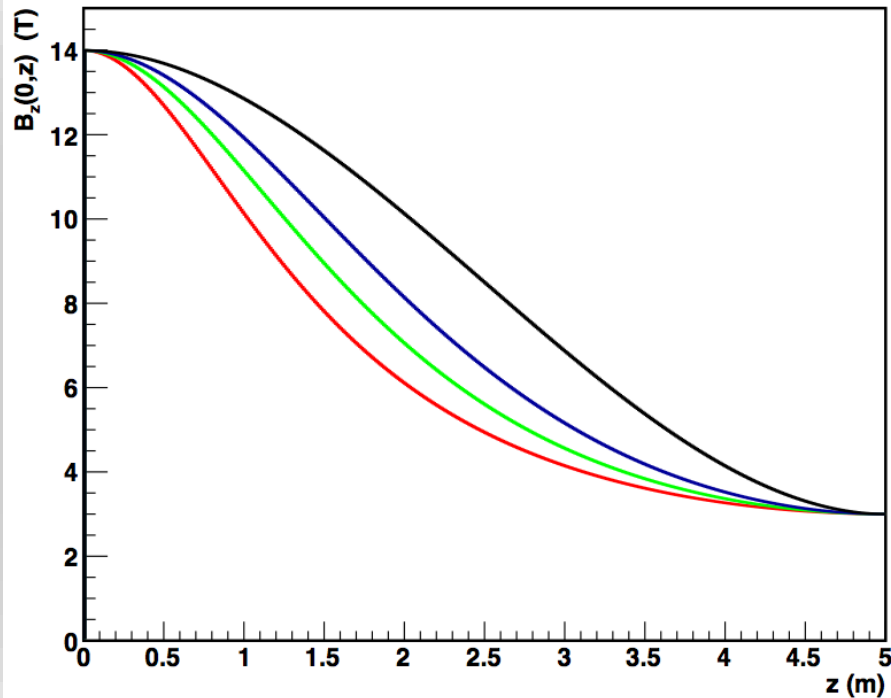


Do this



置于螺线管磁铁中心的靶

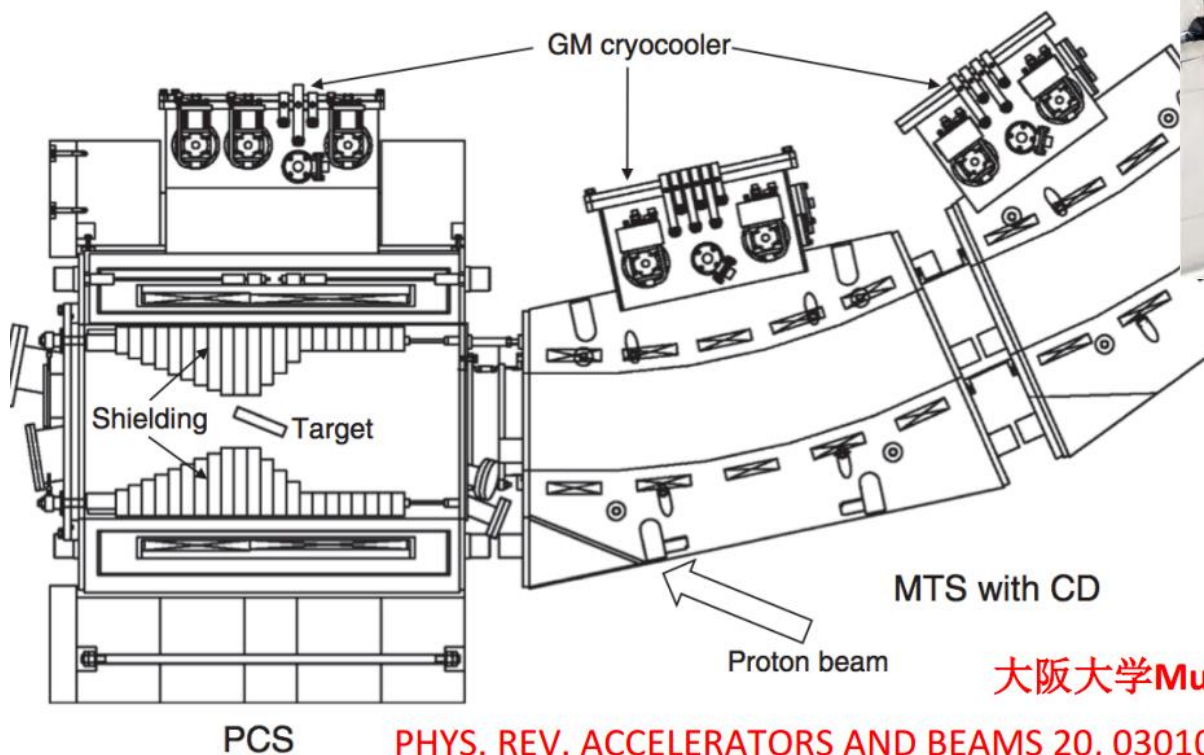
绝热梯度下降磁场俘获



$P_T^2 / B = C$
conservation of
magnetic moment

$P_L \rightarrow P_T$

验证实验: MUSIC @2011



MUSIC muon yields

μ^+ : $3 \times 10^8/\text{s}$ for 400W

μ^- : $1 \times 10^8/\text{s}$ for 400W

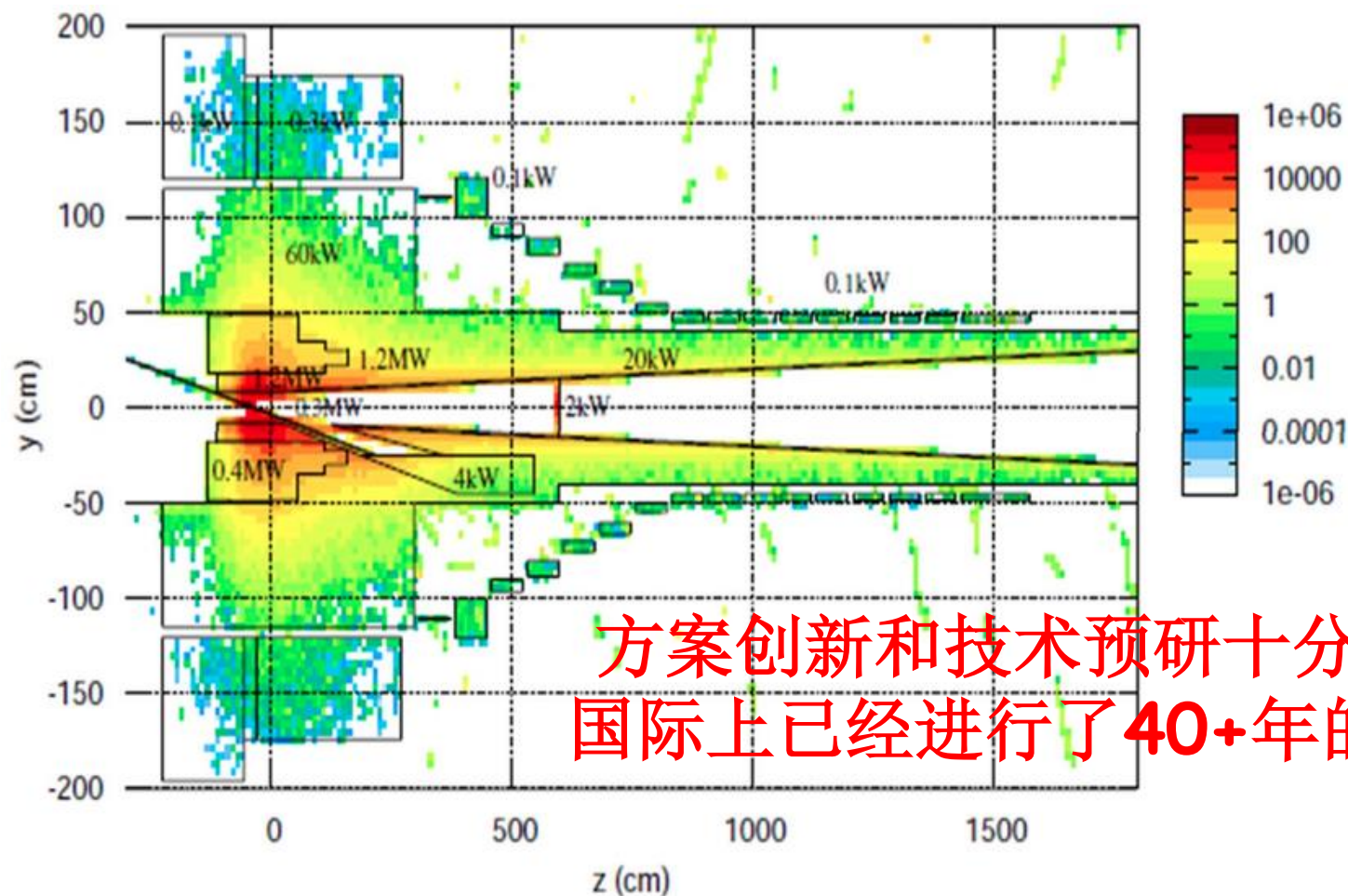
$10^8/\text{s}$ for 1MW @PSI

大阪大学MUSIC

1000倍の效率提升

技术挑战

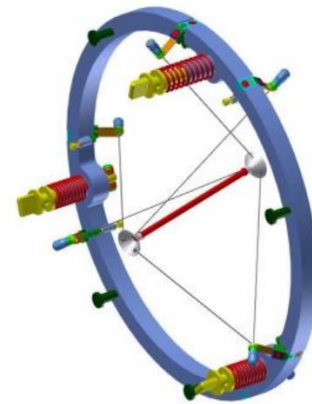
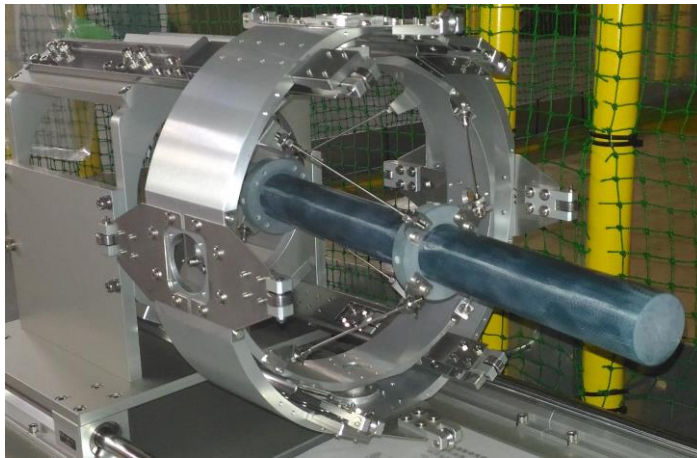
- 抗高辐射冲击的靶系统
- 抗高辐射、高热量沉积的磁铁系统



国际上研究

什么靶？

- 模拟表明细长的靶是最优的选择
- **MUSIC**以及随后开展的**COMET**、**Mu2e**等均采用这一方案并深入优化



- 但当功率达到**Multi-MW**，这一方案就失效了

Radiation damage is still a bottleneck of high intense beam -NuFact2019



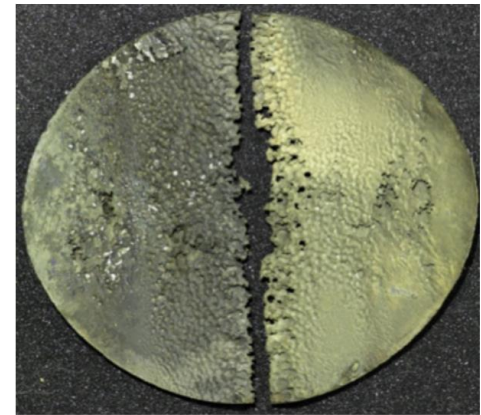
Ir rod after a single proton pulse (1.27×10^{12} pot)
Torregrosa et al. 2016. CERN-EN-2016-004



Cracked NuMI target, FNAL

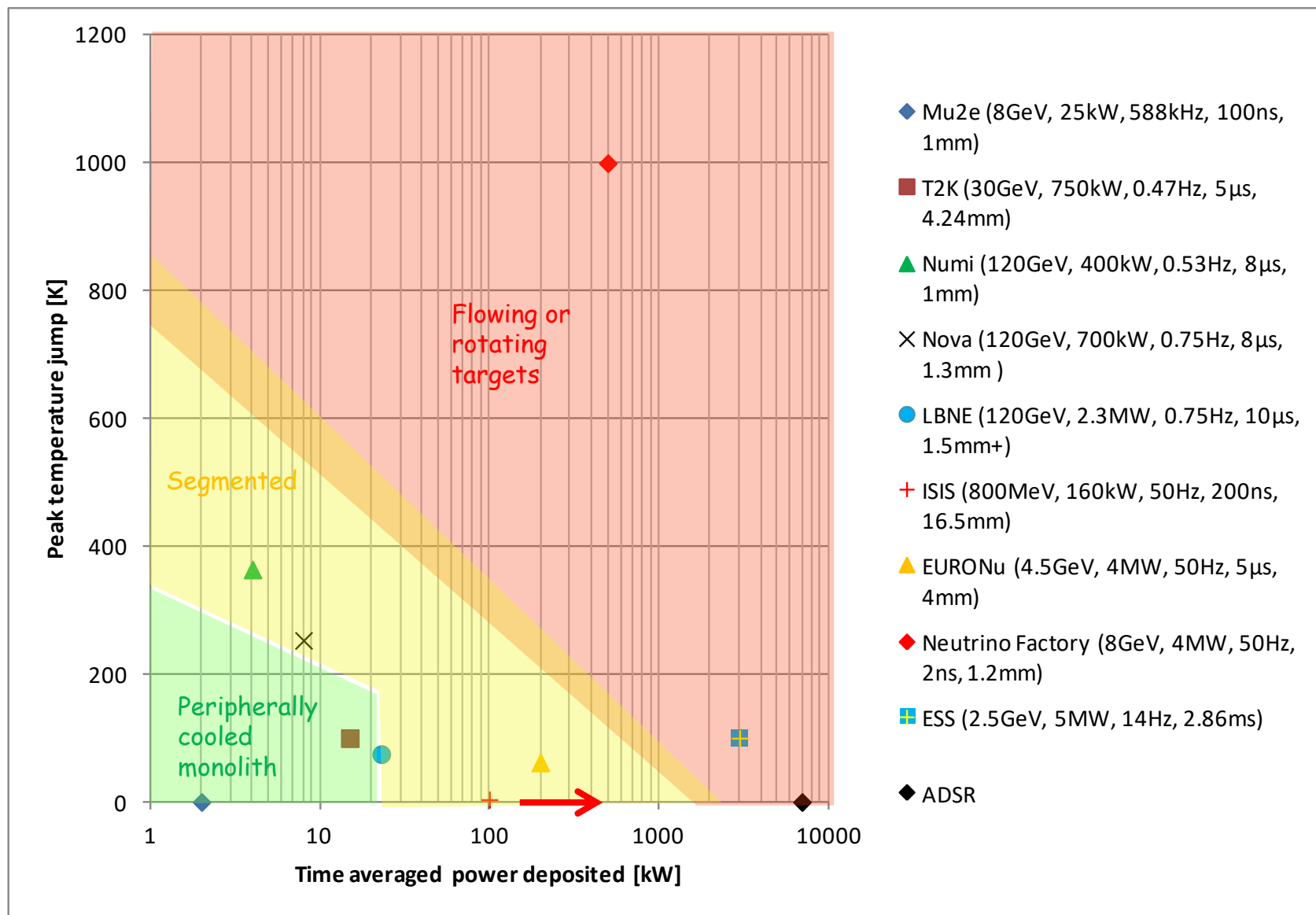


NuMI-MINOS target cooling water leak and radiation-assisted corrosion, FNAL



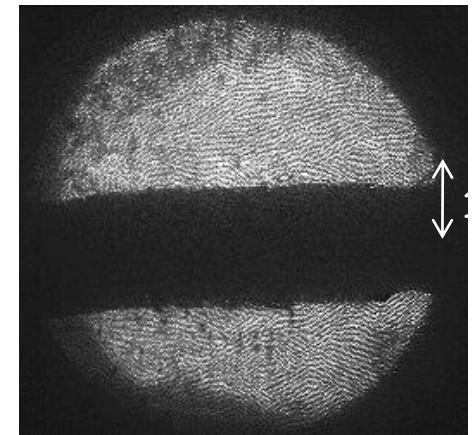
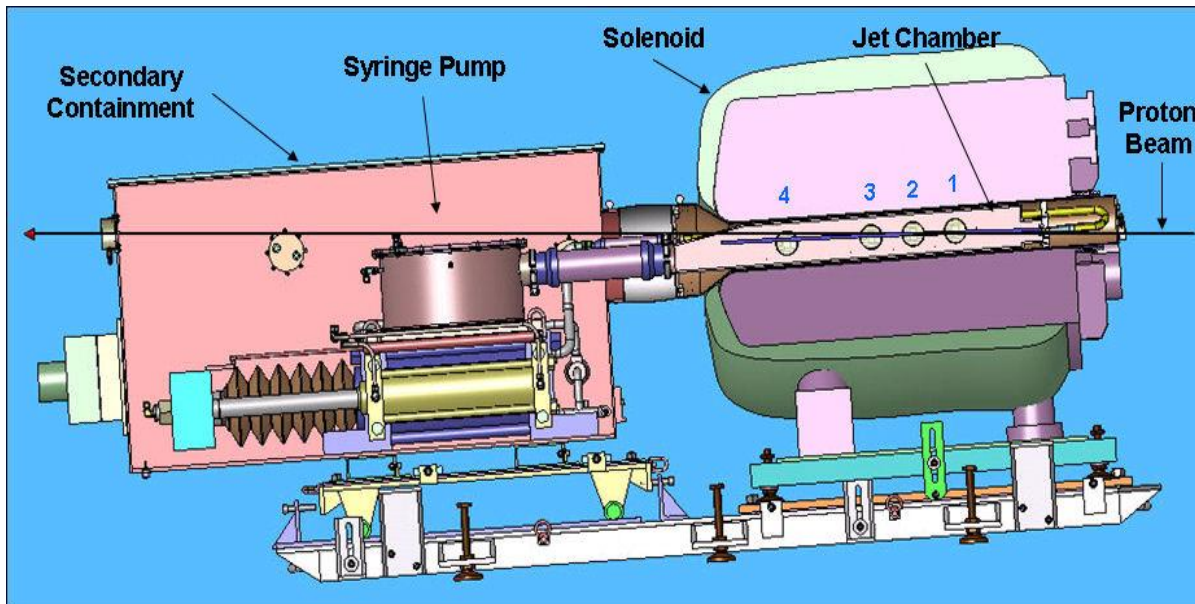
Cavitation-induced erosion of SNS target vessel, ORNL

各种靶技术的局限

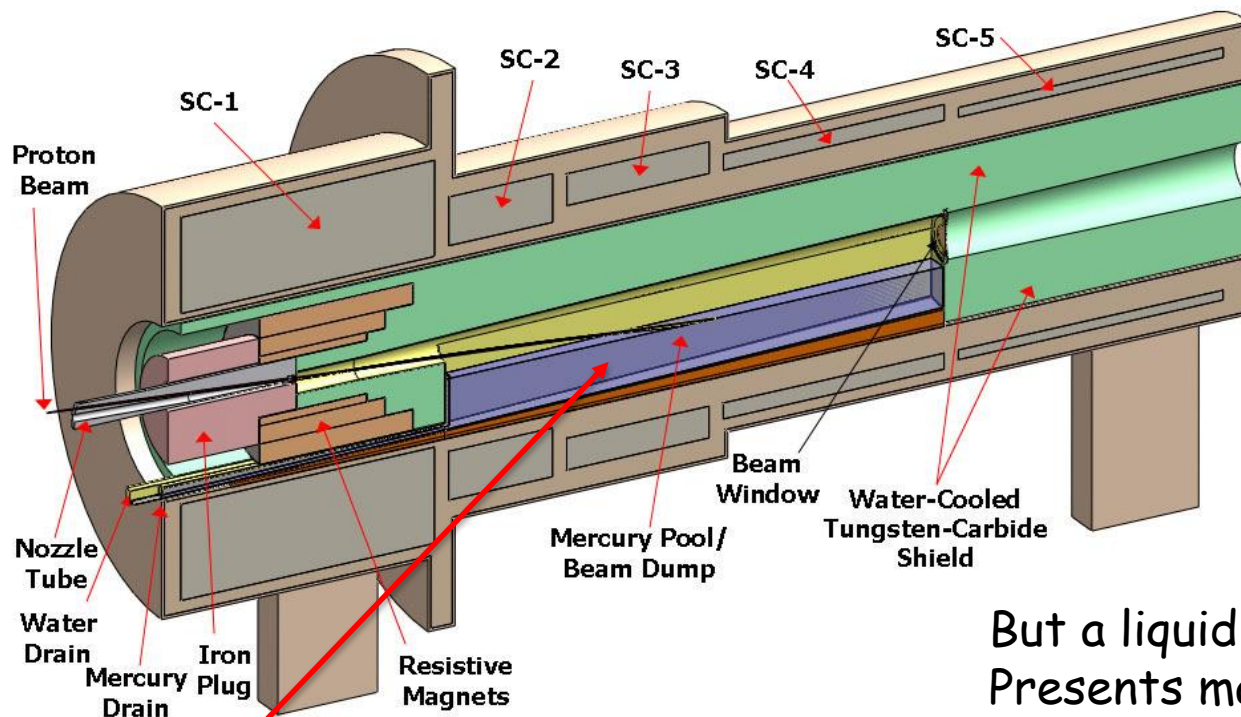


水银喷柱方案

- The MERIT Experiment at the CERN PS
 - Proof-of-principle demonstration of a liquid Hg jet target in high-field solenoid in Fall `07
 - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
- ⇒ Technology OK for beam powers up to 8 MW with a repetition rate of 70 Hz!



基于水银靶方案的靶站设计



But a liquid mercury target
Presents many challenges, e.g.
Interaction of mercury jet
with dump, handling, disposal,
leak, etc.

- 置于20T磁场中的水银喷注靶
 - 使用水银池吸收废弃质子束
- 大大加重靶站负荷，
更大的磁铁，更厚的屏蔽，更高造价

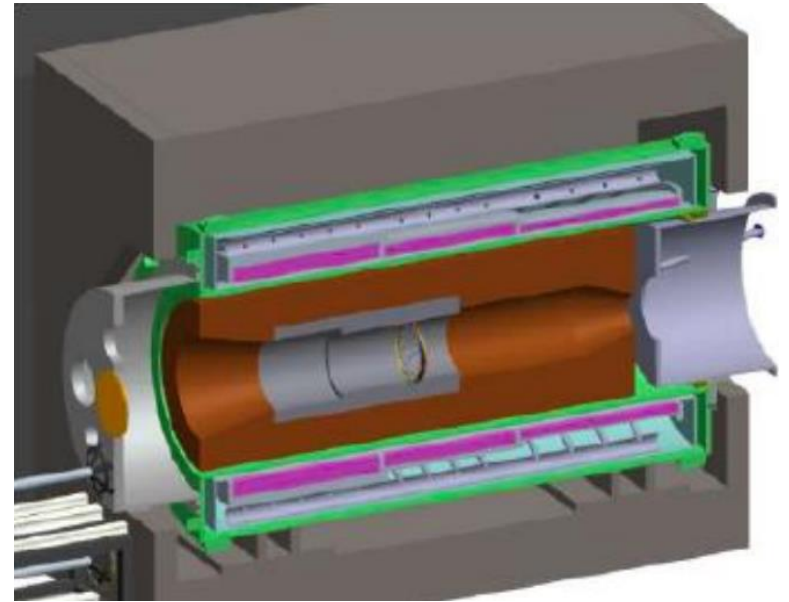
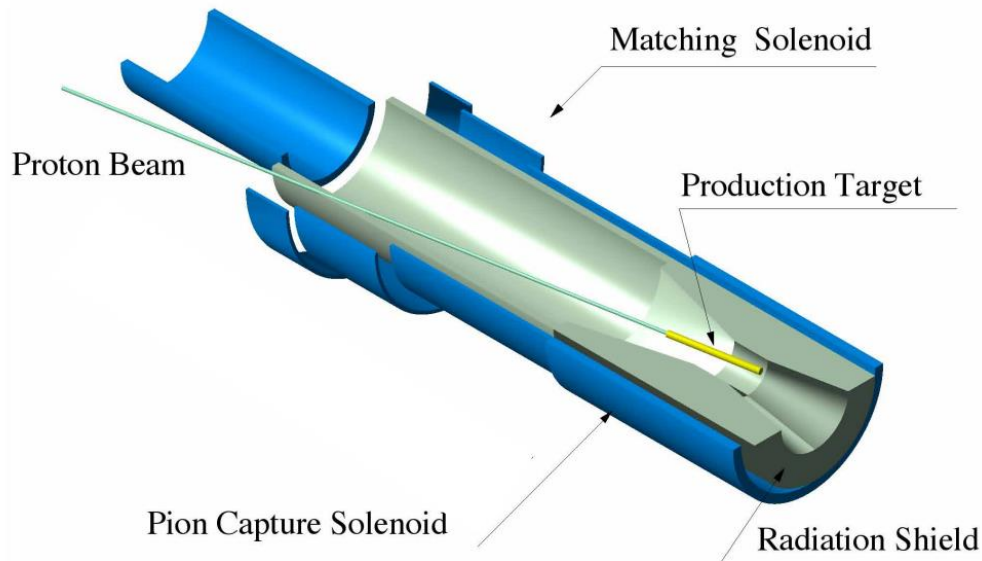
COMET
EMuS
MC

56kW
25kW
O(MW)

φ1.3m
φ1.2m
??

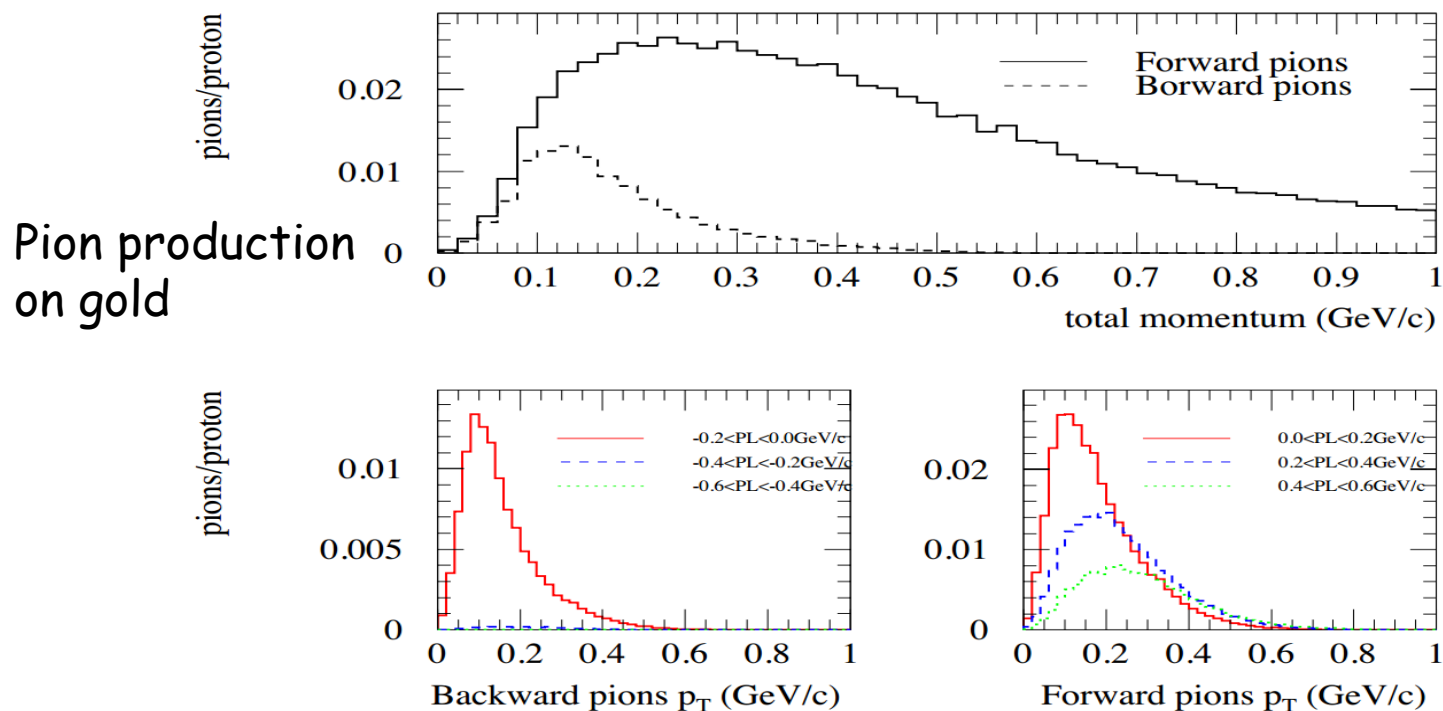
运行1年
运行30年

COMET & Mu2e



- 使用反向收集避免废弃质子束流问题

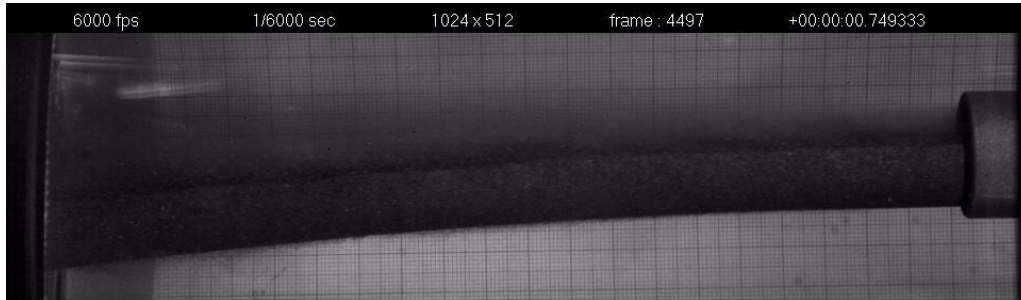
前向还是反向?



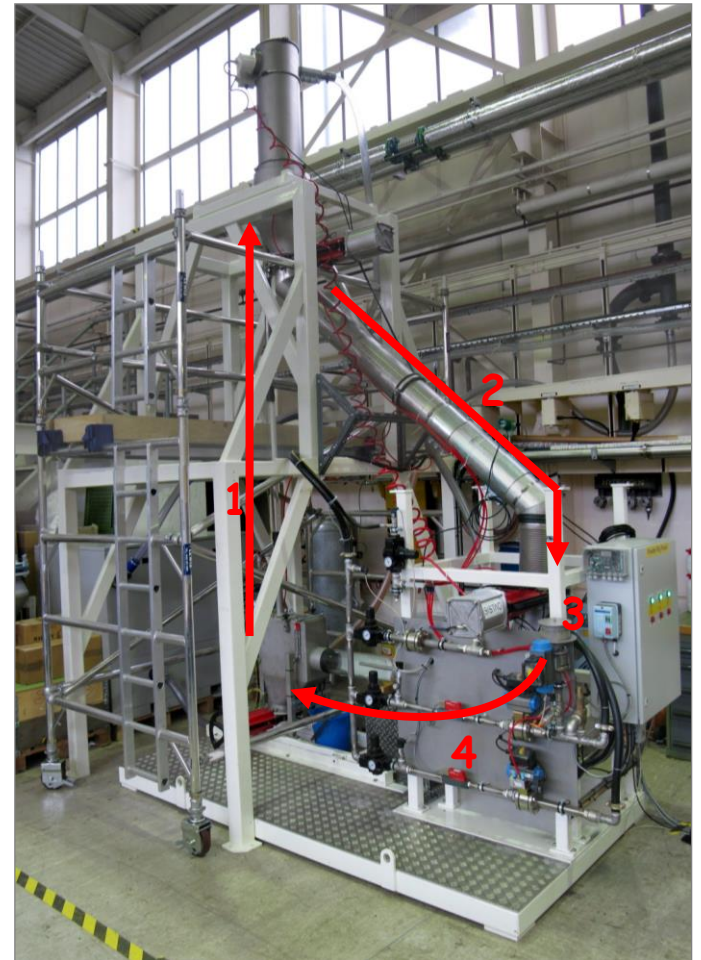
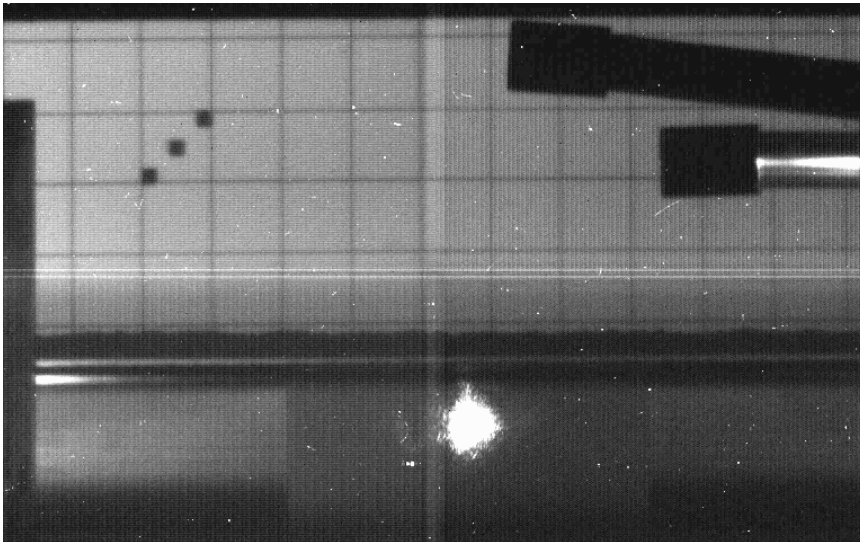
- 反向适合某些特定实验: **mu-e conversion**
- 前向是更广泛目标实验的解决方案

流化钨粉方案

使用氦气流带动钨粉



在CERN的HiRadMat上带束实验结果很不乐观



使用正电子打靶？

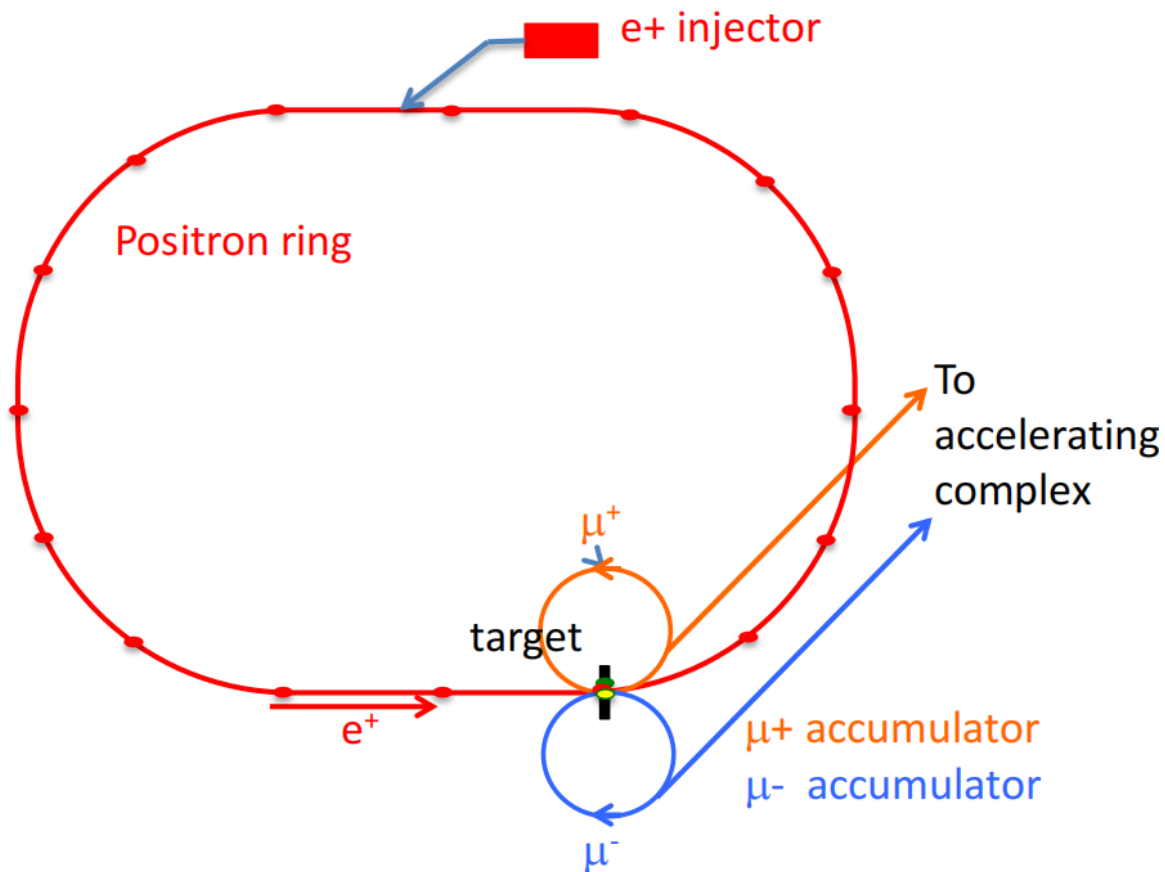
- Low Emittance Muon Accelerator (LEMMA)

- 45GeV positrons $e^+e^- \rightarrow \mu^+\mu^-$

2018在CERN完成初步原理验证实验



- 优点：跳过Muon cooling 这一瓶颈
- 缺点：极低的转化率，相对质子低4个量级以上



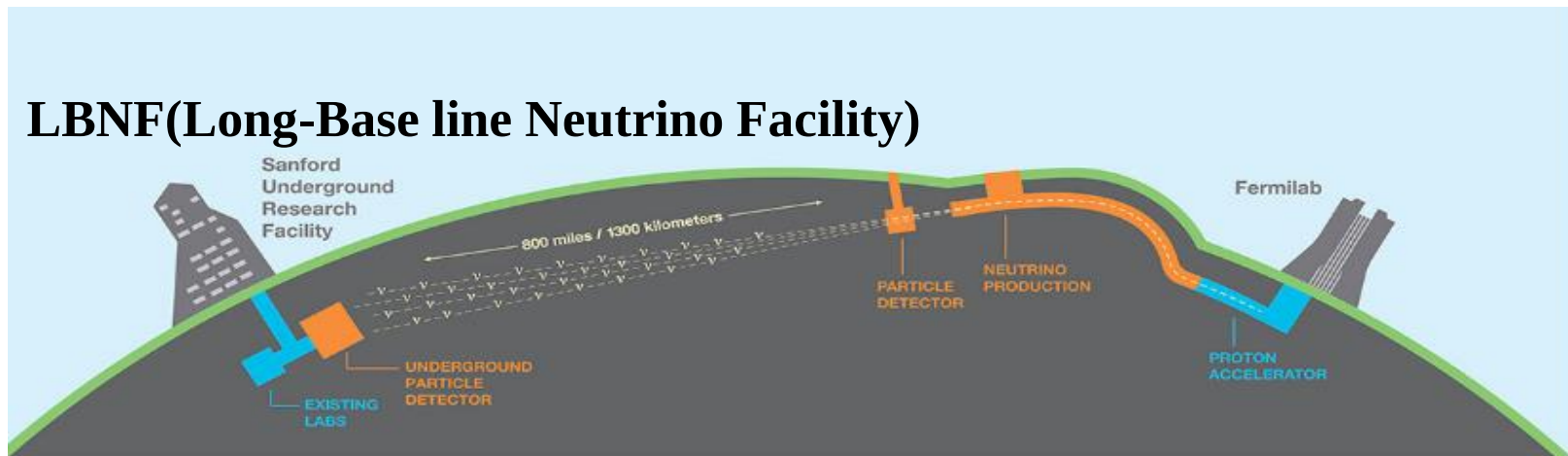
性能和质子打靶可比需要：

- 3倍FCC-he的正电子流强
- 25%动量接受度的正电子储存环

RaDIATE: **R**adiation **D**amage **I**n **A**ccelerator **T**arget **E**nvironments

Lead by Fermi LBNF project, international collaboration

- Primary proton beam @ 60-120 GeV extracted from Main Injector
- Initial 1.2 MW beam power, upgradable to 2.4 MW



Related materials face severe radiation damage

Target: **Graphite, Tungsten**, Decay pipe window: **Beryllium**, Structural material: **Titanium alloy/Aluminum alloy, W, Ta**.

How to study radiation damage

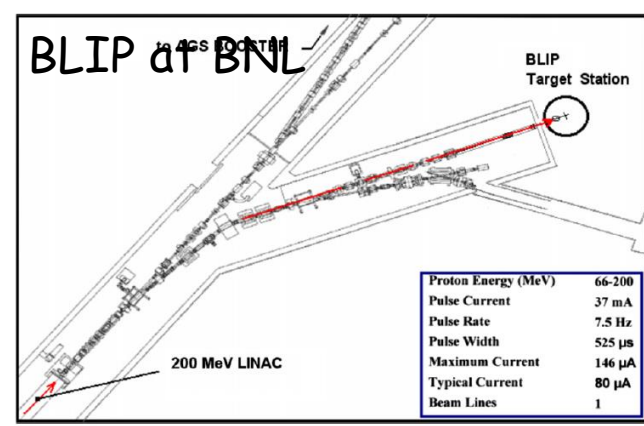
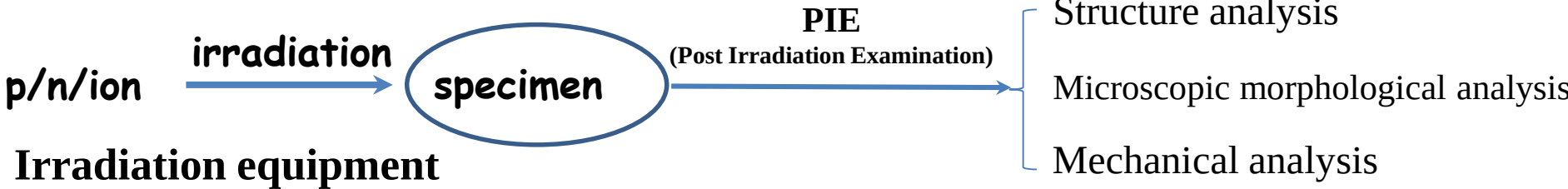


Fig. 1. BNL experimental facilities used in the material irradiation study.

Proton irradiation



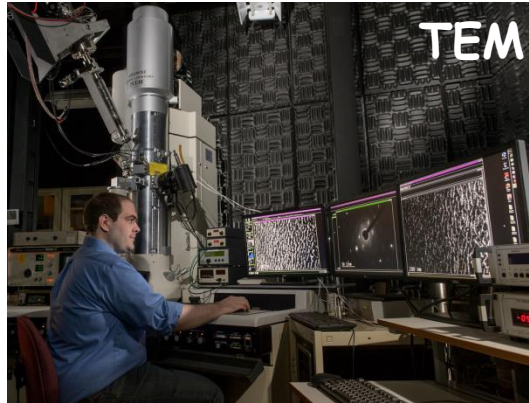
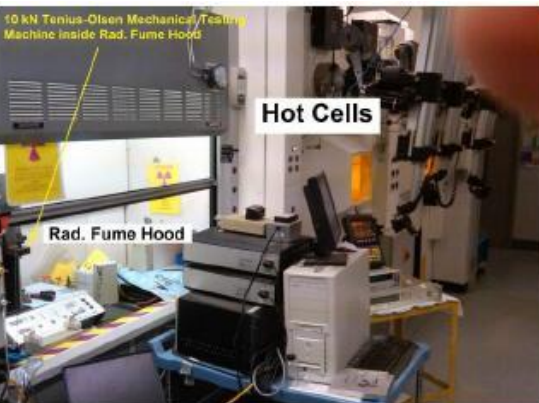
Ion irradiation



Ion implantation

PIE(Post Irradiation Examination)

Culham Center for Fusion Energy, UK



MAP结束之后，靶与靶站的研究有所停滞



中国在此时进入这一领域

CSNS

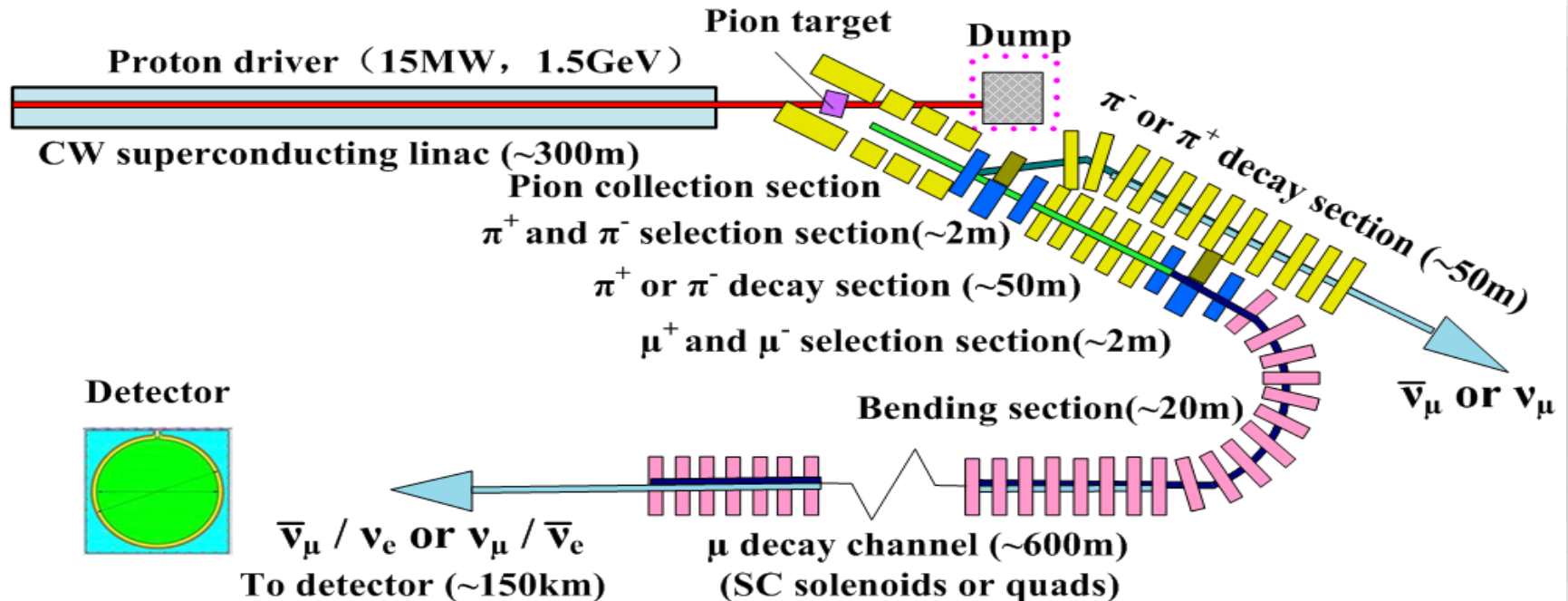
CIADS

HIAF

SPPC

...

MOMENT

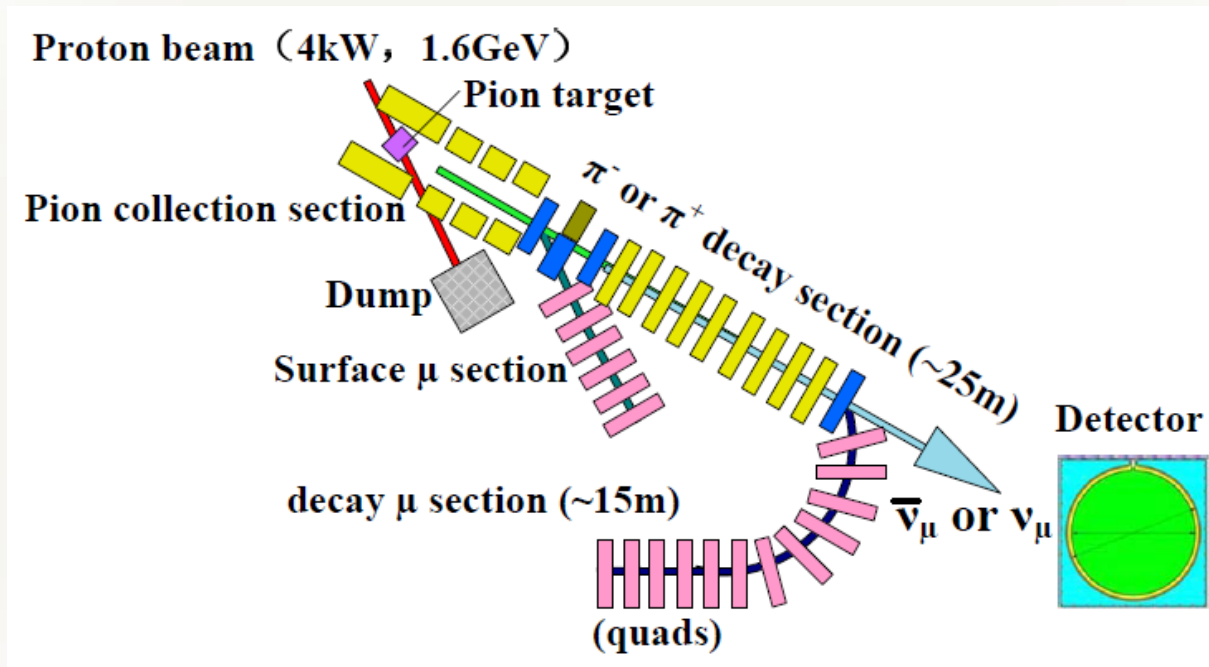


与COMET的合作

- IHEP participating in COMET collaboration on 2012
- Involved in Intensity Frontier muon physics
- Involved in facility design and construct, so we can have real experiences
- Get help from COMET experts

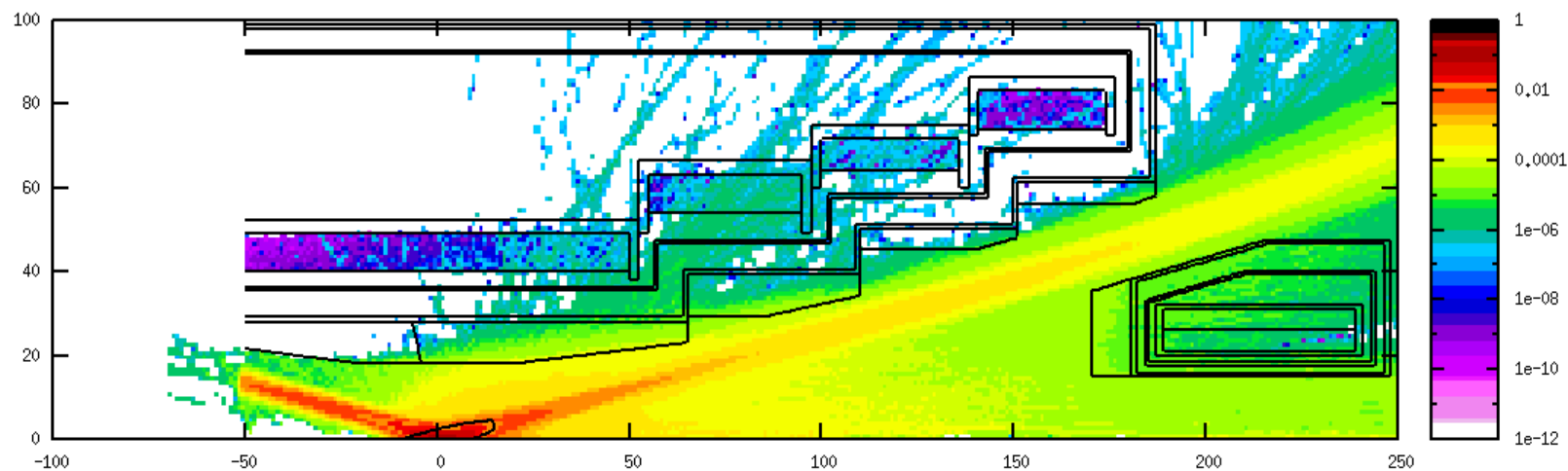
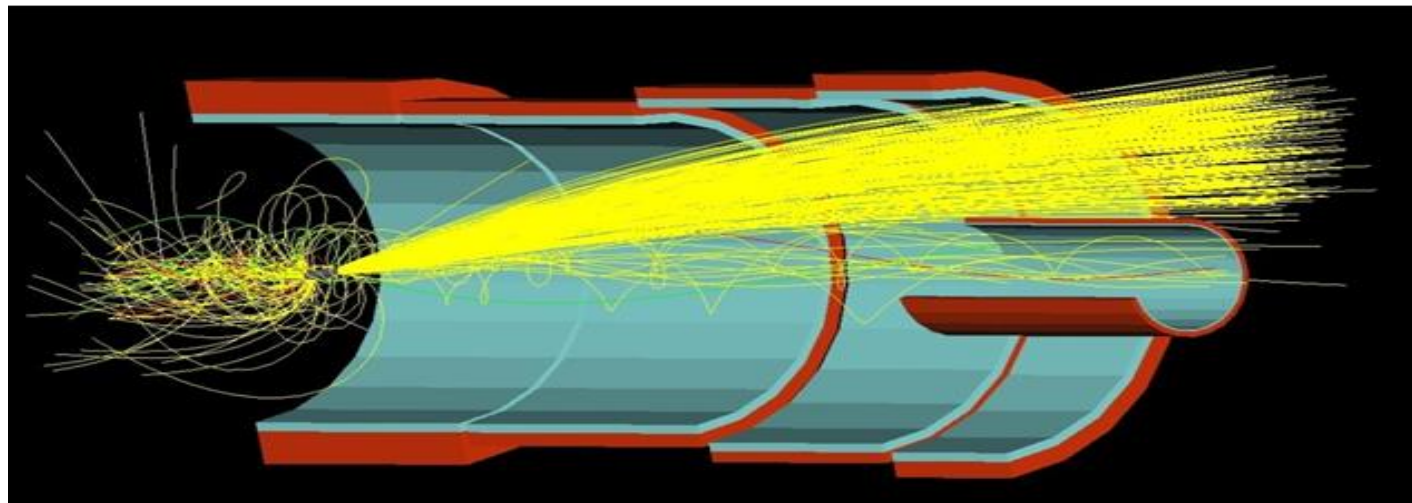
Synergy between Neutrino physics & MuSR

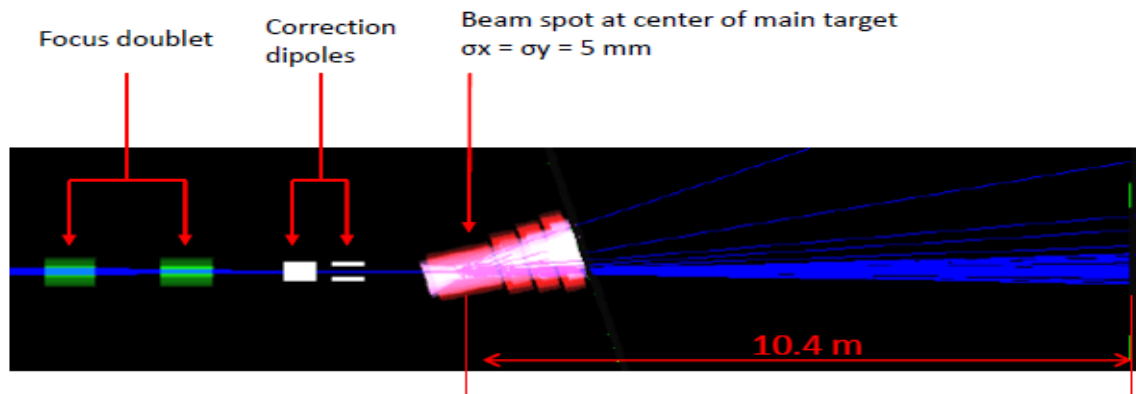
EMuS(Experimental Muon Source)



在基金委经费支持下
开展靶站技术预研

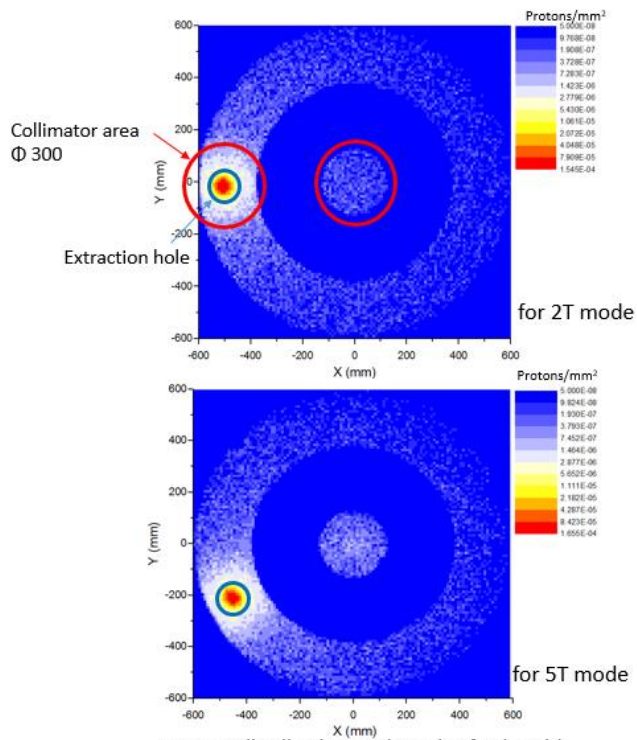
提出废弃束流引出的新方案



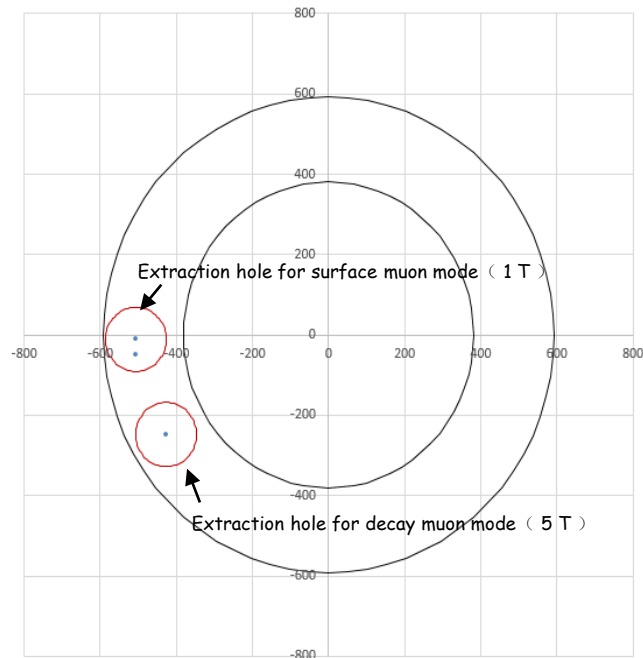


Full geometry in simulation

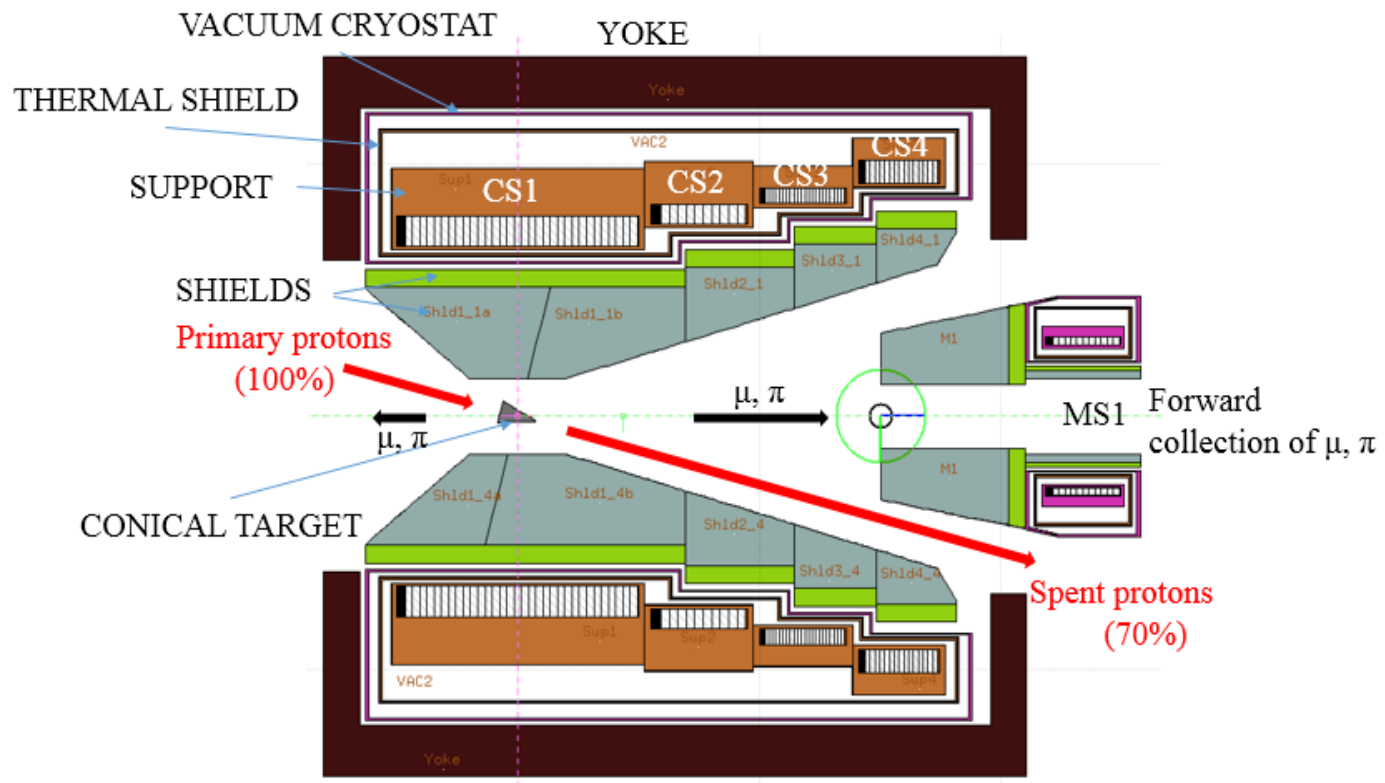
是一个可行的方案



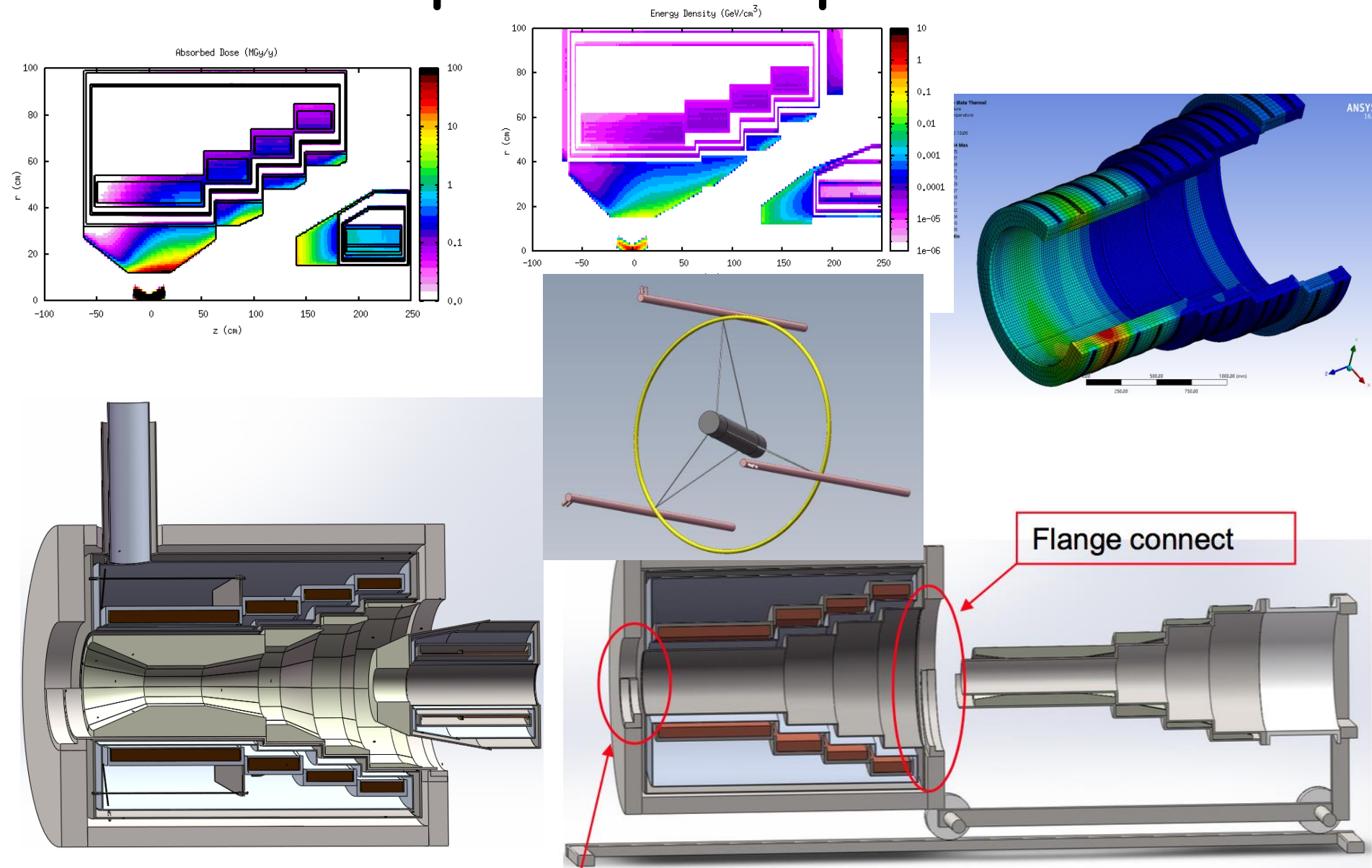
Protons distribution at the exit of solenoid



EMuS 基准靶站设计



Entire process experiences



抗辐射铝基超导线材的必要性

即使在5kW束流功率下

Al stabilizer sample



FIGURE 2. The aluminum sample cut from the aluminum stabilized superconductor attached with a voltage sense wire.

Al's electrical resistance in neutron irradiation

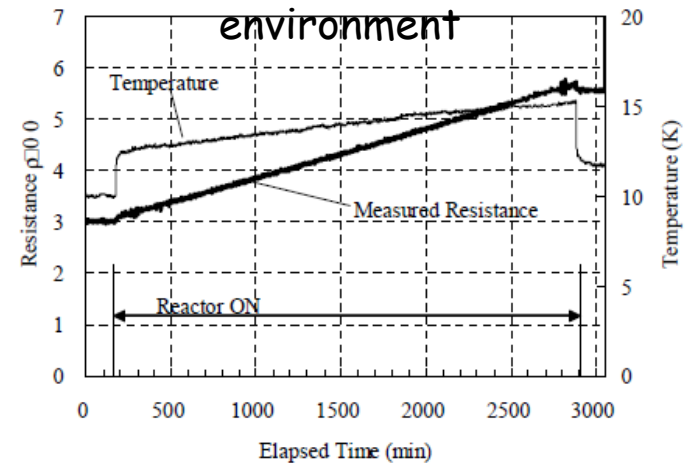


TABLE 2. Summary of the Resistance Changes Observed in the Experiment

Period	Temperature	Integrated Fast-Neutron Fluence	Measured Resistance
Before cool-down	300 K	0	1.37 mΩ
After cool-down	10 K	0	3.0 μΩ
During irradiation	12 K - 15 K	(flux : 1.4×10^{15} n/m ² /s)	3.1 μΩ – 5.7 μΩ (increased monotonically with fluence)
After irradiation	12 K	2.3×10^{20} n/m ²	5.6 μΩ
After warm-up to room temperature	302 K	2.3×10^{20} n/m ²	1.36 mΩ
After the second cool-down	12 K	2.3×10^{20} n/m ²	3.0 μΩ

- ✓ Neutron induced resistance rate is $0.03 \text{ n}\Omega \cdot \text{m}$ for 10^{20} n/m^2
- ✓ The resistance can be recovered by warming up to room temperature

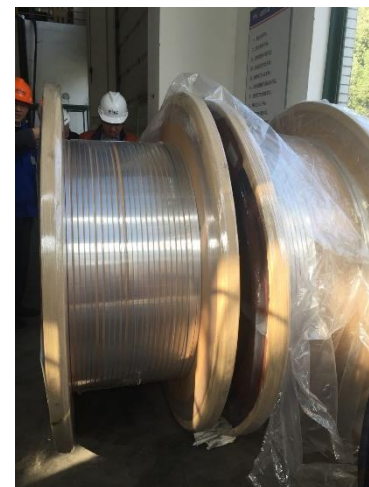
国产铝基卢瑟福超导电缆和 大口径强场螺线管磁铁



Aluminum

Rutherford cable

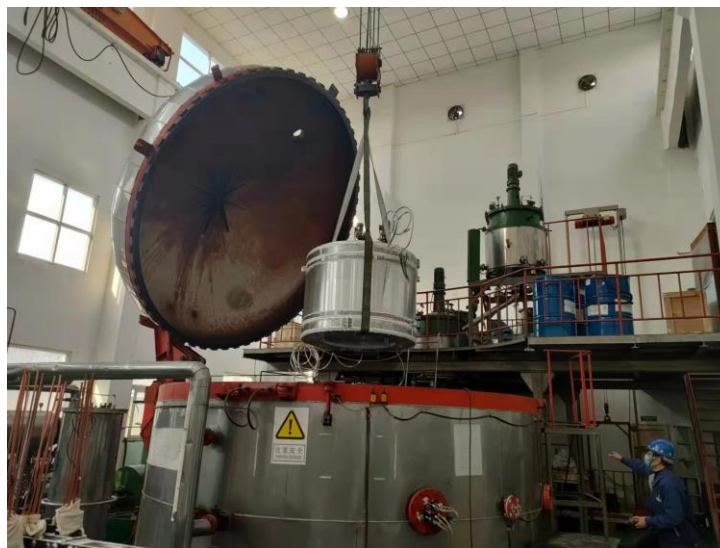
在无锡建成了国产特种超导
电缆生产装备



1.5km长特种超导
电缆产品

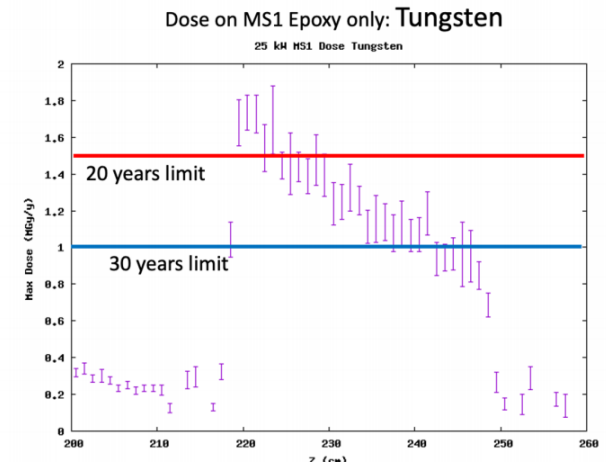
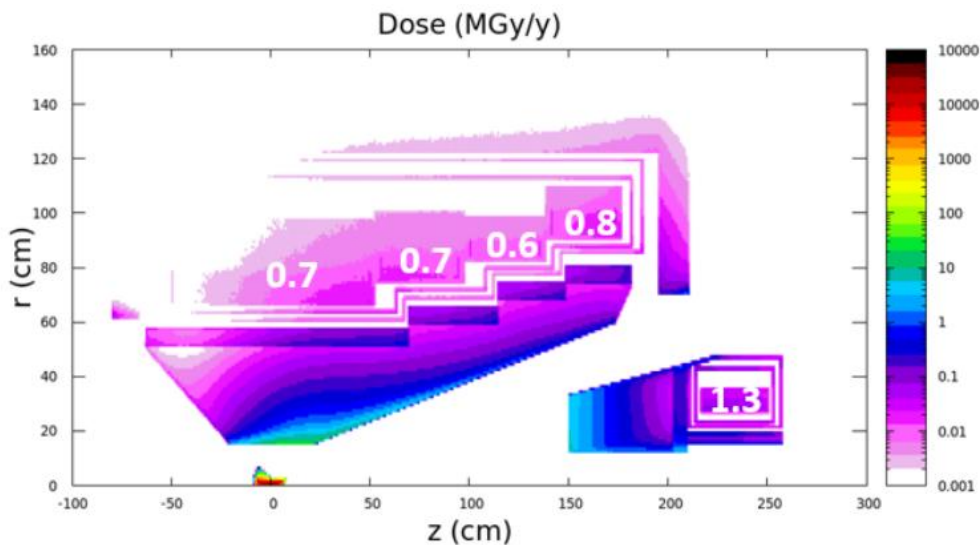


磁铁制造



抗辐射绝缘胶

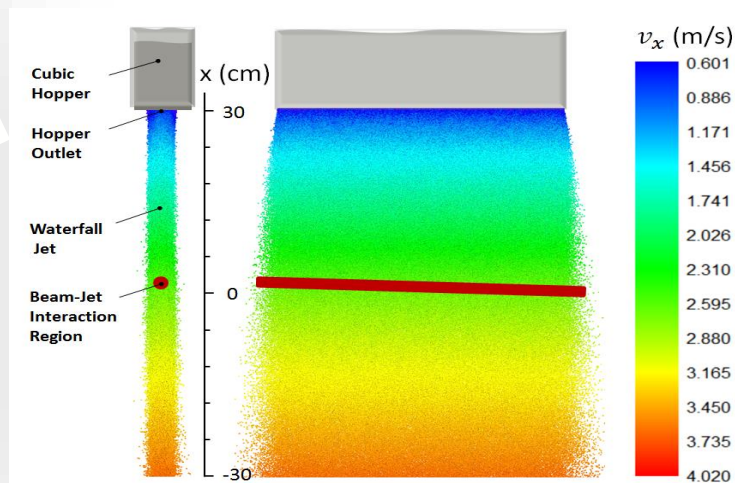
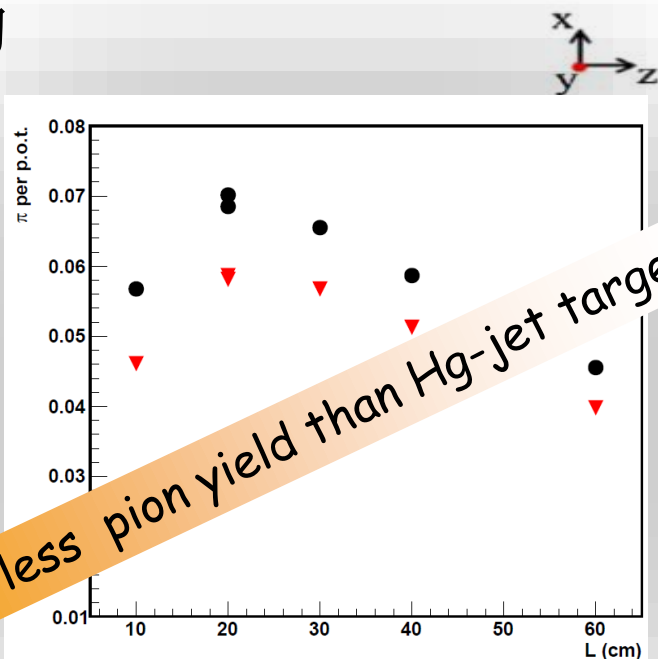
- 制约靶站设计的瓶颈



- 需要至少能够抗**30MGy**辐射剂量，通常抗辐射胶性能是**7MGy**

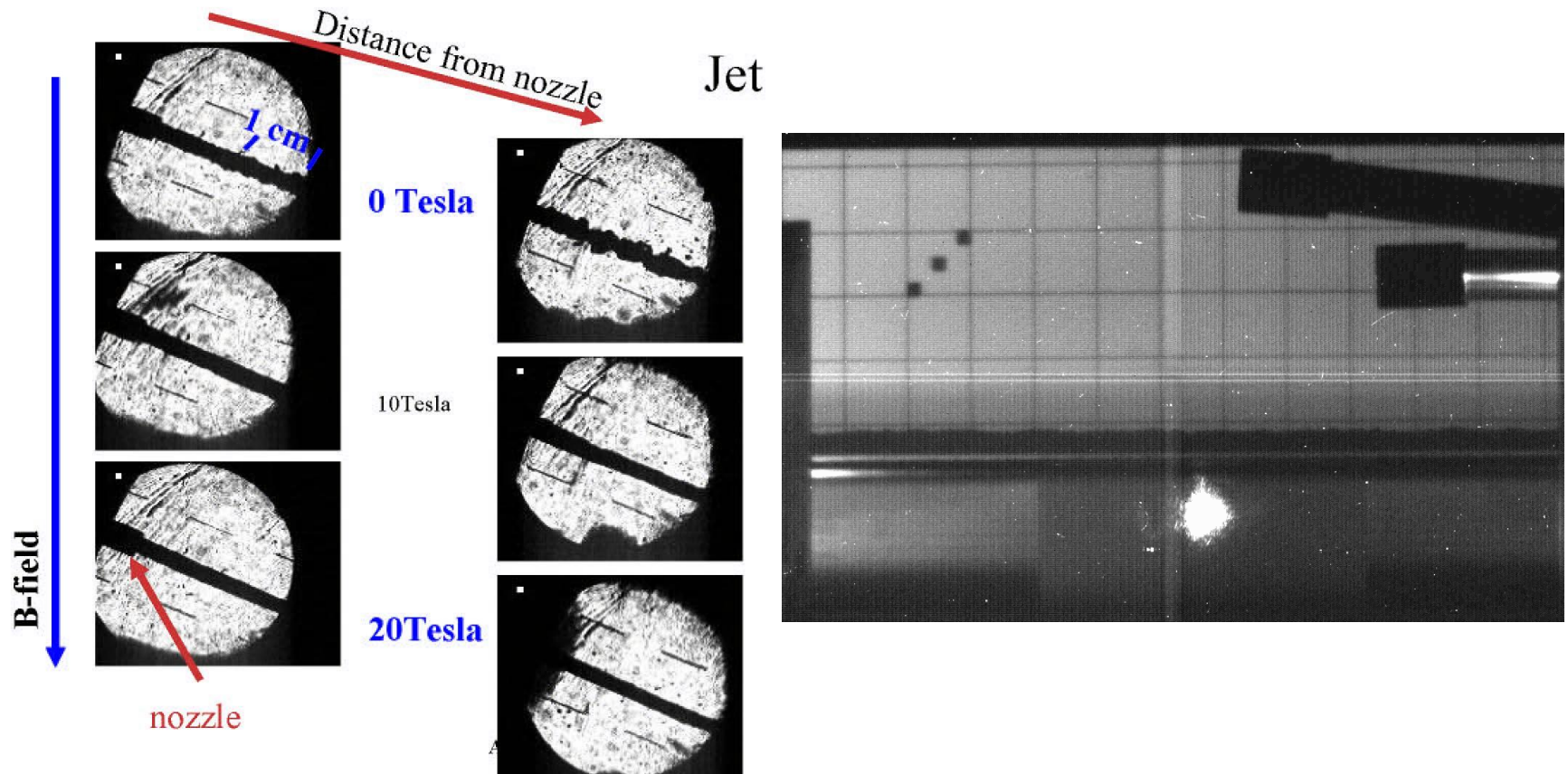
瀑布型颗粒流靶

- 近物所提出的创新概念设计
- 近物所和高能所合作开展原理验证研究
- 大量模拟表明是可行的



水银靶和流化钨粉靶的经验

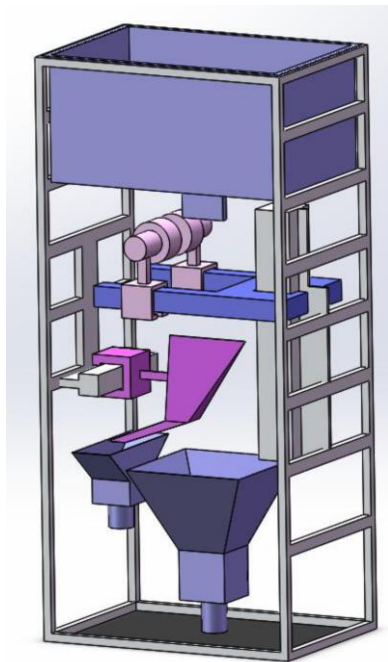
极端条件“无人区”的探索必须依靠实验说话



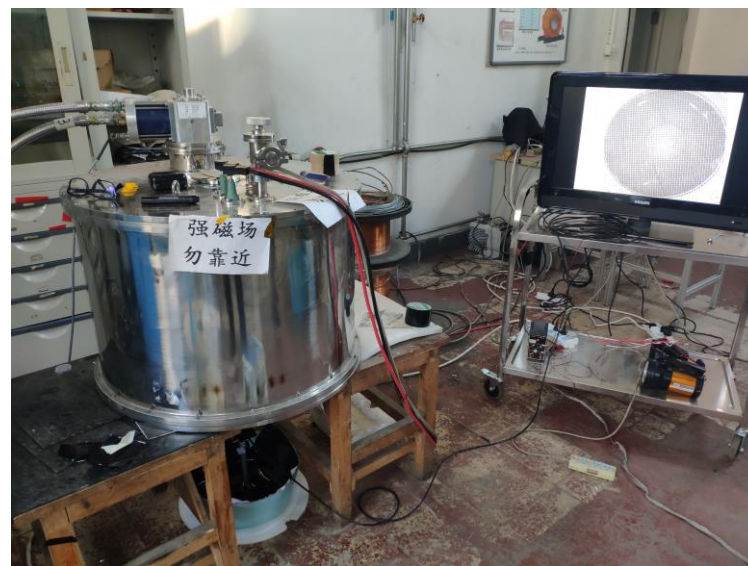
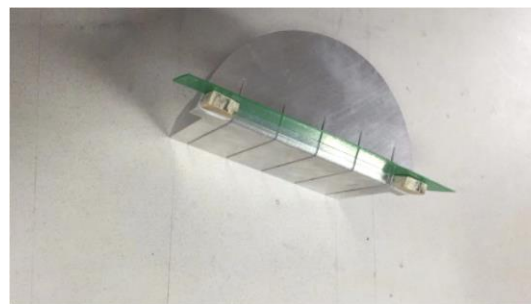
实验中发现无法事先想象的情况

桌面验证实验

近物所进行钨颗粒的流动实验



高能所进行钨颗粒在强磁场中的下落实验



申请经费支持困难

IHEP participation **RaDIATE**

科技部项目支持

1. Actively contact and join the RaDIATE cooperation
2. The first cooperative experiment is accomplished

Thermal shock experiment (440GeV, beam sigma: 0.25 mm, pulse length: 3.6 μ s, 1.87 $\times 10^{13}$ protons)

Experiment address: CERN

The objectives of the experiment were to explore the onset of failure under controlled conditions at highly localized strain rates and temperatures, and validate highly non-linear numerical models with experimental data.

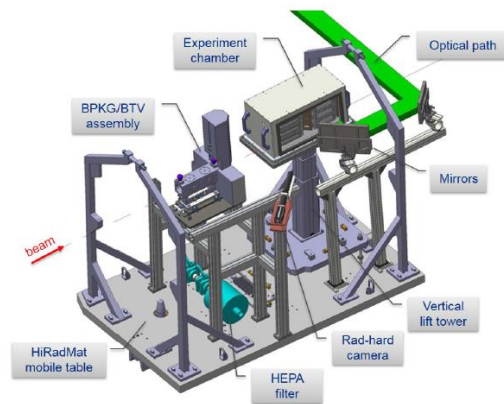
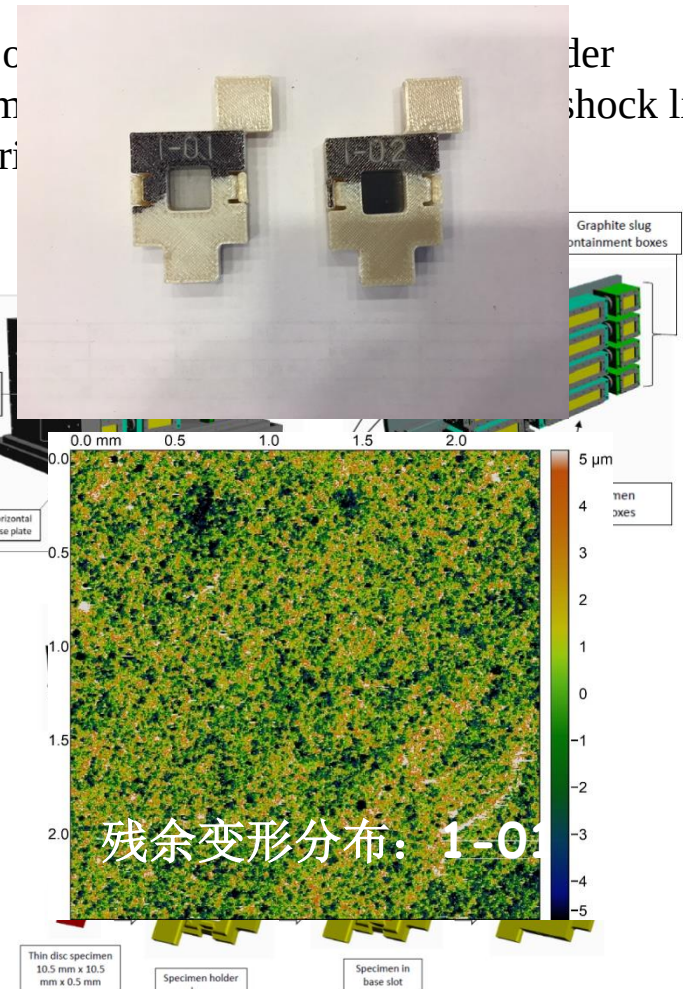


Figure 1: Experimental chamber assembled on mobile table.



美国中断合作，今后必须
自力更生

总结与展望

以NF和MC为目标

- 国际研究重新成为热点

IMCC SNOWMASS

- 还需要根本性技术突破

靶 靶站 冷却 加速等

- 中国布局原创性研究有可能成为国际领先者

HIAF-U

重离子尾场加速

瀑布型颗粒流靶

....

以下一代CLFV为目标

- 在中短期有可能进行
MACE
类**PRISM** 单事例灵敏度 10^{-20}
- 技术上并没有根本性障碍，中国需要掌握并提高，同时这些技术预研也用于**NF**和**MC**

抗高辐射的大口径强场磁铁

抗高辐射的材料：绝缘胶，铍，钨...