Introduction to Cyclotrons

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第六届 OCPA 加速器学校

北京，2010年8月5日

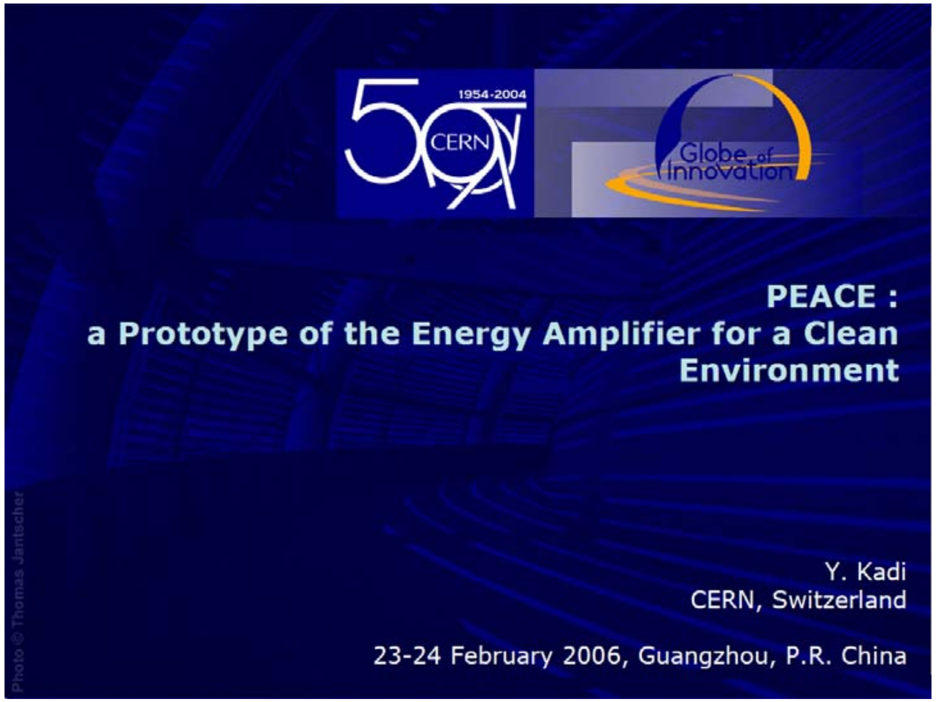
感谢杨建俊博士协助整理讲座材料

- ❑ 发展历史
- ❑ 基本理论
- ❑ 结构特点
- ❑ 工程建造
- ❑ 发展趋势
- ❑ 应用方向

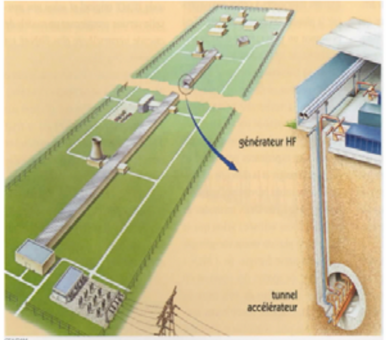
1、高流强

- 高功率质子加速器 ⇒ **直线** / **回旋** ？

上世纪90年代，开展了热烈的讨论



Accelerator choice



❑Cyclotron =
MODULAR, realised on industrial scale
Cost effective ; applicable in isolated regions ;applicable for desalination & cogeneration

❑Linear accelerator =
Solution for Research Centres & highly centralised production

THE CYCLOTRON AS OPTIMAL DRIVER OF A SUBCRITICAL REACTOR : *key choice for PEACE*

P. Pavlopoulos
Basle University & CERN
CERN

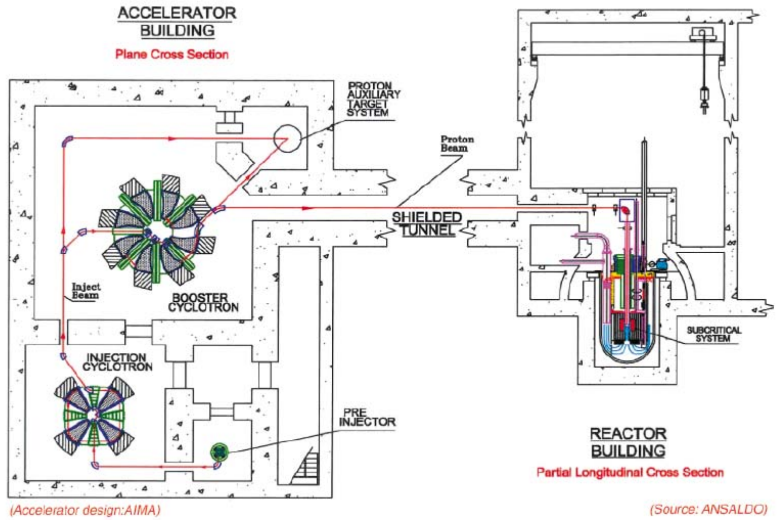
Accelerator choice

- Linear accelerator =
  Solution for Research Centres & highly centralised production
- Cyclotron =
  MODULAR & INDUSTRIALISED
  Cost effective ; applicable in isolated regions ; applicable for desalination & cogeneration (heat)

ACCELERATOR-DRIVEN SUB-CRITICAL REACTORS FOR RADIOACTIVE WASTE TRANSMUTATION AND ENERGY PRODUCTION

诺贝尔奖获得者 ➡ Carlo Rubbia

DEMO Facility reference configuration:layout



(Accelerator design:AIMA) (Source: ANSALDO)

1、高流强

- 高功率质子加速器 → 直线 / 回旋 ？

加速器届许多专家倾向性的观点非常明显，直线加速器有技术优势 ← 上世纪90年代，开展了热烈的讨论

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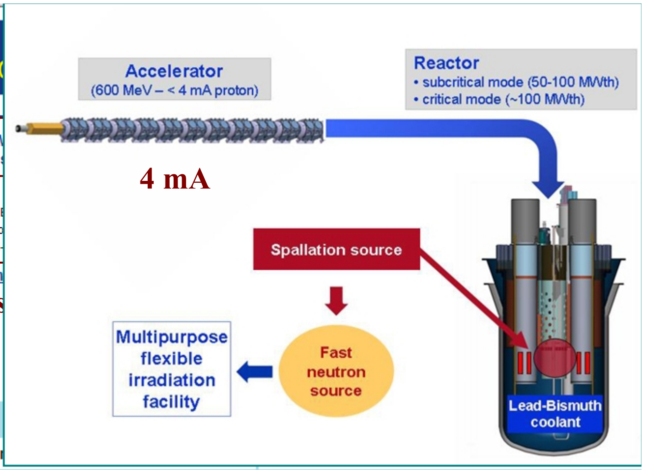
Linac versus cyclotron



LINAC	
Large space requirement (few hundr	
Expensive	Cheaper in construction
Less efficient power conversion	More efficient power conversion
Modularity provides redundancy	No intrinsic redundancy
Upgradable in energy	Difficult to upgrade in energy
Straightforward beam extraction	Difficult extraction and related beam losses
Capable of high beam current (100 mA) **100 mA**	Modest beam current capability (5 mA) **5 mA**

Types of high power accelerators CSNS

CHINA SPALLATION NEUTRON SOURCE

- CW facilities
  - Driven by a high i
  - 1.2 MW SINQ (PS
- Long (ms) pulse fa
  - Driven by a high i
  - 1 MW LANSCE (L
- Short (μs) pulse f
  - Driven by a combination of linacs and rings
  - Partial energy linac and rapid-cycling synchrotron(s):
    - ISIS (RAL) driven by 70 MeV linac/800 MeV RCS
    - J-PARC driven by 400 MeV linac/3 GeV RCS/50 GeV MR
  - Full-energy linac and an accumulator ring:
    - PSR (LANL) driven by 800 MeV linac/accumulator
    - SNS (ORNL) driven by 1 GeV linac/accumulator

90年代以来，相继立项、建设
美国SNS（1 mA, 1MW）
日本J-Parc （330μA, 1MW）
中国CSNS （62.5μA,100kW）
等等

未来高平均功率加速器展望

Paper presented at Cyclotrons and their Applications 98, Caen, 14–19 June 1998 369

HIGH INTENSITY PROBLEMS, REVISITED OR CYCLOTRON OPERATION BEYOND LIMITS

TH.STAMMBACH

PSI, 5232 Villigen-PSI, Switzerland

High intensity problems in cyclotrons are reviewed in response to the growing interest in new applications like neutron spallation sources, hybrid reactor systems (as e.g. the "energy amplifier"), inertial fusion and accelerator driven transmutation technologies. The feasibility of high power cyclotrons is discussed based on the experience gained from the upgrade of the PSI accelerator facility and an overview is given on the progress on high intensity cyclotrons and ...

1998年，PSI，T.Stammbach，

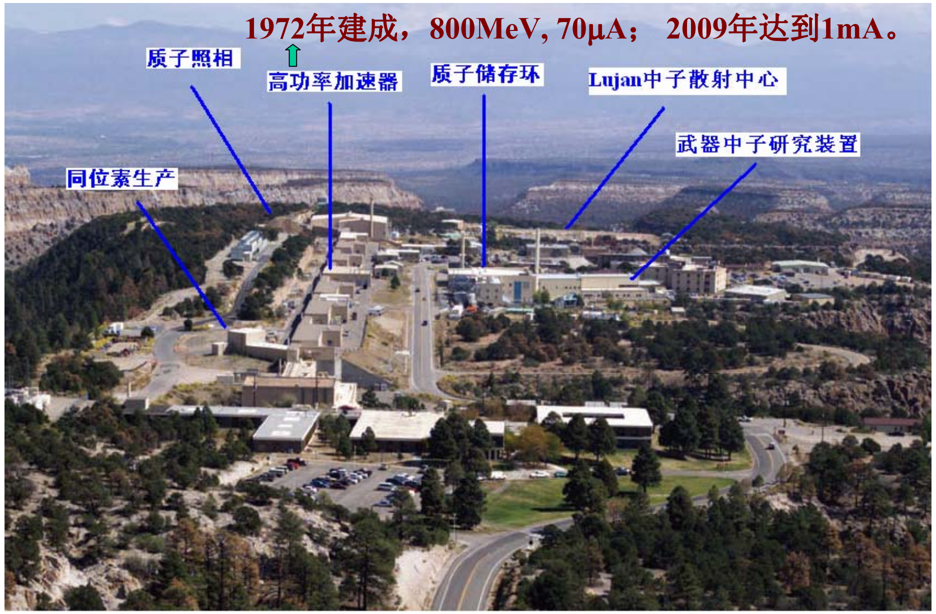
High Intensity Problems. Revisited or Cyclotron Operation Beyond Limits

1、高流强

- 高功率质子加速器 → **直线** / **回旋** **？**

上世纪90年代，开展了热烈的讨论 → **加速器届许多专家倾向性的观点非常明显，直线加速器有技术优势**

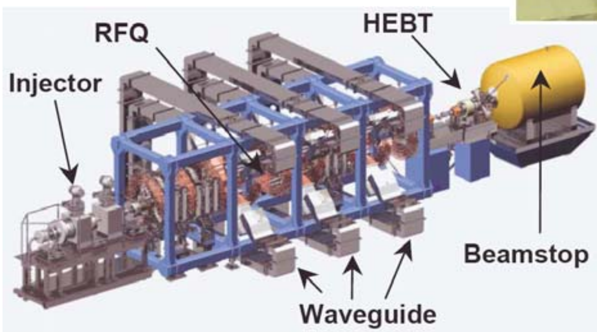
2010年，又10年过去了，当前状况？



美国LANL的LANSCE装置

未来高平均功率加速器展望

LANL低能强流RFQ加速器LEDA

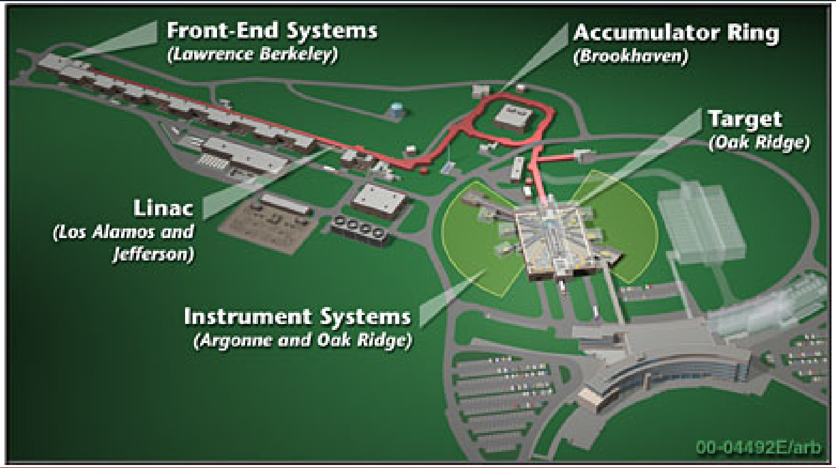


注入能量：75keV
引出能量：6.7MeV
平均流强：100mA
平均功率：0.67MW

– 经美国DOE专家论证，LANL的质子直线加速器，不可能升级到1－2MW的束流功率（Again, however, it will not be possible to upgrade the LANSCE facility to reach the 1-to 2-MW level.）[8]。

– 美国自1996年开始设计，2006年出束的散裂中子源SNS建设计划，由6个DOE国家实验室 (Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos, and Oak Ridge) 联合研制，总建设费用约为116.47亿人民币，年度费用详见表三。

– 该加速器设计指标是束流功率是1.4MW。2006年建成验收30kW；2007年90kW；2008年底～2009年初700kW[9]；目前达到1MW 。



表三、SNS 的年度投资经费

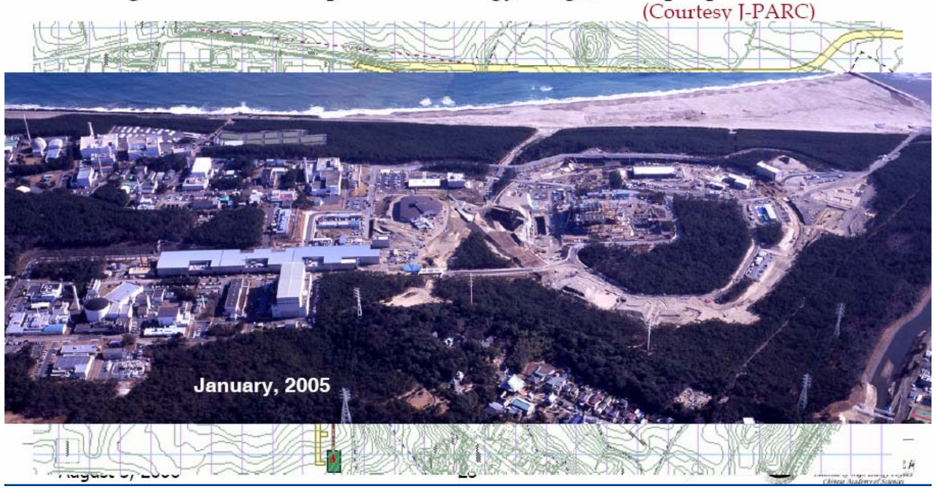
年度	前期	2002	2003	2004	2005	2006	总计
经费概算/百万美元	564.5	291.4	225	143	112.9	74.9	1411.7
经费概算/亿人民币	46.57	24.04	18.56	11.80	9.31	6.18	116.47

J-PARC schematic layout

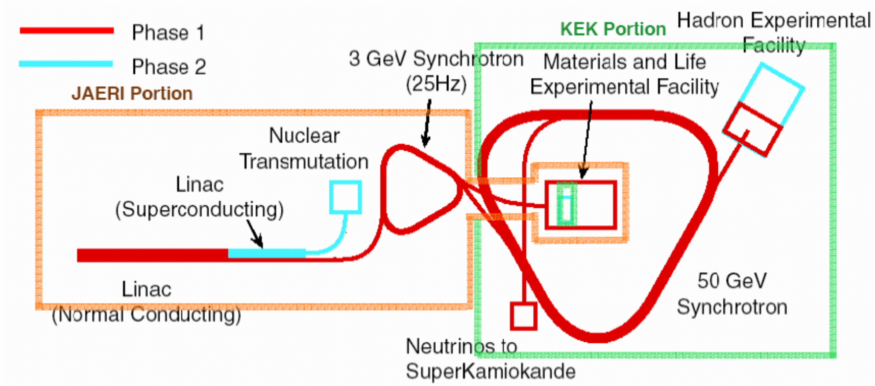
Japan Proton Accelerator Research Complex

- Similar cost, similar schedule (due 2006 ~ 2007)
- Ring clusters with expandable energy range; multipurpose

(Courtesy J-PARC)

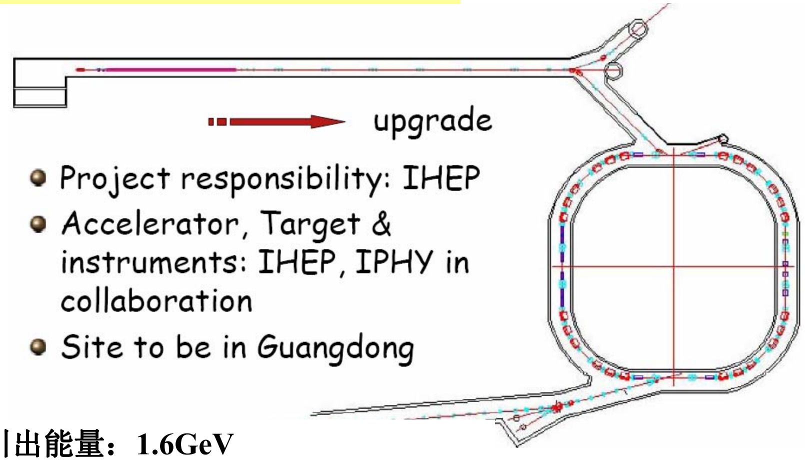


J-PARC in phases



– Phase 1 + Phase 2 = 1,890 Oku Yen (= $1.89 billions if $1 = 100 Yen).
– Phase 1 = 1,527 Oku Yen (= $1.5 billions) for 7 years.
– JAERI: 860 Oku Yen (56%), KEK: 667 Oku Yen (44%).

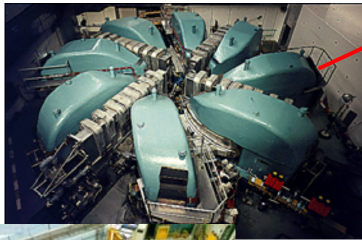
中国散裂中子源CSNS（设计）

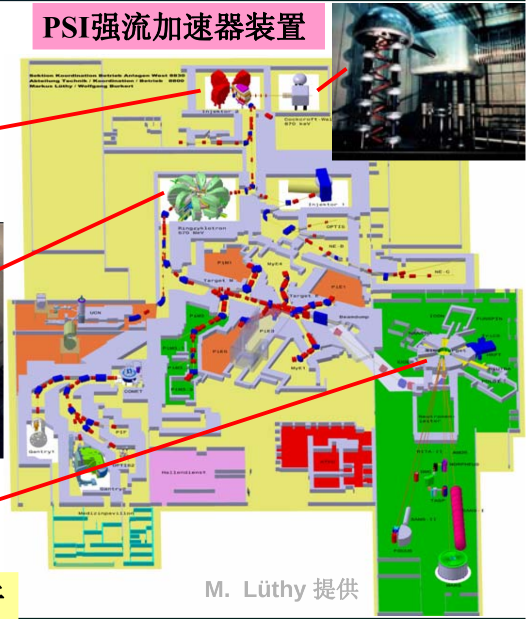


引出能量：1.6GeV
一期流强：62.5μA（三期：315 μA ）
平均功率：0.1MW

世界最高功率的加速器是怎样炼成的？ 590MeV, 2.3mA

PSI强流加速器装置

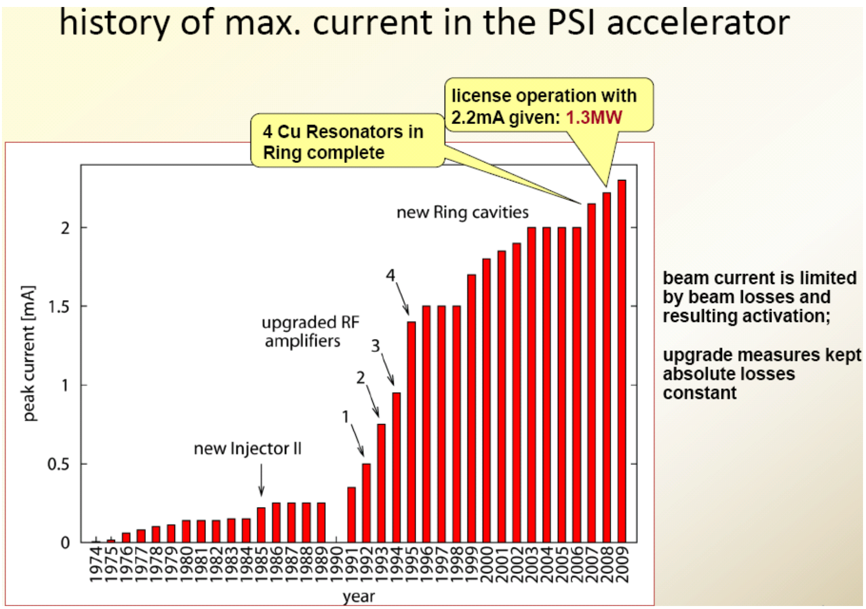




散裂中子源SINQ

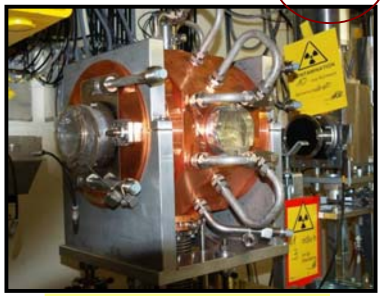
M. Lüthy 提供

世界最高功率的加速器是怎样炼成的？



世界最高功率的加速器是怎样炼成的？

- 升级内容：
  更换高Q值高频腔、增加聚束器
- 升级目标：2.2mA → 3.0mA
- 1.3MW → 1.8MW



72MeV 10'th harmonic buncher

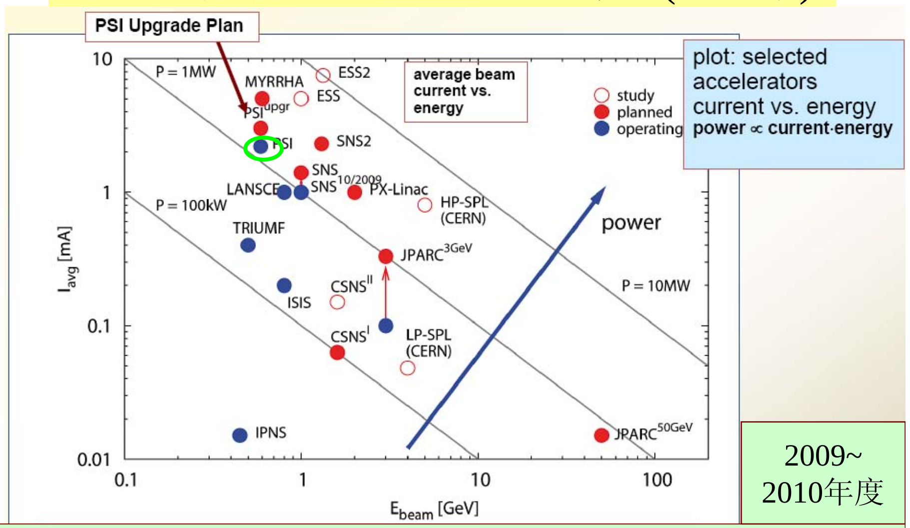
4 New Cavities for Ring

2 New Cavities for Injector II

M. Seidel报告, IPAC'10，2010，东京

世界最高功率的加速器是怎样炼成的？

国际上质子加速器流强Vs.功率图(2010年)



2009~2010年度

Cyclotron: max Power, 1.3MW, Beam time on target: 5000 hrs
Linac: max Power, 1.0MW, Beam time on target: 2000 hrs

未来高平均功率加速器展望

Proceedings of IPAC'10, Kyoto, Japan TUYRA03

PRODUCTION OF A 1.3 MW PROTON BEAM AT PSI

M.Seidel, S.Adam, A.Adelmann, C.Baumgarten, Y.J.Bi*, R.Doelling, H.Fitze, A.Fuchs, M.Humbel, J.Grillenberger, D.Kiselev, A.Mezger, D.Reggiani, M.Schneider, J.J.Yang*, H.Zhang, T.J.Zhang*
PSI, Villigen, Switzerland
*CIAE, Beijing, China

Abstract
With an average beam power of 1.3 MW the PSI proton accelerator facility is presently at the worldwide forefront of high ... aspects ... and tran... based ... resonato... significa... also the ... performa... topics i... beam lo... interlock...

Walton pre-accelerator and a chain of two isochronous cyclotrons, the Injector II and the Ring cyclotron. The beam is produced in continuous wave (CW) mode at a ... neutrons are moderated in volumes filled with heavy

FACILITY OVERVIEW

原子能院积极参予国际上质子束流功率最高的、1.3MW的加速器的研究与发展工作，在大规模并行计算核心算法发展和数值模拟仿真、72MeV低能端和590 MeV引出区物理过程研究、实验测量比对等方面取得了一些有意义的结果。

未来高平均功率加速器展望

MOPEC085 Proceedings of IPAC'10, Kyoto, Japan

STATUS OF THE SNS POWER RAMP UP*

M. Plum, on behalf of the SNS accelerator team,
Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract
The Spallation Neutron Source accelerator complex consists of a 2.5 MeV H⁻ front-end injector system, a 186 MeV normal-conducting linear accelerator, a 1 GeV superconducting linear accelerator, an accumulator ring, and associ... operations ... steadily incr... September 2... time, and op... status of th... operational ...

The SNS ... parts – the l... a design output beam power of 1.5 MW, comprises an H ion source, an RFQ, a DTL, a CCL, and finally an SCL, with design output beam energies of 0.065, 2.5, 87, 186,

beam-power-limiting factor.
A recent history of the beam loss per unit beam charge in the superconducting linac is shown in Fig. 2. The data show significant improvements from December 2008 to December 2009, primarily due to a new, empirically ...ents, which ...ginal design ...be explained ... intrabeam ...nents in the ... in the beam ...ptance; and ...on levels in ... high power ...h at 30 cm, ...ration levels ...f the SCL.
A history of the beam loss in the Ring is shown in Fig. 3. In this case the improvement in the loss per

美国自1996年开始设计，2006年出束的散裂中子源SNS建设计划，由6个DOE国家实验室 (Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos, and Oak Ridge) 联合研制。束流功率目前达到1.0MW。

世界最高功率的加速器是怎样炼成的？

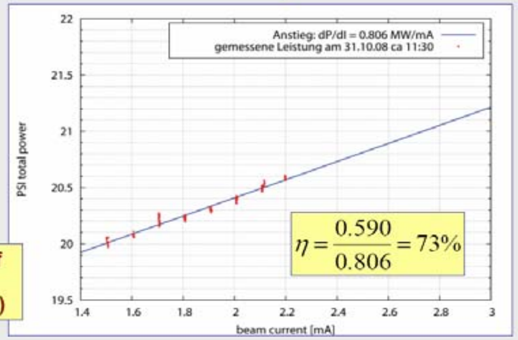
Grid to Beam Power Conversion Efficiency

for industrial application, transmutation etc., the aspect of **efficient usage of grid power** is very important

PSI: ~10MW Grid → 1.3MW Beam

$$P_{grid}(I) \approx (8.0 \pm 0.5)\mathrm{MW} + 0.81\mathrm{MW} \cdot I[\mathrm{mA}]$$

contains many loads not needed for optimized ADS facility!



$$\eta = \frac{0.590}{0.806} = 73\%$$

► **differential measurement of electrical power vs. beam power (total PSI power shown)**

- 根据PSI和TRIUMF等回旋加速器主要研究机构最近的两个5年研究计划判断，国际大型质子回旋加速器将继续向高平均流强和高稳定性的方向发展。2009~2010年度，PSI回旋加速器束流功率为1.3MW，年靶上束流时间为5000小时。
- 回旋加速器仍然是高平均功率质子束应用（比如ADS、嬗变等领域）的有力竞争者。

- 未来高功率加速器面临的问题与挑战：

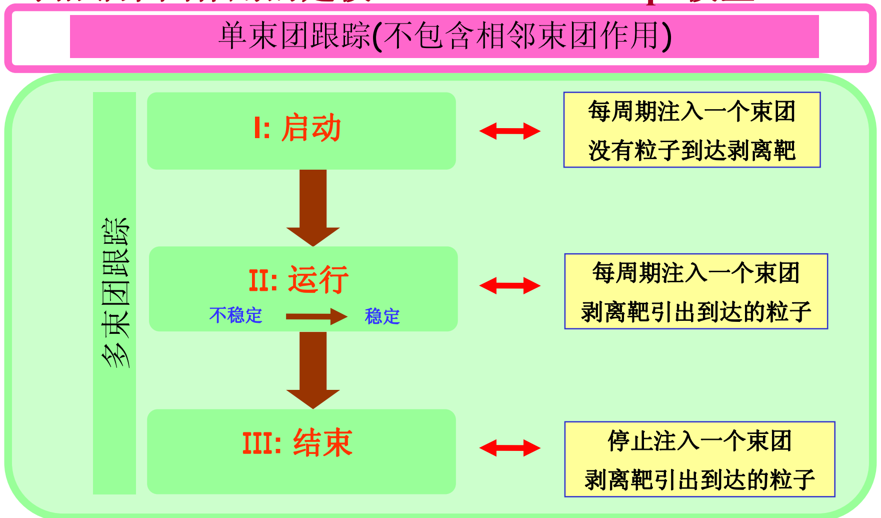
✓ 空间电荷效应等束流集体效应；
✓ 高功率RF系统的稳定性、可靠性；
✓ 高亮度强流离子源技术、
✓ 引出过程束流损失的控制
✓ 提升电能的转换效率 ……

 90年代论证期，00年代建设期

强流回旋加速器在最近20年来的发展，超出了人们的预期。到底是回旋加速器超水平发挥，还是以前的观念需要修正？为此，原子能院和PSI开展合作，致力于定量地研究回旋加速器中的强流问题和理论流强极限，目前已取得一定的阶段性结果：

1. 为数值模拟紧凑型和分离扇强流回旋加速器中两种不同束流工作状态下的空间电荷效应，分别建立了“Start-to-Stop”模型和“中心束团”模型。两个模型都考虑了束团自身的空间电荷效应和径向相邻的多束团相互作用。
2. 发展了基于PIC 的并行计算方法，编写完成了第一个模拟强流回旋加速器中三维大规模粒子的并行计算程序OPAL-CYCL，研究强流回旋加速器中的空间电荷效应。硬件方面：1、依托瑞士高性能计算中心CSCS；2、构建小规模的高性能计算集群。
3. 应用OPAL-CYCL 程序，首次研究了强流回旋加速器中自身空间电荷及径向相邻多束团相互作用对束流性能的影响。
4. 在PSI的Ring上开展了实验测量工作，并和理论研究进行比较

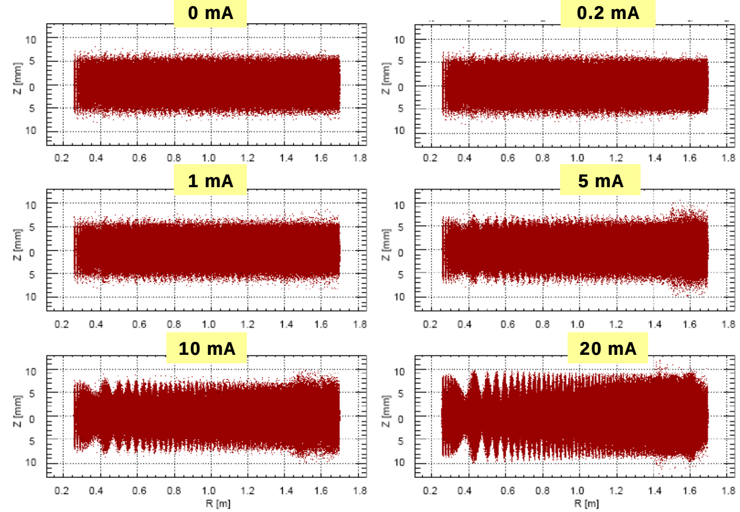
对相邻束团作用的建模——“Start-to-Stop”模型



“Start-to-Stop”模型动画演示

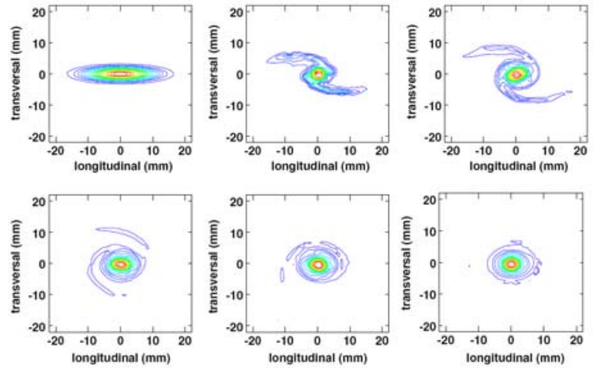
对CYCIAE-100中空间电荷效应的研究

轴向空间电荷限制流强的模拟



对于初始匹配束团，空间电荷限制流强约为1mA以上

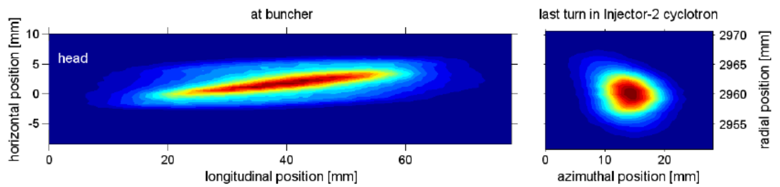
对Injector II中“圆形紧凑”的模拟和测量



OPAL-CYCL程序模拟 PSI Injector II 中1mA，3MeV的束团在束团演化为“圆形紧凑”的电荷分布过程。

上排从左到右依次为第0、 5 和 10 圈；下排从左到右依次为第 20、 30 和 40 圈。

杨建俊等PRST-AB



M.Seidel等 IPAC’10

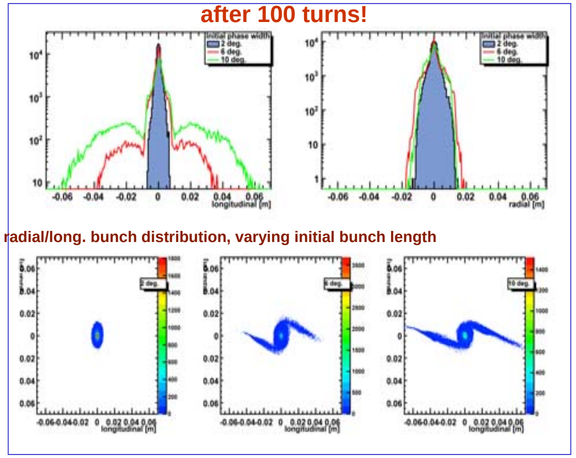
对590MeV Ring中不同初始相宽束团行为的模拟

→ behavior of short bunches, generated by 10’th harmonic buncher

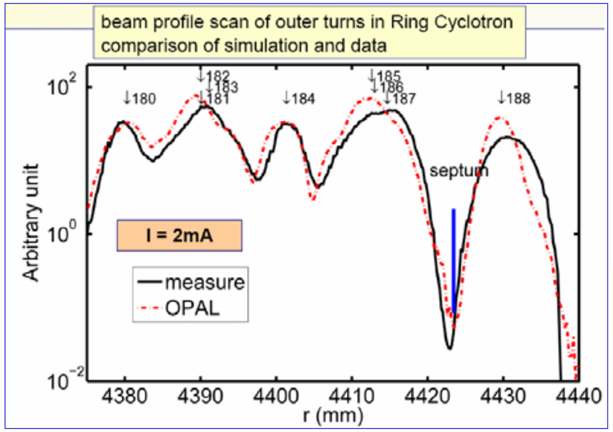
→ optimum parameters of flat-top cavity at these conditions

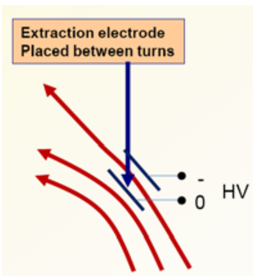
- -multiparticle simulations
- -10^5 macroparticles
- - precise field-map
- - bunch dimensions: **σ_z ~ 2, 6, 10 mm**; σ_{xy} ~ 10 mm

→ operation with short bunches and reduced flattop voltage seems possible



对590MeV Ring中径向束流包络的模拟和测量





PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 064201 (2010)

Beam dynamics in high intensity cyclotrons including neighboring bunch effects: Model, implementation, and application

J. J. Yang (杨建俊),[1,2,3,*] A. Adelmann,[2,†] M. Humbel,[2] M. Seidel,[2] and T. J. Zhang (张天爵)[1]
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[2]Paul Scherrer Institut, Villigen, CH-5234, Switzerland
[3]Department of Engineering Physics, Tsinghua University, Beijing, 100084, China
(Received 16 March 2009; published 14 June 2010)

Space-charge effects, being one of the most significant collective effects, play an important role in high intensity cyclotrons. However, for cyclotrons with small turn separation, other existing effects are of equal importance. Interactions of radially neighboring bunches are also present, but their combined effects have not yet been investigated in any great detail. In this paper, a new particle in the cell-based self-consistent numerical simulation model is presented for the first time. The model covers neighboring bunch effects and is implemented in the three-dimensional object-oriented parallel code OPAL-CYCL, a flavor of the OPAL framework. We discuss this model together with its implementation and validation. Simulation results are presented from the PSI 590 MeV ring cyclotron in the context of the ongoing high intensity upgrade program, which aims to provide a beam power of 1.8 MW (CW) at the target destination.

DOI: 10.1103/PhysRevSTAB.13.064201 PACS numbers: 29.20.dg, 29.27.Bd, 41.20.Cv

I. INTRODUCTION

Since the invention of the classic cyclotron several decades ago, increasingly higher beam intensities are re-

Nonlinear space-charge effects in cyclotrons are complex because of the complicated magnetic topology (reference trajectory with nonconstant curvature). Typically there are two approaches to deal with this difficulty: one

▪美国LBL的著名加速器专家R. Ryne在2008年欧洲加速器会议(EPAC'08)的特邀报告中回顾过去十年加速器计算物理进展时认为本工作是过去五年来国际上加速器计算物理的两个重大进展之一 ：

Two more important firsts occurred recently using parallel beam dynamics codes that illustrate the increasing complexity of modern beam dynamics models: … and this year the first parallel beam dynamics simulation of neighboring bunch effects in a cyclotron was performed using OPAL-cycl .
(Invited Talk, EPAC08, p. 2947-2951, Genoa, 2008).

▪加拿大TRIUMF的著名加速器专家R. Baartmann在HB'08会议总结中指出：

The space charge code OPAL-CYCL is now developed to the point that it can model a bunch surrounded by 9 (radially) neighbouring bunches. The new result is that the effect of the space charge from the neighbours is to sharpen the bunches further, making for better turn separation. This is a surprise.
(Proceeding of HB08, Nashville, 2008)

2010年

- 美国MIT , J. M. Conrad and M. H. Shaevitz, Multiple Cyclotron Method to Search for CP violation in the Neutrino Sector, Phys.Rev.Lett.104:141802,2010
- 欧洲INFN, L. Calabretta et Al , A Multi MegaWatt Cyclotron Complex to search for CP violation in the Neutrino Sector, ICC2010
- They proposed to use high-power proton accelerators able to deliver a proton beam whit energy 800 MeV, 1.5 MW power and duty cycle of 20% (100 msec beam on, 400 msec beam off).
- It consists in a two cascade cyclotron complex. The injector cyclotron, is a four sector machine, which accelerates a beam of H2+ up to energy of 35 MeV/n. The extraction radius is set around 130 cm and the energy gain is fixed at 1.1 MeV/turn, to obtain a turn separation of about 11 mm and then to make very efficient the extraction by the electrostatic deflector. The beam is then injected inside a 8 sectors Superconducting Cyclotron Ring. The energy gain is set at about 3 MeV/turn to reduce the number of turns inside the Ring cyclotron. The beam is extracted by the stripper method.

A New Method to Search for CP violation in the Neutrino Sector

J.M. Conrad[1] and M.H. Shaevitz[2]
[1] *Massachusetts Institute of Technology and*
[2] *Columbia University*

A 250 MeV, 1 mA cyclotron is under construction at MIT and a GeV-energy, megawatt-class cyclotron is presently under design.

I. INTRODUCTION

With the discovery of neutrino oscillations, particle physicists have been inspired to develop theories that explain very light neutrino masses. The most popular models invokes GUT-scale Majorana partners which can decay, producing a matter-antimatter asymmetry in the early universe through the mechanism of CP violation. Observation of CP violation in the light neutrino sector would be a strong hint that this theory is correct.

To incorporate CP violation, the light-neutrino mixing matrix is expanded to include a CP violating phase, δ_{CP}. Sensitivity to δ_{CP} comes through muon-to-electron flavor oscillations at the atmospheric mass-squared difference, Δm^2_{31}. The oscillation probability, neglecting matter effects, is given by [1]:

The neutrino sources would be based on commercially-developed small (2.5 m diameter), high-power proton cyclotron accelerators that are under development [7]. A 250 MeV, 1 mA cyclotron is under construction at MIT and a GeV-energy, megawatt-class cyclotron is presently under design. When in production, because of new, inexpensive superconducting technology, these machines are expected to cost 5% of a conventional proton accelerator (< \$20M). These machines will demonstrate the beam physics and engineering needed for this experiment.

This experiment requires accelerators that target 2 GeV protons at 2.5 mA during a 100 μs pulse every 500 μs, delivering 9.4×10^{22} protons per year to a beam stop. The result is a high-intensity, isotropic, decay-at-rest (DAR) neutrino beam arising from the stopped pion decay chain: $\pi^+ \to \nu_\mu + \mu^+$ followed by $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$. The flux, shown in Fig. 1, has an endpoint of 52.8 MeV.

2009年

- 中国CIAE, 提出中国国内已有大约100台的PET回旋加速器，特别是少数基于外部离子源的加速器，可升级改造、加速H2+ 剥离引出mA量级的质子束，用于BNCT，并申请了专利, 2010
- 中国CIAE, 邀请PSI专家来华合作，研究、设计800MeV、mA量级回旋加速器。2010年提出3～5MW加速器概念设计方案。
- 原子能院通过积极参予PSI提升质子束流功率到1.8MW的加速器研究、发展工作，并邀请专家合作研究，已经基本具备在国际力量的支持下，自主设计、建造这样加速器的能力。

未来高平均功率加速器展望

Peter Sigg

未来高平均功率加速器展望

W. Joho

A. Adelmann

未来高平均功率加速器展望

个人观点：

平均质子束流功率3~5MW水平，回旋加速器在技术上是可行的，在经济（包括造价和运行成本）上是有明显优势的。

ADS drivers: Linac & cyclotrons

Dr. Klaus Bongardt, July 21, 2010

加速器驱动次临界反应堆：加速器产生的快中子

3MW质子束（CW） → **50~100MW反应堆**

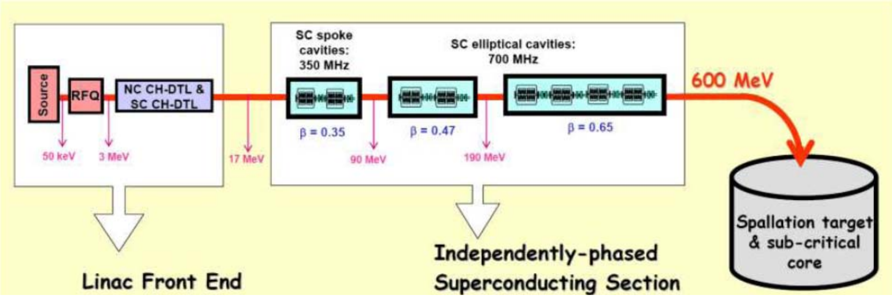
>100MW质子束（CW） → **3GW反应堆**

加速器需求：

- **Linac:** 5mA，0.6GeV （CW）
- **Cyclotrons:** 3mA, 1GeV (CW)

ADS drivers: Linac （**CW?**）

0.6 GeV, 5 mA MYRRHA H^+ Linac, 240m： NC(常温)+SC（超导）



前端： ~20m:

RFQ(3MeV, 4.5m)
NC-CH-DTL(+2MeV)
SC-CH-DTL(+17MeV)

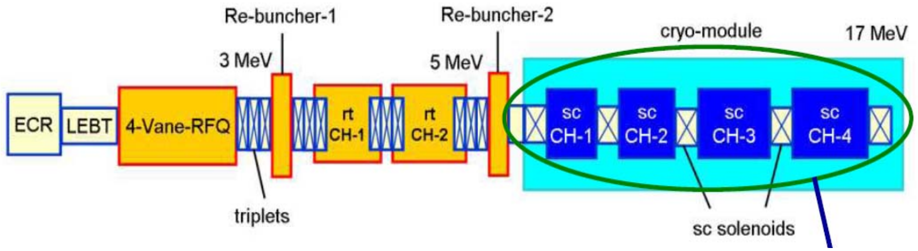
ADS drivers: Linac （**CW?**）

0.6 GeV, 5 mA MYRRHA H^+ Linac, 240m： NC(常温)+SC（超导）

前端： ~20m:

SC-CH-DTL(17MeV)：共4段，超导螺线管

SC – CH 结构正在建造，预计2011年在德国的GSI投入测试

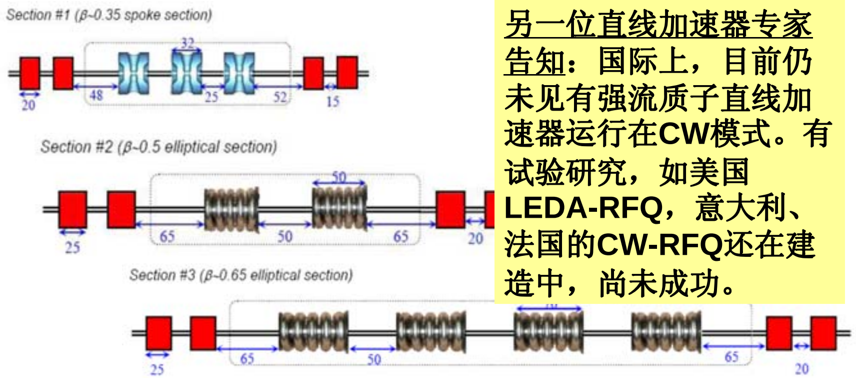


ADS drivers: Linac （**CW?**）

0.6 GeV, 5 mA MYRRHA H^+ Linac, 240m： NC(常温)+SC（超导）

后端： 350/700MHz，~220m:

SC-CH-DTL(→0.6GeV)：共3段，157个独立提供功率的SC腔体



另一位直线加速器专家告知：国际上，目前仍未见有强流质子直线加速器运行在CW模式。有试验研究，如美国LEDA-RFQ，意大利、法国的CW-RFQ还在建造中，尚未成功。

ADS drivers: Cyclotron （**CW！**）

Cyclotrons: 3mA, 1GeV (CW)：两级回旋加速器

离子源：100 keV , >5mA

前级回旋加速器：100MeV， >3mA

后级回旋加速器：1GeV，3mA

PSI目前的升级： 3mA → 1.8 MW

对于3MW左右的质子加速器，回旋的方案比较现实、造价低、运行费用低。

2、多用途

- 能源领域
- 国土安全
- 医疗卫生

核物理基础研究

•在核物理基础研究中，强流质子束及其产生的中子、放射性核束，对核天体物理、新核素合成、核结构等都有很重要的意义。

能源领域

– 强流加速器在能源等国民经济重大领域有重要作用：

–除了目前的轻水堆核电站、快堆；

–核废物嬗变；

–加速器驱动次临界装置ADS。

强流高平均功率加速器技术

中子靶技术次临界驱动

•嬗变处理长寿命核废物

•化学固化后深埋，封闭储存有时长达几万年，即使这种方式非常安全有效，对于公众能否长期接受仍然是一个问题。

•用强流加速器提供的质子束产生中子，嬗变长寿命放射性核废物；

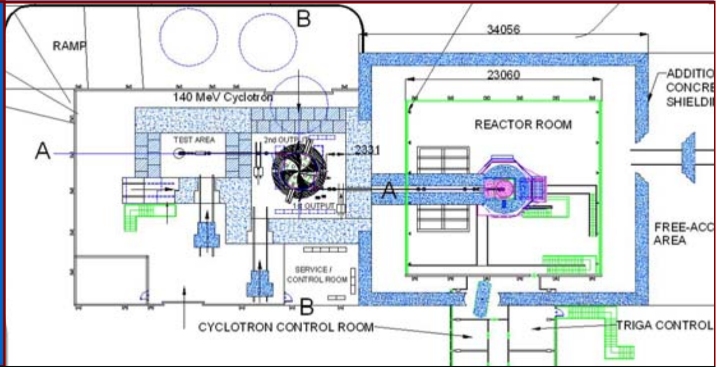
•这样的废物处理过程也是资源再利用的过程。因为在核废料的反应过程中大量地释放出能量。

•加速器驱动裂变装置

•ADS能源系统实验研究已在进行。

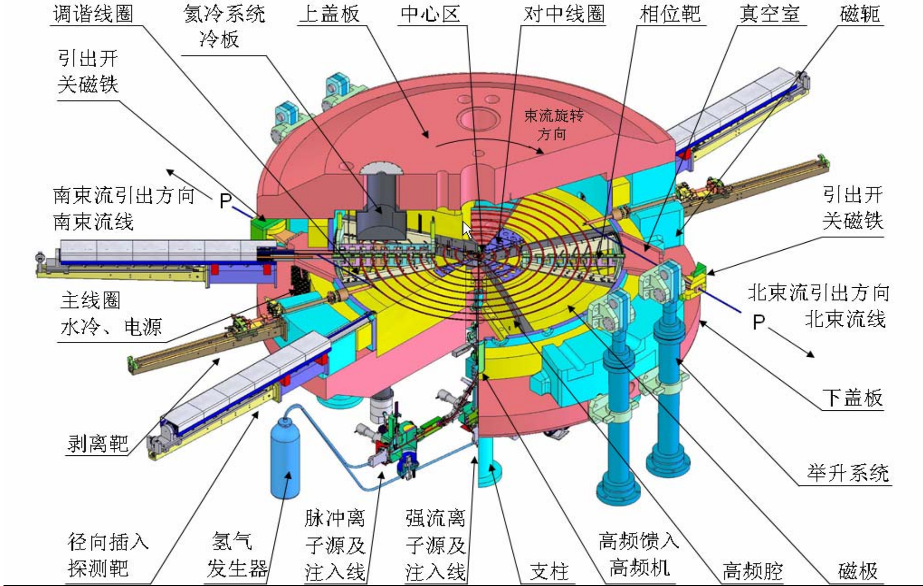
•欧洲CERN、意大利ENEA、瑞士PSI、比利时IBA、美国ANL等国家实验室和商业公司均提出强流的加速器试验方案。

ENEA:
C.Rubbia,
TRADE:
TRIGA
Accelerator
Driven
Experiment



2004年原子能院确定100MeV强流回旋加速器采用紧凑型结构作为建造方案，2个月后ENEA项目建议书140MeV回旋也为紧凑型结构

2004年中国原子能科学研究院提出100MeV强流回旋加速器采用紧凑型结构作为建造方案



2004-C.Rubbia Group: No machine of this type has been constructed up to now, 2005-Nantes, 2008-INFN-LNL, ORNL, 70MeV, compact

Subcritical nuclear reactor developments

Integrated Project on European Transmutation: EUROTRANS
Steps towards a Demonstrator

EUROTRANS has started on April 1st, 2005

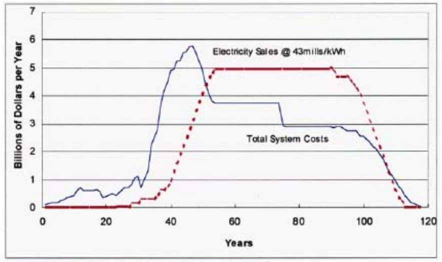
(with 23 M€ EC contribution and 43 M€ total eligible costs)

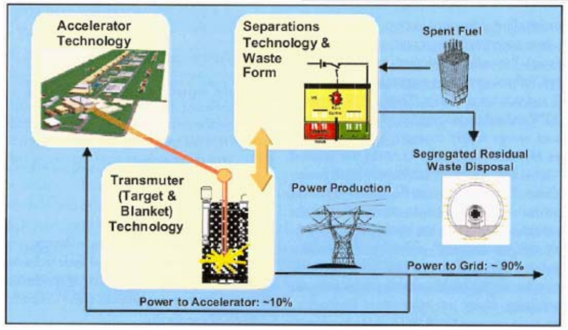
Huangzhou February 23-24 2006

DOE Roadmap's scenario

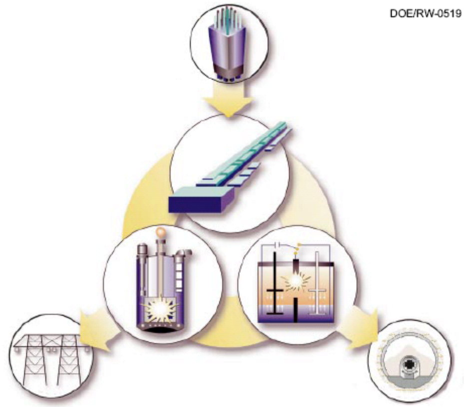
Performance parameters of ADS plant (Sample case)

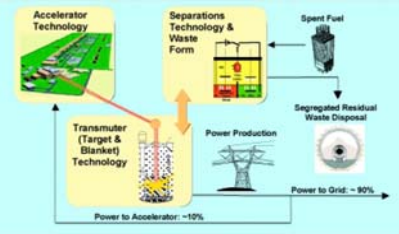
- Proton beam: 1.5GeV, 40mA
  - neutrons per incident proton: ~30
- Spallation target and coolant : Lead-Bismuth
  - flow speed: 2m/sec
- Fuel material: Nitride MA : Pu = 60 : 40
- Thermal output(fission power): 820MW
  - coolant temperature: inlet/outlet = 330/430℃
- Effective neutron multiplication: initial/max/min = 0.95/0.95/0.94
- Initial inventory of MA: 2500kg
- MA transmutation (fission) rate:250kg/y





DOE/RW-0519





A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology

A Report to Congress

October 1999

LANL - ATW

A REVIEW OF LINACS AND BEAM TRANSPORT SYSTEMS FOR TRANSMUTATION

J-M Lagniel, CEA-Saclay
DSM-DAPNIA-SEA, 91191 Gif-sur-Yvette Cedex, France

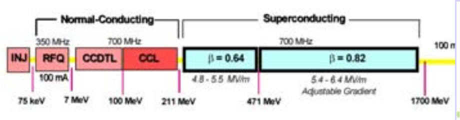


Figure 3 : APT layout for a 3-kg/yr production rate (Linac length = 1220 m)

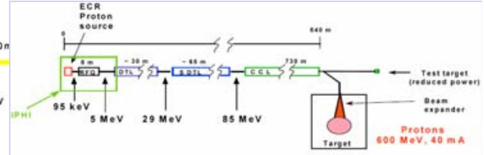


Figure 5 : TRISPAL layout

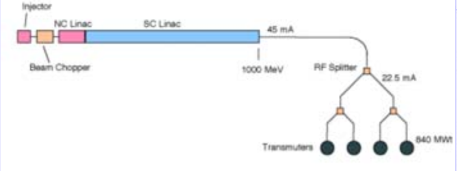


Figure 2.2. Reference Accelerator and Beam-Transport Concept for the Deployment-Driven ATW plant

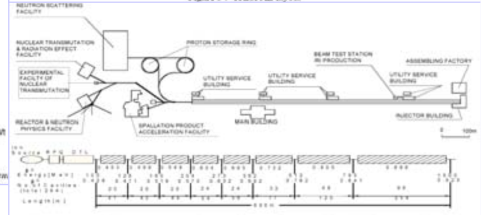
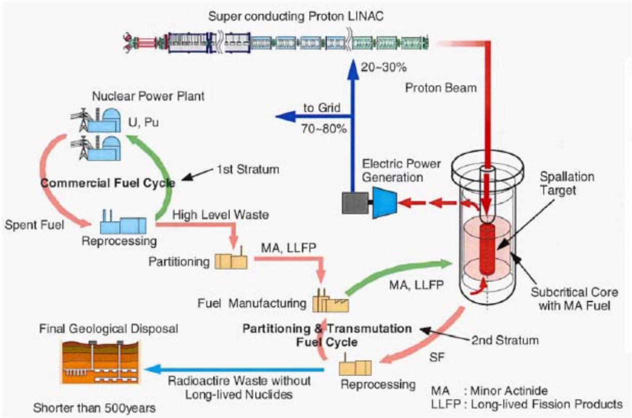


Figure 4 : Layout of the JAERI Neutron Science Project (top) and 1.5 GeV linac design (bottom) (from [11])

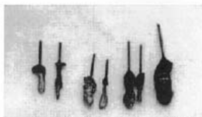
LANL - ATW

第六届 OCPA 加速器学校 China Institute of Atomic Energy

Japanese Proposal (JAERI/KEK)

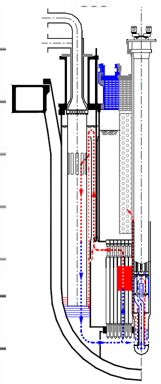


- *Nitride fuel*
  - Thermochemical stability
  - Good thermal property
  - High heavy-metal density
- *Pyroprocess*
  - Compact facility with minimum envelope
  - Easy recovery of **N-15** (to avoid C-14 from N-14)



Metal Pu from PuN

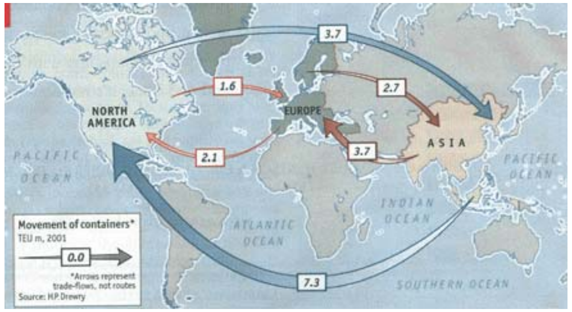
比利时核子研究中心（SCK•CEN）

	LBE-cooled XADS	Gas-cooled XADS	MYRRHA
Core Power (MW)	80	80	50
Primary Coolant	LBE	Helium at ~6 MPa	LBE
Core Inlet Temperature (°C)		200	200
Core Outlet Temperature (°C)		450	350
Coolant Flow Rate in the Core (Kg/s)		61.6	2500
Coolant Velocity in the Core (m/s)		~30	< 2
Core Pressure Loss (Pa)		60000	> 200000
Secondary Coolant		Water	Water
IHX Sec. Coolant Inlet Temperature °C)		25	140
IHX Sec. Coolant Outlet Temp (°C)		65	170

Design Data (nominal) of the three XADS design

国土安全

Major Container Ports in the world
- 1st Hong Kong :18,1 MTEU/y
- 2nd Singapore : 17,0 "
- 5th Rotterdam : 6,2 "
- Le Havre (F) : 1,5 "
TEU/y = Twenty Equivalent Feet Unit per Year



Of all the world's great industries, shipping is arguably the most international, and today the global commerce is more accurately defined as international trade by ship.
In fact approximately **95% of the world's cargo moves by ship**. That translates into **over 200 million cargo containers moving between major seaports around the world each year**.
It is estimated that **less than 10% of all containers are checked** to verify that transported goods corresponds to the declared content. The very large movement of containers around the world **increases the risk that the containers could be used by a terrorist group**. As a result, the maritime industry must take any potential threat for disruption of the trade very seriously.

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Plutonium under Pressure

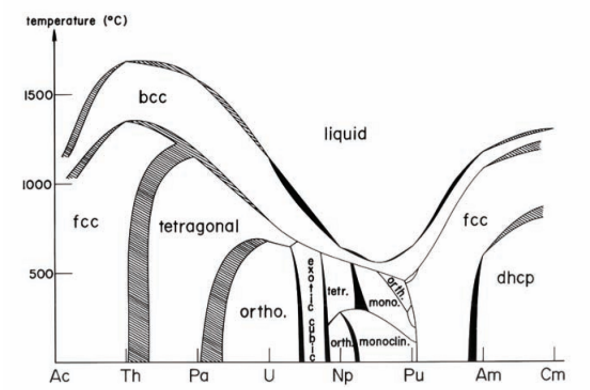


Figure 1. Kmetko-Smith Composite Phase Diagra
This diagram shows how the structures and melting po of the light actinides vary across the periodic table. The deep minimum in m ing point is coincident with maximum structural complexity near plutonium's p ition.

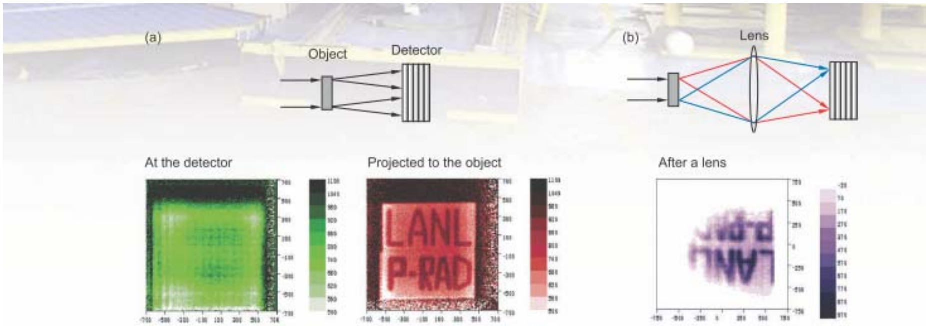


Figure 1. Demonstrating pRad with Magnetic Focusing
A beam of protons (188 MeV in energy) from the P3W channel at LAMPF was sent through an object—a 6-mm-thick steel plate with the words LANL P-RAD machined halfway through—and the positions and trajectories of the transmitted protons were recorded by a layered proton detector (see diagram). (a) With nothing between the object and the detector, we obtained a blurred radiograph (green) showing the positions of the protons as they entered the detector, but by projecting the proton trajectories recorded at the detector back to the object, the letters on the sign became visible (red radiograph). (b) The purple radiograph (inverted image) was obtained by placing a triplet of quadrupole magnets between the object and the detector and directly recording the positions of the protons entering the detector. Because the magnets act like a proton lens, focusing the protons at the detector, they allow a clear image to be recorded. Magnetic focusing makes flash radiography possible because each proton does not need to be individually measured.

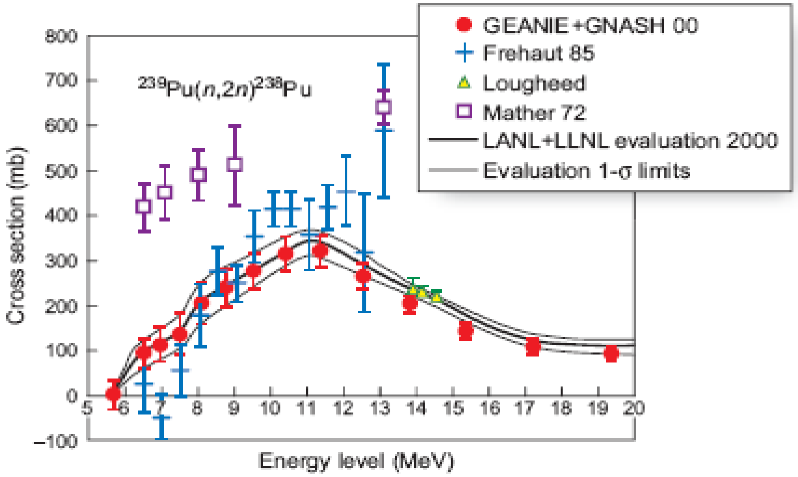


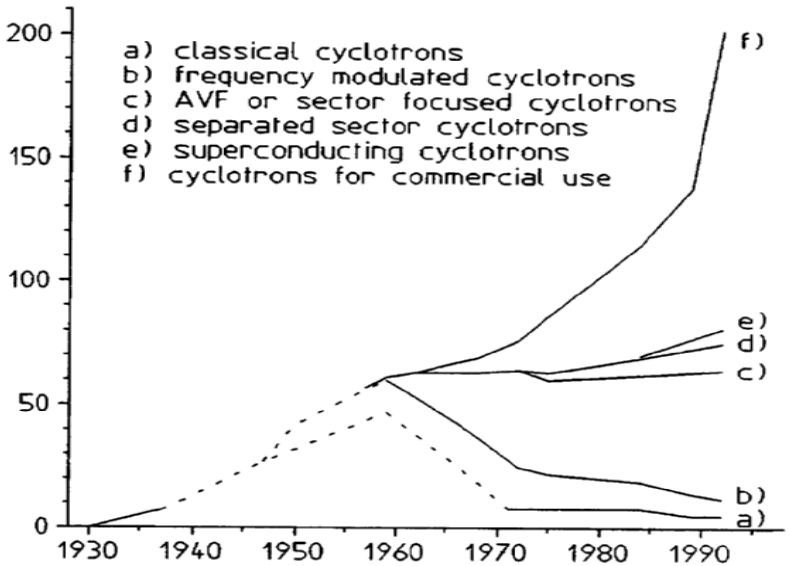
Figure 6. Measurement Results of *n*,2*n* on Plutonium at GEANIE vs Previous Data

The ^{239}Pu(*n*,2*n*)^{238}Pu cross section results deduced from the GEANIE

2、多用途

- 能源领域
- 国土安全
- 医疗卫生

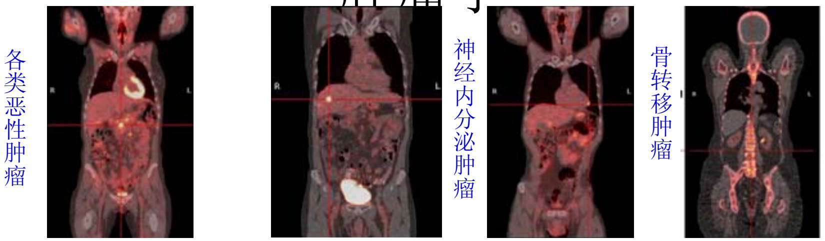
→ **核医学**
放射医学



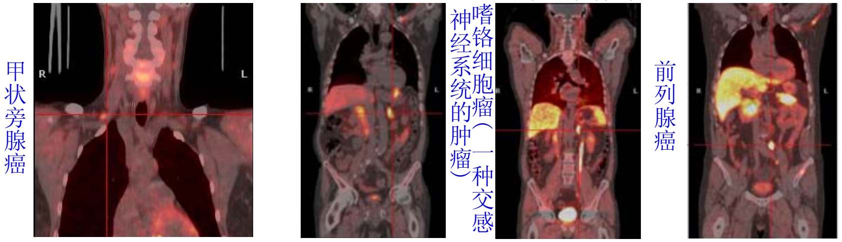
- **回旋加速器在核医学中的应用**
  - **正电子断层用放射性同位素（PET）**
    ～10 MeV
  - **其他放射性诊断、治疗用放射性同位素**
    ～20 MeV
    ～30 MeV
  - **中子、质子治疗**
    ～50 MeV
    ～70 MeV
    ～250 MeV

mA量级，BNCT

肿瘤学

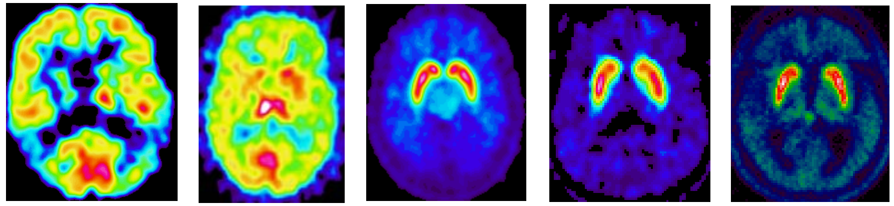


Malignant tumors ^{18}F Fluorodeoxyglucose | **Neuroendocrine tumors** ^{68}Ga DOTA-GOC | **Neuroendocrine tumors** ^{11}C 5-Hydroxytryptophan | **Bone metastases** ^{18}F-Fluorine

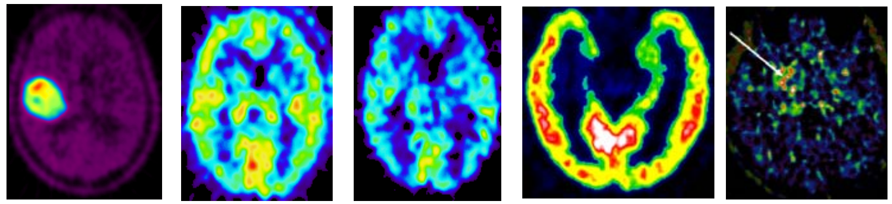


Parathyroid cancer ^{11}C Methionine | **Adrenocortical tumors** ^{11}C Metomidate | **Pheochromocytomas** ^{11}C Hydroxyephedrine | **Prostate cancer** ^{11}C Acetate

神经学

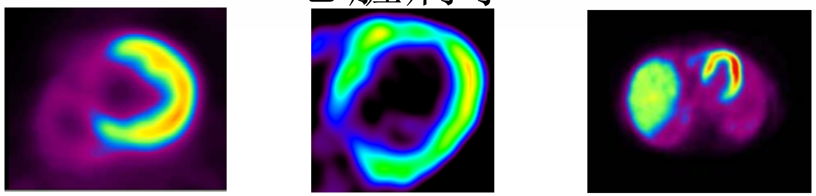


Glucose metabolism ^{18}F Fluorodeoxyglucose | **Inflammation** ^{11}C D-Deprenyl | **Dopamine reuptake** ^{11}C BCIT | **D2-receptors** ^{11}C Raclopride | **Dopamine synthesis** ^{18}F Dopa

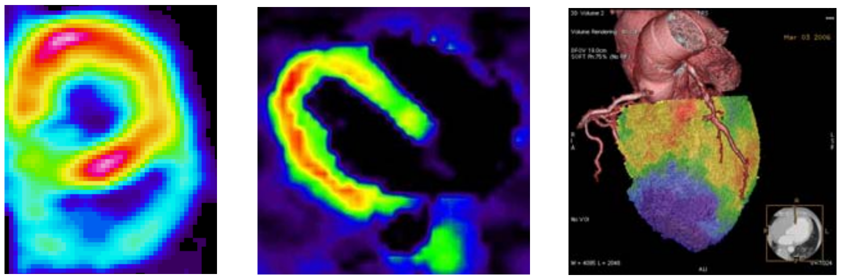


Amino acid uptake ^{11}C Methionin | **Blood flow** ^{15}O Water | **Oxygen Consumption** ^{15}O Oxygen | **Central BZ-receptors** ^{11}C Flumazenil | **Microglia activation** ^{11}C PK11195

心脏病学



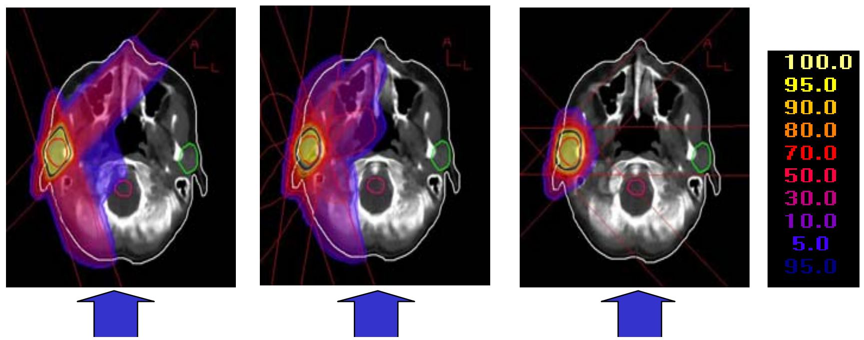
Glucose metabolism ^{18}F Fluorodeoxyglucose | **Oxidative metabolism** ^{11}C Acetate | **Adrenergic innervation** ^{11}C Hydroxyephedrin



Lactate metabolism ^{11}C Lactate | **Blood flow** ^{15}O Water | **Anatomofunctional fusion**

质子与X射线治疗的比较

腮腺癌

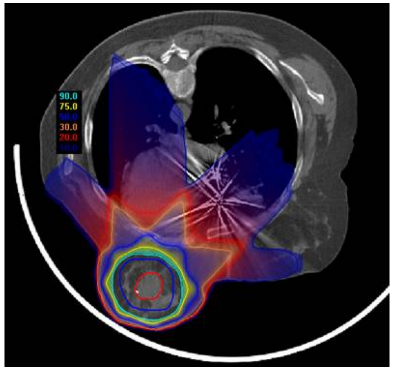


X射线2向照射 | X射线5向照射 | 质子3向照射

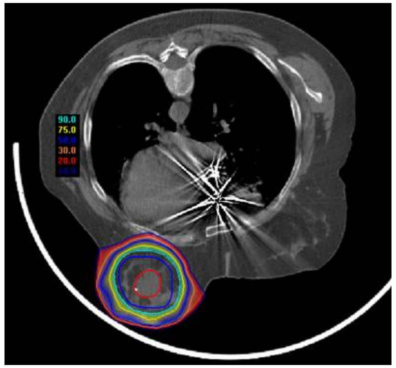
质子与X射线治疗的比较

乳癌

X-rays

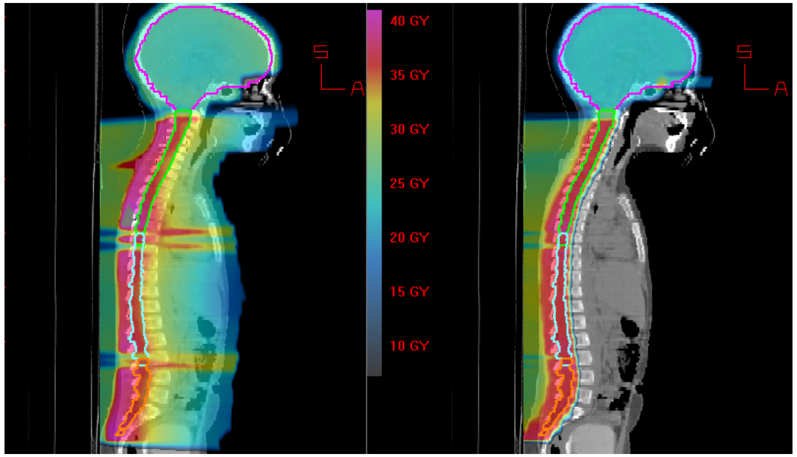


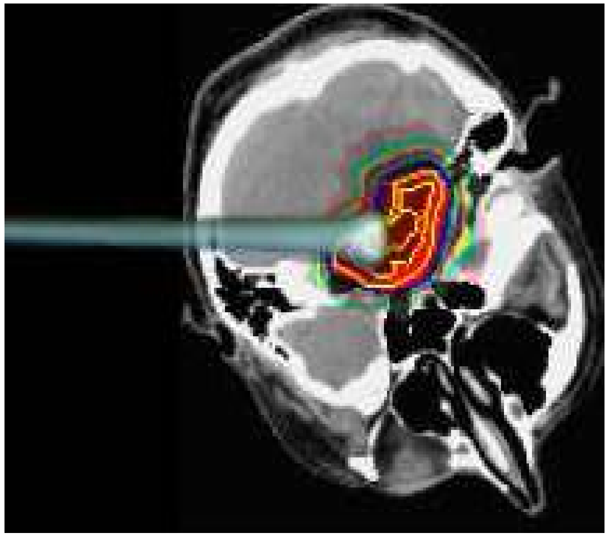
质子



与常规射线治疗比较：患者将负担更少的剂量

X射线　　质子





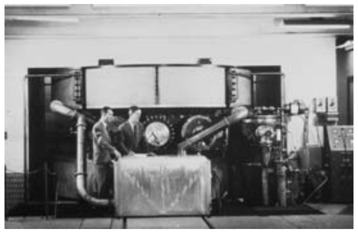
脑癌治疗

质子照射脑癌的束斑

(E.Pedroni, PSI)

Accelerators used for proton therapy in 2006

	Total	Non Hospital	Specific/Hospital
Cyclotrons	15	11	4
Synchrocyclotrons	4	4	
Synchrotrons	6	2	4



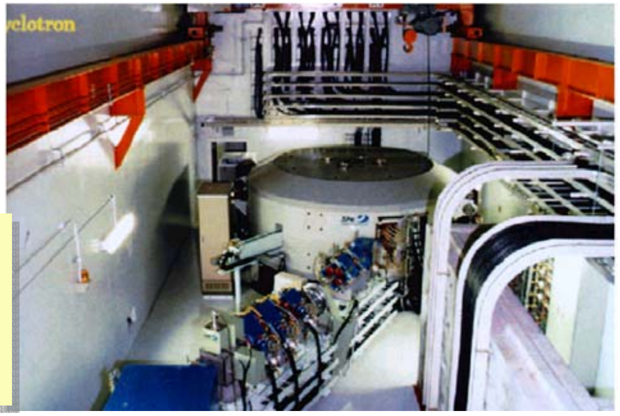
HCL
1949-2002

FHBPTC
2001 –

常用的医用回旋加速器：

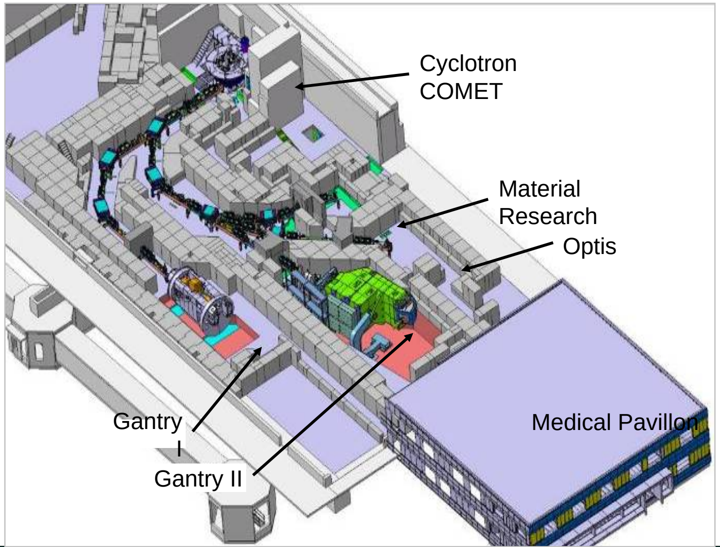
质子治疗用

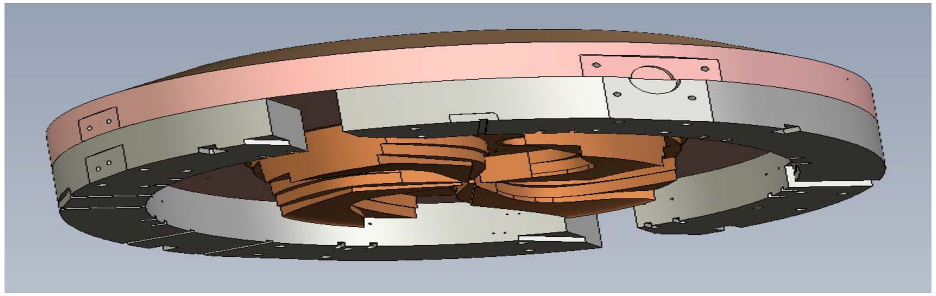
IBA质子治疗回旋加速器235MeV



第一台质子治疗用的回旋加速器

ACCEL质子治疗用回旋加速器(PSI)



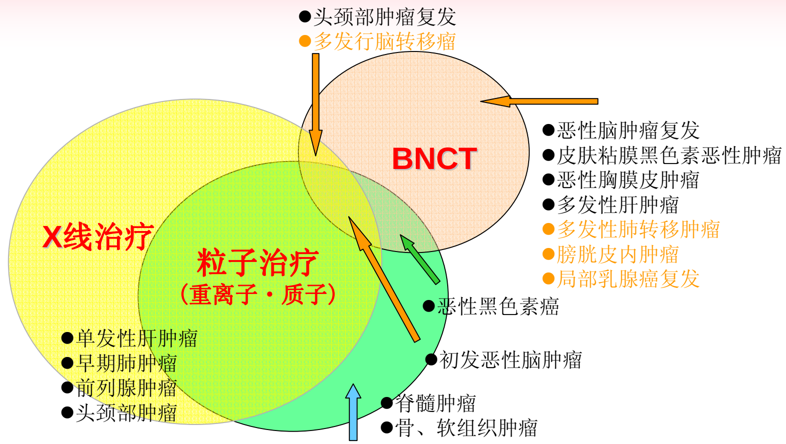


CYCIAE-230

原子能院具备设计、建造230MeV质子回旋加速器的能力，已经开展了必要的前期研究

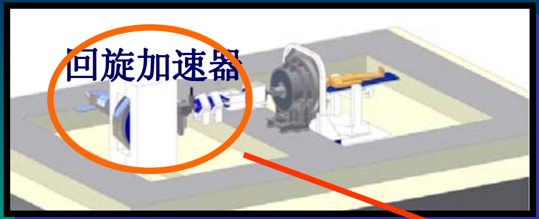
各种肿瘤治疗统计

※资料来源：京都大学原子反应研究所・鈴木実教授提供



BNCT对恶性脑肿瘤、头颈部肿瘤、侵润性、多发性、复发肿瘤有较好效果

BNCT硼中子俘获治疗系统



回旋加速器

型号：HM-30
质子：30MeV，2mA

用外部离子源的
高束流回旋加速器

- 回旋加速器在核医学中的应用
  - 正电子断层用放射性同位素（PET） ～10 MeV
  - 其他放射性诊断、治疗用放射性同位素 ～20 MeV ～30 MeV

用加速器生产反应堆生产的同位素

  - 中子、质子治疗 ～50 MeV ～70 MeV ～250 MeV

mA量级，BNCT

回旋加速器的能量

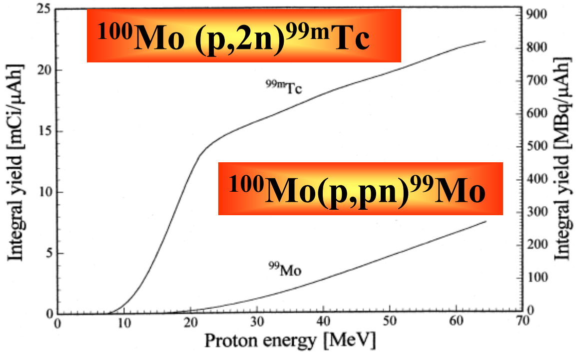


表 1、不同小型回旋加速器的 ^{99m}Tc 产额比较

PET Cyclotron	Energy on target (MeV)	Yield (mCi)
CYCIAE-14	14	5600
GE PETtrace	16	2600
IBA Cyclone 18	18	4000
ACSI TR19	19	4200 +

THUNDER BAY Regional Health SCIENCES CENTRE

Request for Proposal

RFP # 10- 04

Supply and Install (1) Cyclotron

招标：15MeV回旋加速器生产Mo-99, Tc-99m

quest for Proposal

Participating Agency	Thunder Bay Regional Health Sciences Centre (TBRHSC) Thunder Bay Regional Research Institute (TBRRI)
Date issued	May 17, 2010
Closing Date	June 8, 2010

Non-reactor-based Isotope Supply Contribution Program

招标：35MeV回旋加速器生产Mo-99, Tc-99m

Request for Project Proposals
Applicants' Guide
(June 2,2010)

Ce document est aussi disponible en français. Veuillez envoyer un courriel à nisp-ppin@nrcan-rncan.gc.ca en indiquant à la ligne Objet «Guide du proposant» (sans les guillemets).

Natural Resources Canada　　Ressources naturelles Canada

2、多用途

- 能源领域
- 国土安全
- 医疗卫生

→ **核医学**
放射医学

其它

仁科蔵王　　御衣黄

御衣黄　　仁科蔵王

図4　新色サクラ"仁科蔵王"
緑がかった"御衣黄"に重イオンビームを照射して、淡黄色の"仁科蔵王"をつくった。野依理事長が命名し、理研が初めて種苗登録した品種。

日本RIKEN的回旋加速器辐照樱花
改变颜色、延长花期

CIAE回旋

CYCIAE-30` 1994

Y-120，50年代

CYCIAE-10` 2009

Welcome to visit CIAE

Tjzhang@ciae.ac.cn