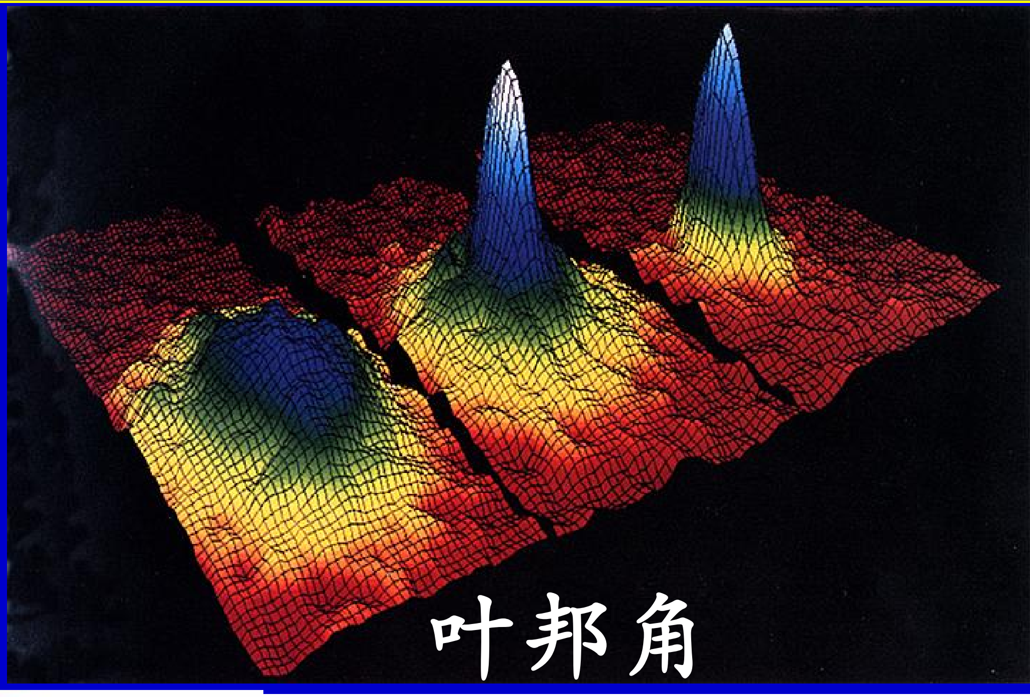
正电子概况XIII

Positronium Bose-Einstein Condensation



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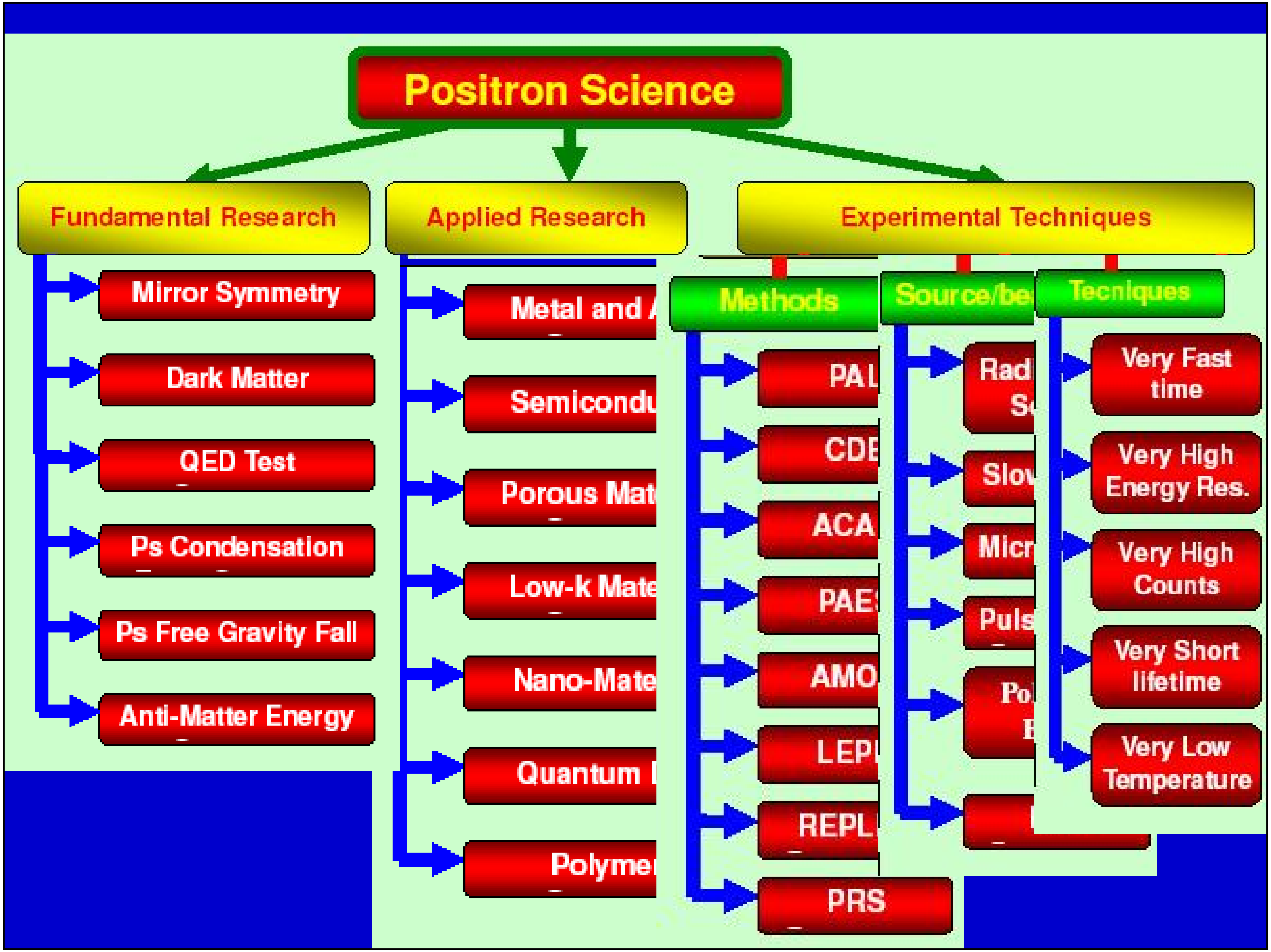
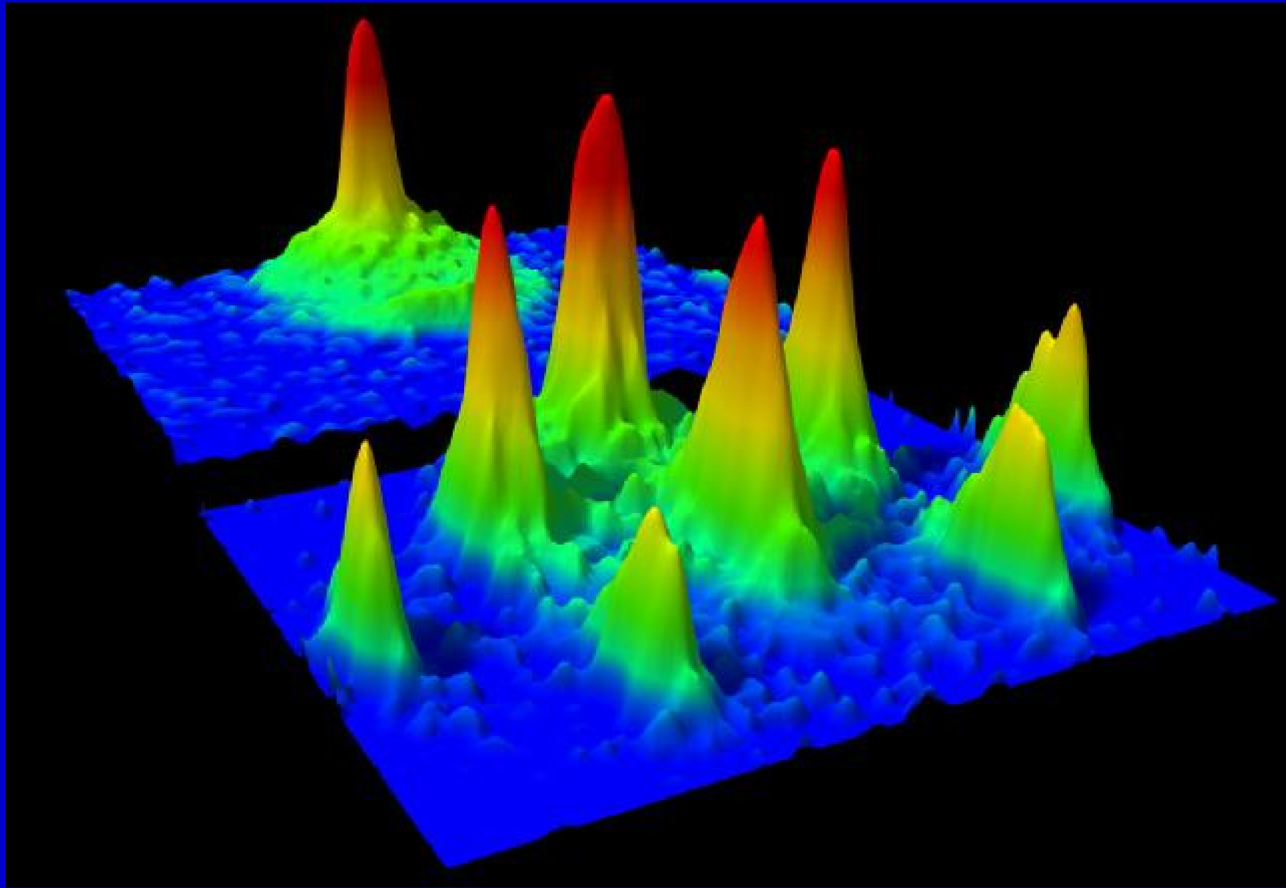


Positron Science
Fundamental Research
Applied Research
Experimental Techniques
Mirror Symmetry
Dark Matter
QED Test
Ps Condensation
Ps Free Gravity Fall
Anti-Matter Energy
Metal and
Semicondu
Porous Mat
Low-k Mate
Nano-Mate
Quantum
Polyme
Methods
PAL
CDE
ACA
PAE
AMO
LEP
REPL
PRS
Source/be
Slov
Micr
Puls
Tecniques
Very Fast time
Very High Energy Res.
Very High Counts
Very Short lifetime
Very Low Temperature

内容提要

- 什么是BEC
- 什么是Positronium BEC
- Positronium BEC状况和发展

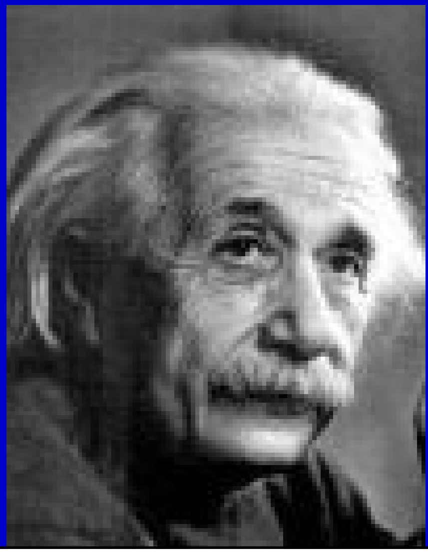
一、什么是BEC



玻色 — 爱因斯坦凝聚 —— BEC

—— 1924年印度物理学玻色提出黑体辐射是光子理想气体的观点，研究了“光子在各能级上的分布”问题，以不同于普朗克的方式推导出普朗克黑体辐射公式

—— 爱因斯坦将其观点和方法推广到某一类原子，预言当这类原子的温度足够低时，所有的原子就会突然聚集在一种尽可能低的能量状态



- 在很长一段时间里，没有任何物理系统被认为与玻色－爱因斯坦凝聚现象有关。
- 1938年，伦敦提出低温下液氦的超流现象可能是氦原子玻色凝聚的体现，玻色－爱因斯坦凝聚才真正引起物理学界的重视。
- 在20世纪50年代，物理学家发展了很多弱相互作用玻色系统的理论，美籍华人物理学家杨振宁、李政道和黄克逊在这方面做了很出色的工作。然而这些理论在1995年之前都没有得到很好的验证。由于气体中原子之间的相互作用很弱，更接近于爱因斯坦提出这一概念的系统，同时也使得理论与实验的比较变得容易。在气体中实现玻色－爱因斯坦凝聚成为物理学家长期的梦想。

- 由于激光冷却技术的发展，20世纪80年代初物理学家开始了在气体中实现玻色－爱因斯坦凝聚的尝试。
- 1995年6月威依迈和科纳尔的研究组在铷（87Rb）原子蒸气中第一次直接观测到玻色－爱因斯坦凝聚。他们先在磁光阱中对原子进行激光冷却，然后将原子转移到磁阱中进行蒸发冷却以达到玻色－爱因斯坦凝聚所需的低温。由于磁阱的特点，原子很容易从中心逃出，科纳尔发展了一套有效的方法堵住了原子出逃的漏洞，最终他们将温度降到170nK，从而观测到了玻色一爱因斯坦凝聚现象。
- 几个月后麻省理工学院的沃尔夫冈．凯特纳研究组在钠（23Na）原子蒸气中实现了玻色一爱因斯坦凝聚。他们采用了类似的技术路线，只是为防止原子从磁阱中心逃出使用了不同的方法。
- 目前世界上已有近30个研究组在稀薄原子气中实现了玻色－爱因斯坦凝聚。

The Nobel Prize in Physics 1989

- "for the development of the ion trap technique"

Hans Dehmelt
University of Washington
USA

Wolfgang Paul
Universität Bonn
Germany

The Nobel Prize in Physics 1997

- for development of methods to cool and trap atoms with laser light"
-

Steven Chu
Stanford University
Stanford, CA, USA

Claude Cohen-Tannoudji
Collège de France; Paris, France

William D. Phillips
NIST
Gaithersburg, MD, USA

The Nobel Prize in Physics 2001

Eric A. Cornell

JILA & NIST, Boulder, Colorado.

1961-

Wolfgang Ketterle

MIT

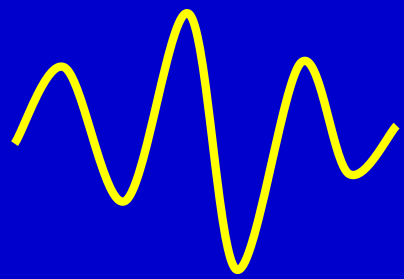
1957-

Carl E. Wieman

JILA & University of Colorado, Boulder.

1951-

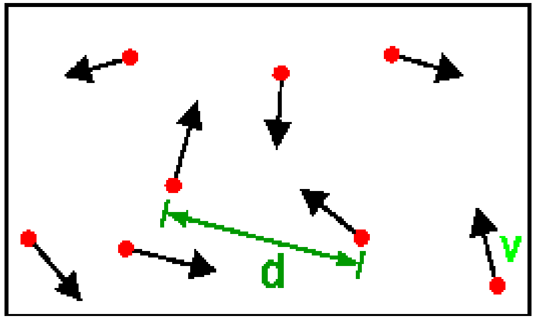
What Is Bose-Einstein Condensation?



De Broglie (1929 Nobel Prize winner) proposed that all matter is composed of waves. Their wavelengths are given by

$$l = \frac{h}{mv}$$

What is Bose-Einstein condensation (BEC)?

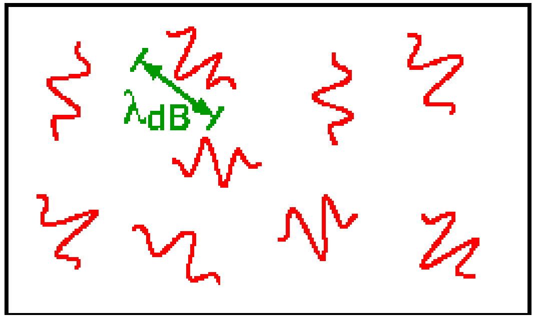


High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

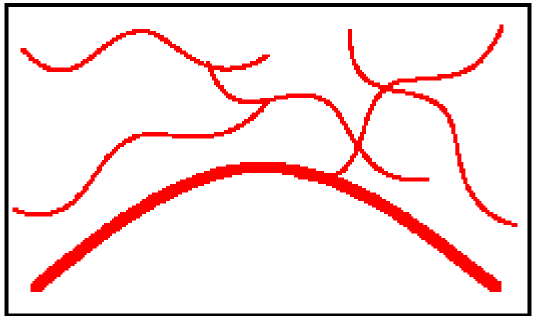


Low Temperature T:

De Broglie wavelength

$\lambda_{dB}=h/mv \propto T^{-1/2}$

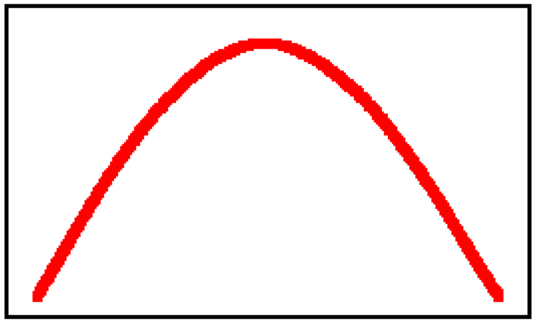
"Wave packets"



$T=T_{crit}$: Bose-Einstein Condensation

$\lambda_{dB} \approx d$

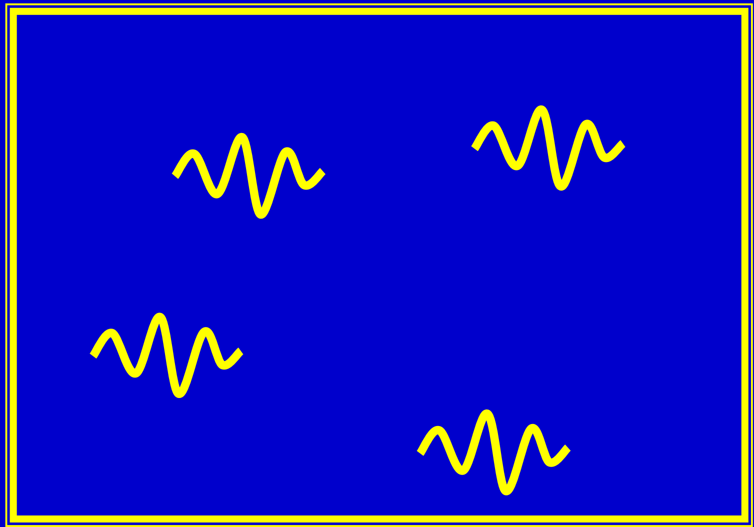
"Matter wave overlap"

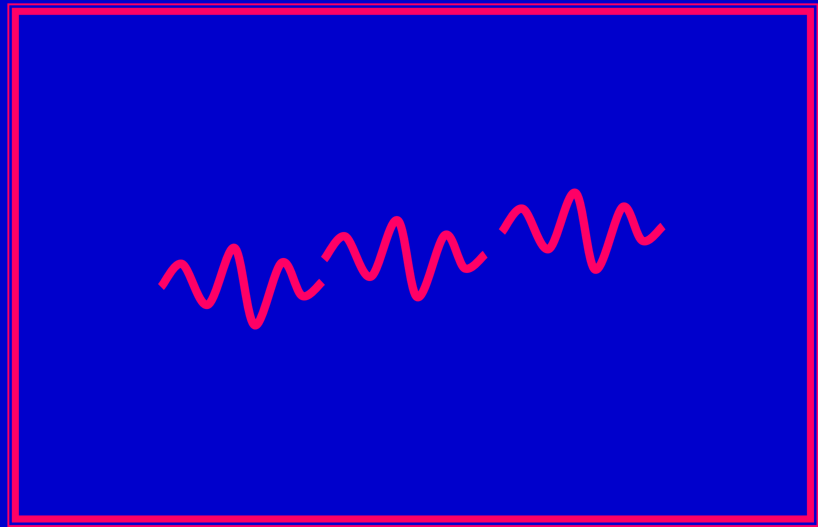


T=0: Pure Bose condensate

"Giant matter wave"

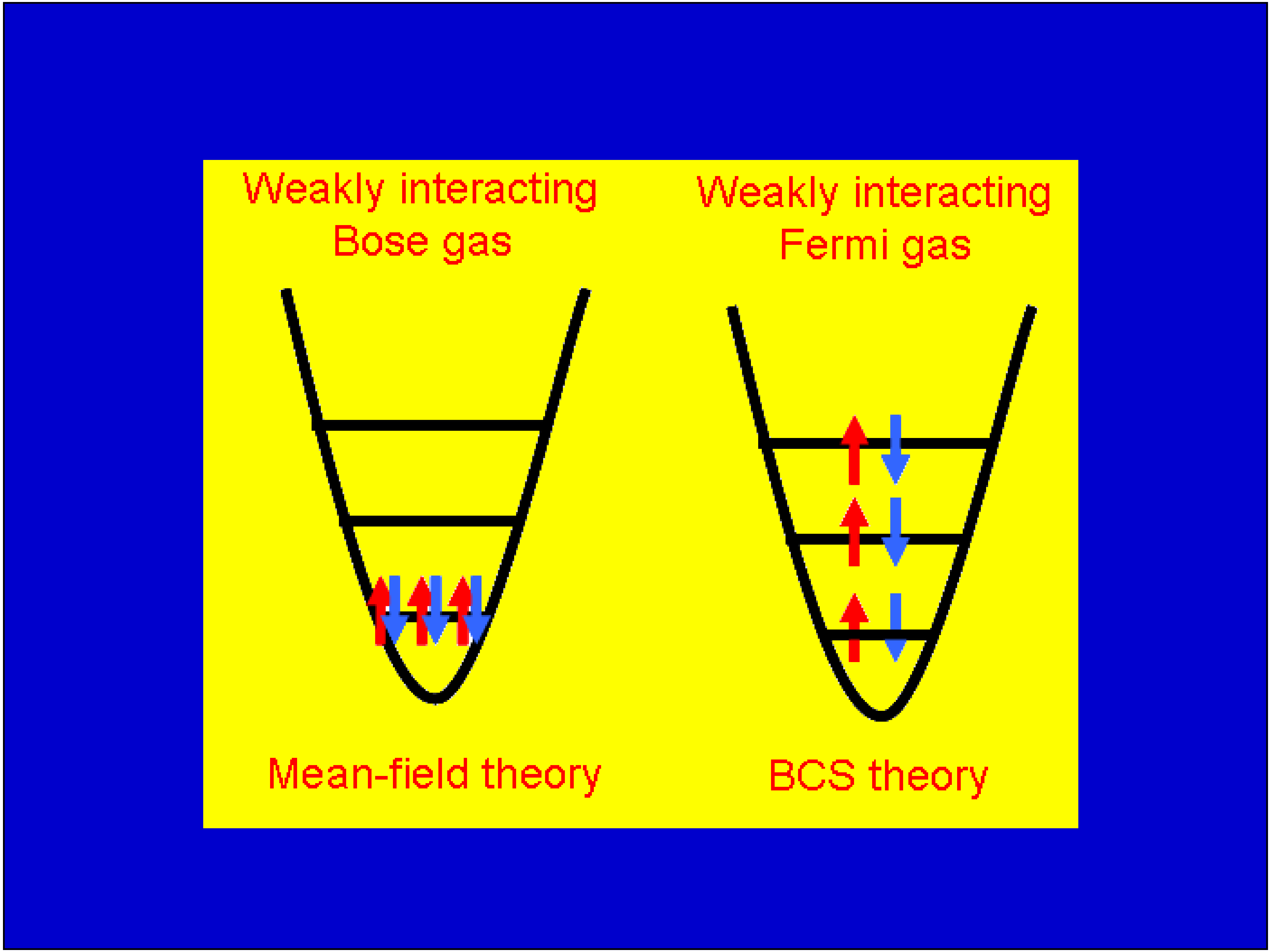
Against Our Intuition?!



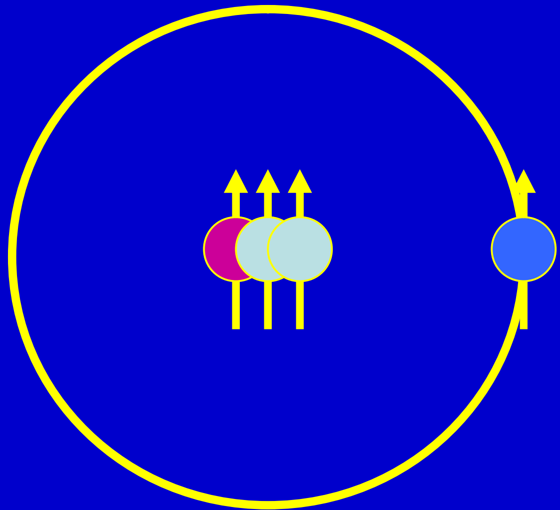


- In most everyday matter, the de Broglie wavelength is much shorter than the distance separating the atoms. In this case, the wave nature of atoms cannot be noticed, and they behave as particles.
- The wave nature of atoms become noticeable when the de Broglie wavelength is roughly the same as the atomic distance.
- This happens when the temperature is low enough, so that they have low velocities.

- Not all particles can have BEC. This is related to the spin of the particles.
- The spin quantum number of a particle can be an integer or a half-integer.
- Single protons, neutrons and electrons have a spin of $\frac{1}{2}$. They are called fermions. They cannot appear in the same quantum state. BEC cannot take place.
- Some atoms contain an even number of fermions. They have a total spin of whole number. They are called bosons.
- Bosons show strong "social" behaviour, and can have BEC.
- Example: A ^{23}Na atom has 11 protons, 12 neutrons and 11 electrons.


Weakly interacting
Bose gas
Weakly interacting
Fermi gas
Mean-field theory
BCS theory

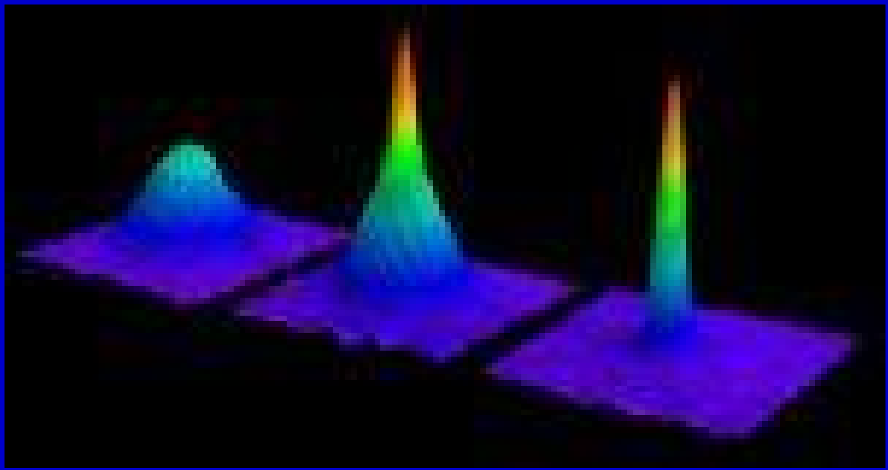
The Material For BEC

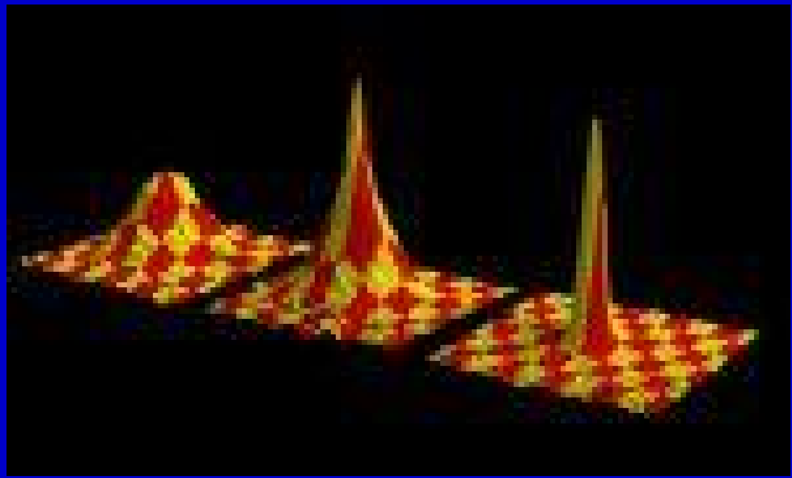


ùBEC was found in alkali metals e.g. ^{87}Rb (铷), ^{23}Na , ^{7}Li because:

- ùThey are bosons.
- ùEach atom is a small magnetic compass, so that a cooling technique called magnetic cooling can work.
- ùThe atoms have a small repulsion, so that they do not liquefy or solidify down to a very low temperature.

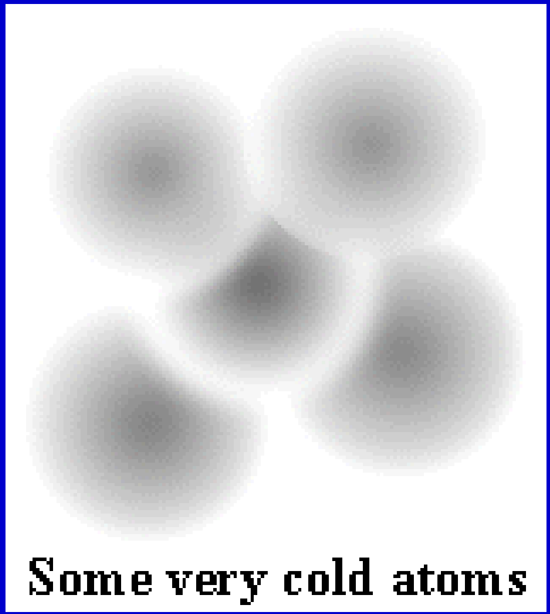
Cooling Down the Atoms

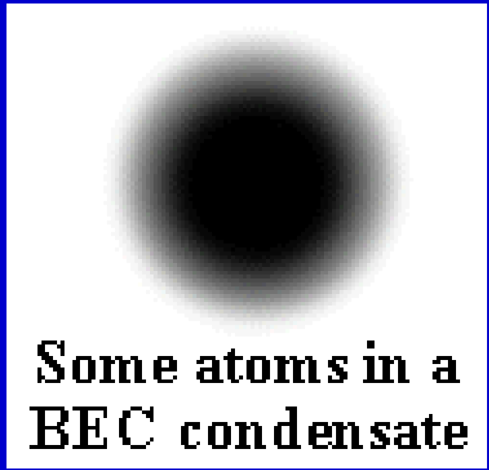




- When the temperature is very low, a large fraction of atoms suddenly crash into the lowest energy state. This is called *Bose-Einstein condensation.*

The Strange State of BEC



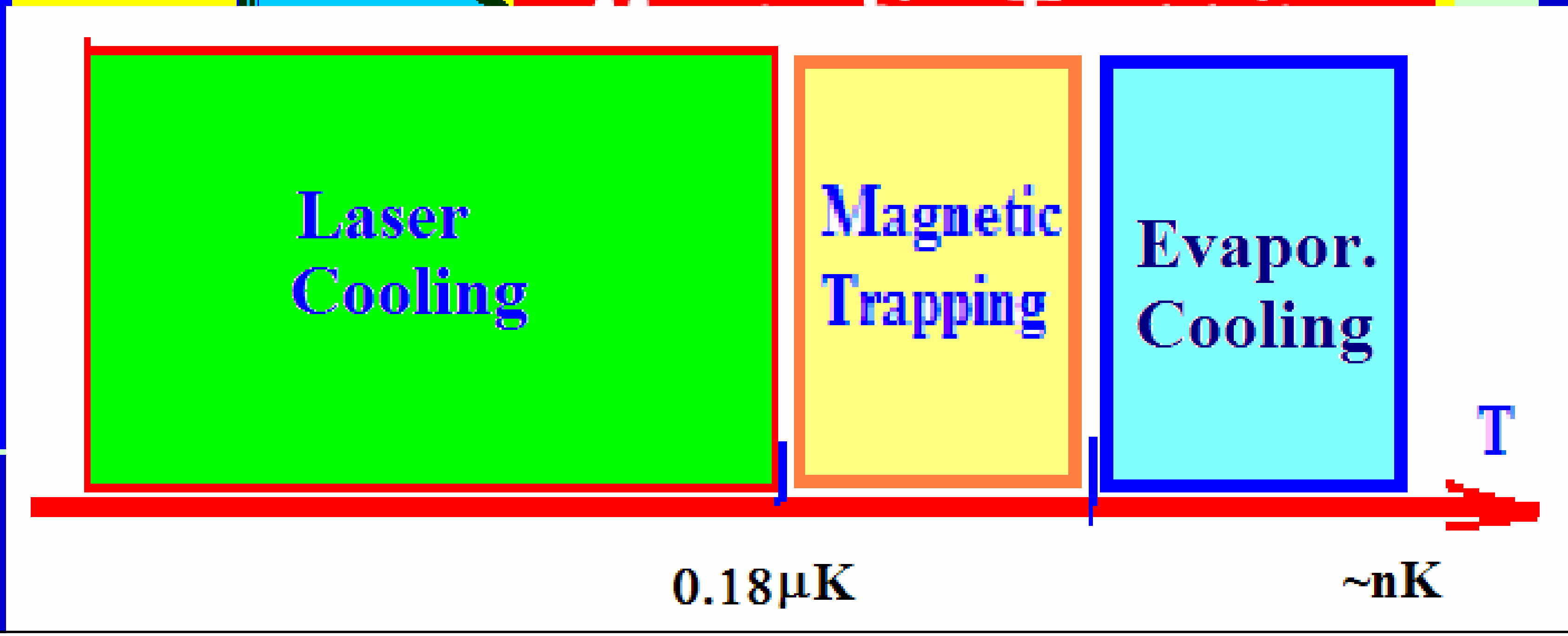


- When all the atoms stay in the condensate, all the atoms are absolutely identical. There is no possible measurement that can tell them apart.
- Before condensation, the atoms look like fuzzy balls.
- After consdensation, the atoms lie exactly on top of each other (a superatom).

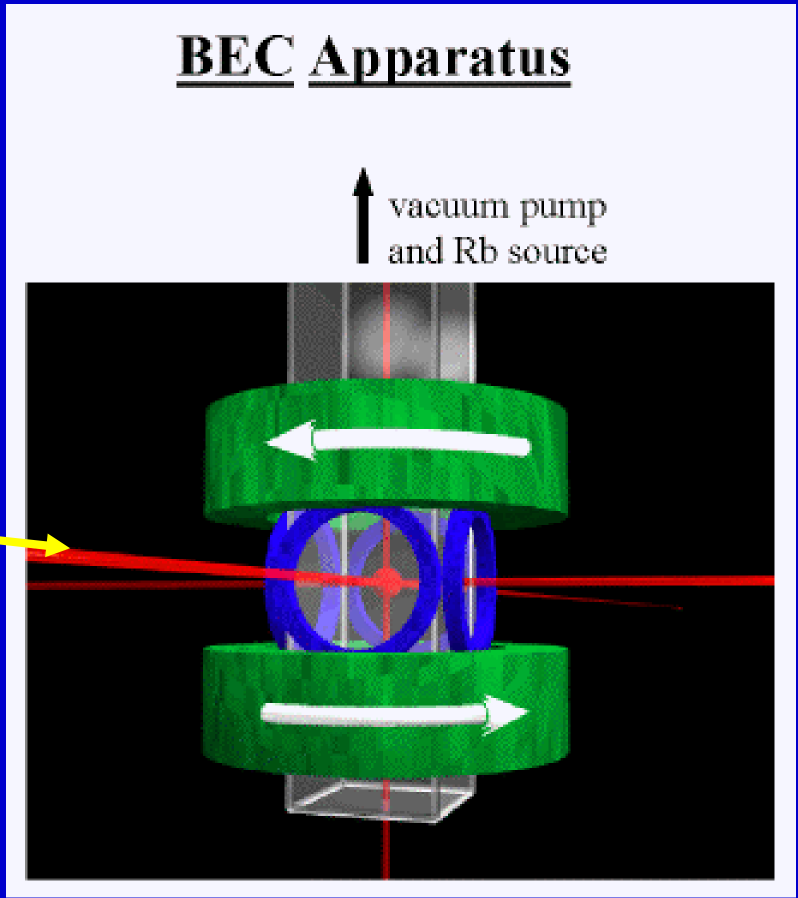
How cooling atom?

冷却

Laser Cooling



Laser Cooling



Laser beam

Other equipment: laser equipment, computer, electronics
Cost less than US$100,000

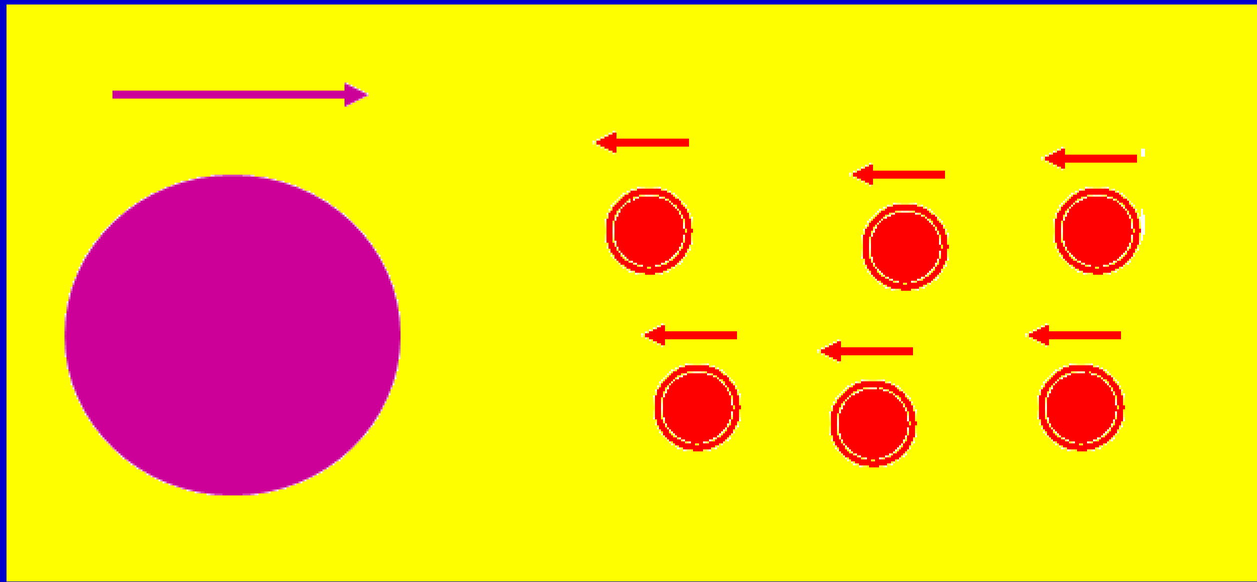
Chu 朱棣文

Cohen-Tannoundji

Phillips

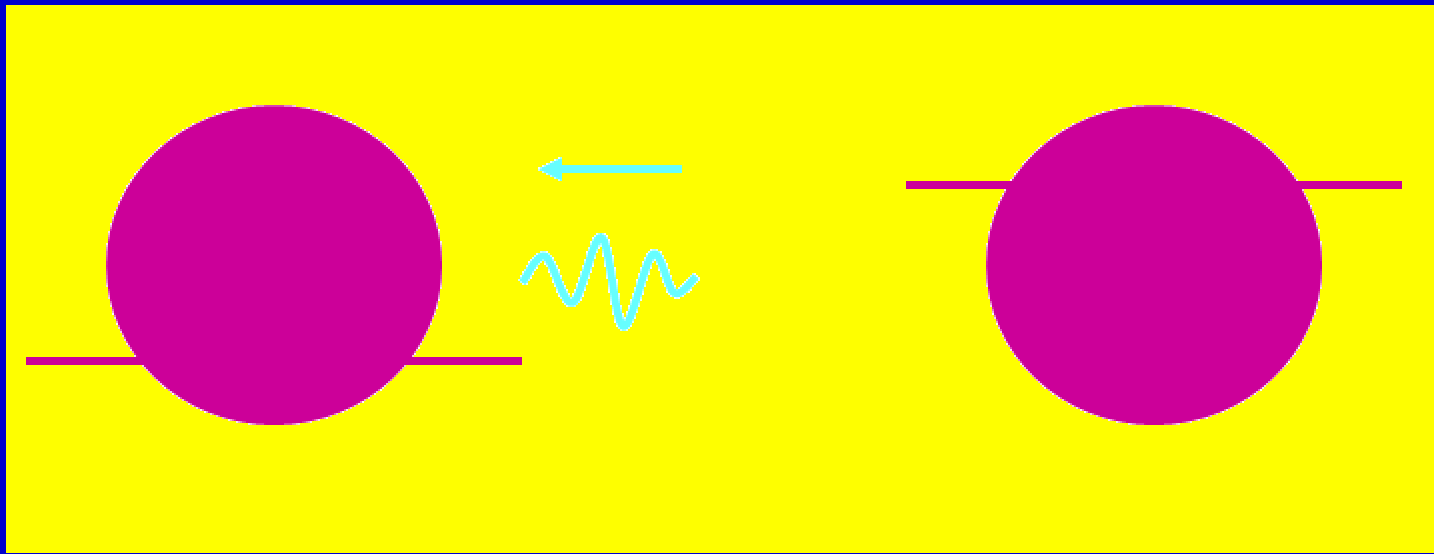
- The technique of laser cooling was developed by the winners of the 1997 Nobel Prize winners.
- In the physical world, the lowest temperatures approach a limit of –273ºC. This is called the absolute zero. Nothing can be as cold as the absolute zero because all atomic and subatomic motions stop.
- Laser cooling can get to the low temperature of 0.18μK.

Ping-pong Balls



- Photons are particles. They carry momenta like ping-pong balls.
- You can slow the motion of an atom by bouncing laser light off the atoms.

Tuning the Laser



- Only laser light with the correct colour (frequency) can be absorbed by the atoms.
- If the colour is wrong, the atoms cannot absorb the photons.

激光减速中性原子思想

运动的原子共振吸收迎面射来的光子，原子从基态跃迁到激发态，动量和速度减小

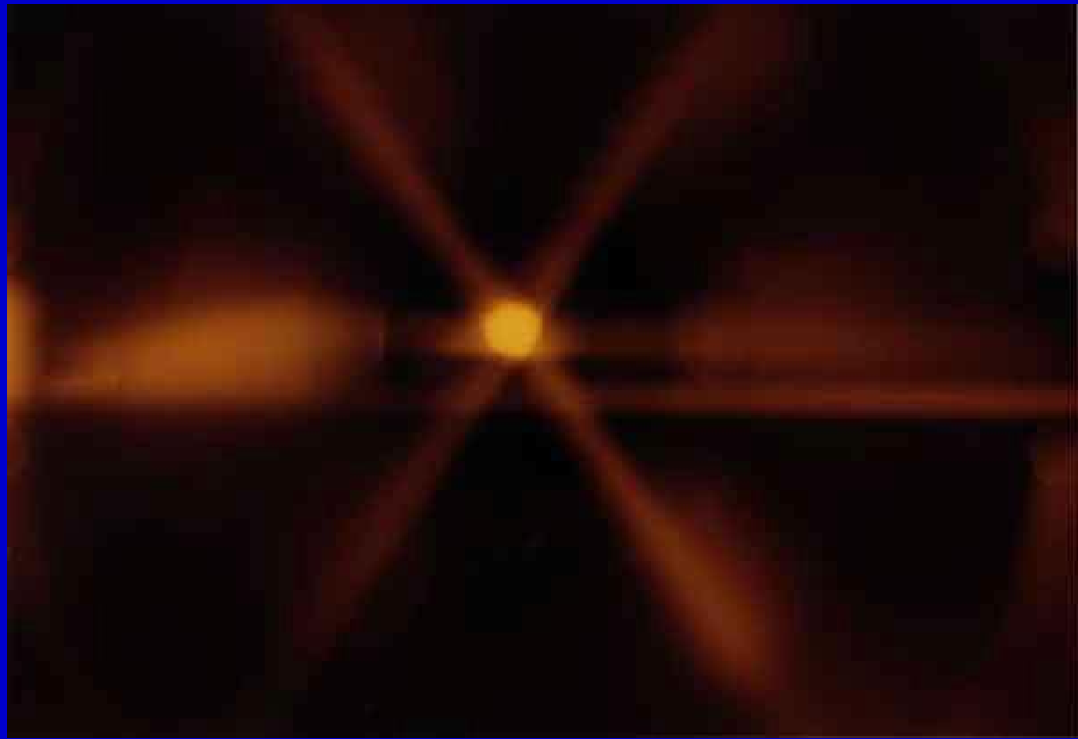
速度的减小 $$\Delta v = -\frac{hn}{Mc}$$

—— 从激发态自发跃迁到基态放出光子，由于反冲又获得动量。此后又吸收光子减小动量，又放出光子获得动量

吸收光子是来自同一束、同方向的激光，总使原子的动量减小

自发辐射出光子的动量是随机的，这样多次自发辐射的平均效果并不增加原子的动量

—— 对于冷却钠原子的波长为l=589 nm的共振光，减速效果相当于10万倍的重力加速度



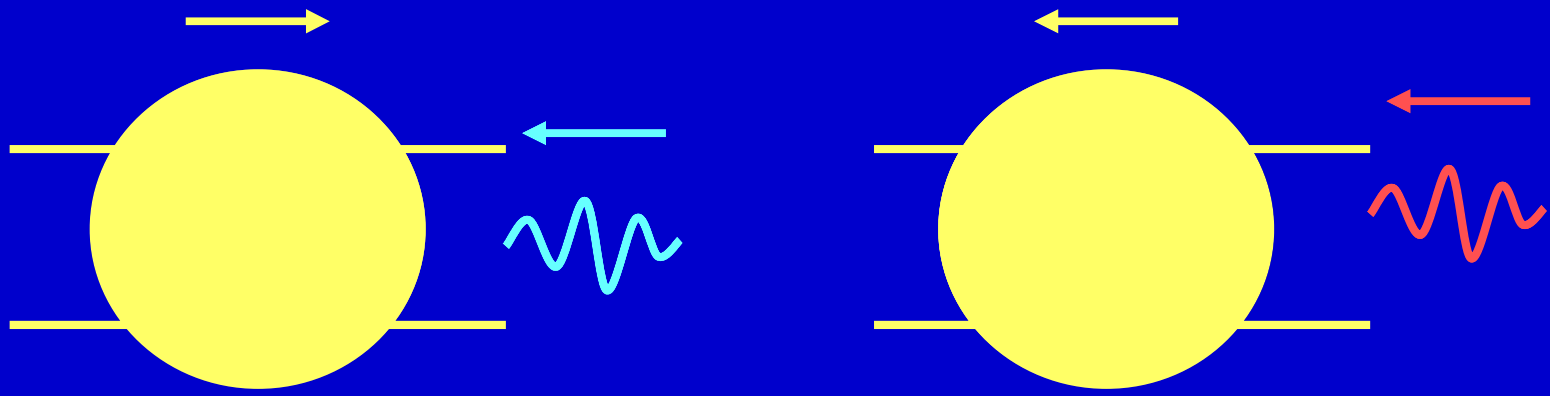
1985年贝尔实验室的朱棣文小组用三对方向相反射来的共振激光l=589 nm照射钠原子，在六束激光的交汇处钠原子团被冷却下来，温度2.4×10^{-8} K

1995年左右，朱棣文等人利用钠原子喷泉方法将一群钠原子降到2.4×10^{-11} K（24 pK）的温度

Using the Doppler Effect

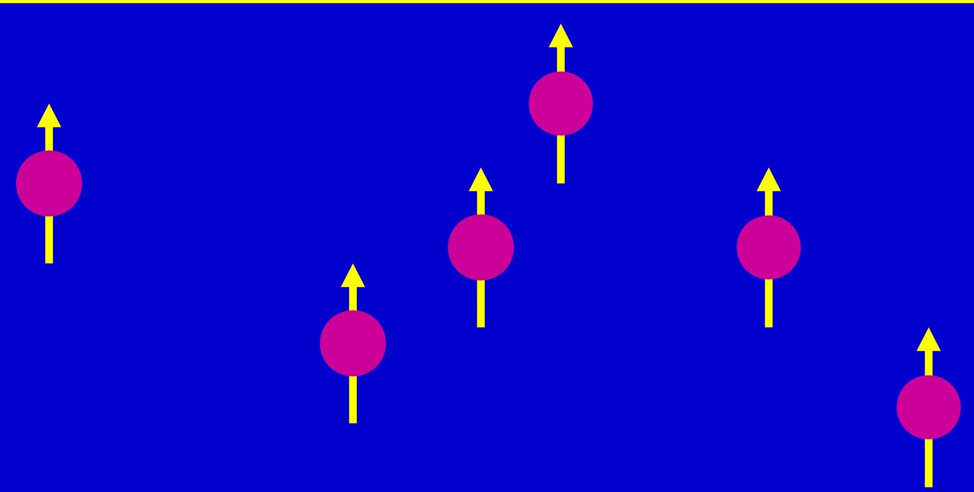
- Problem: The laser can slow the approaching atoms, but it can also blast off the receding ones.
- Solution: Use Doppler shift.
- When the atom is receding from the laser source, the wavelength is lengthened and there is a redshift.
- When the atom is approaching the laser source, the wavelength is shortened and there is a blueshift.

Laser Trapping



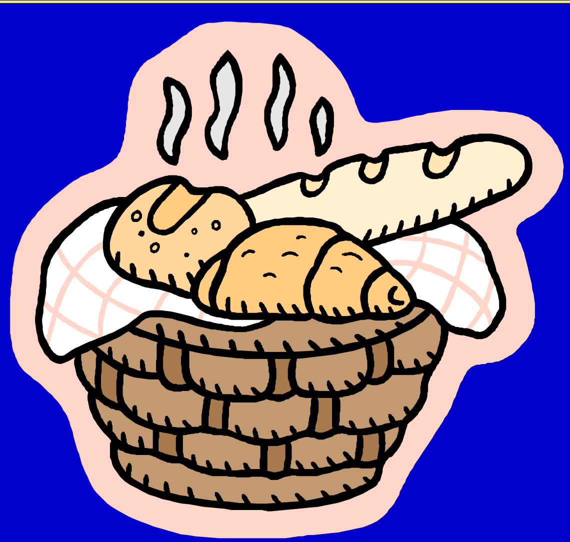
- Suppose the laser has the right colour for the photons to be absorbed by an approaching atom, then the atom will be slowed down.
- However, the laser will not have the right colour for the photons to be absorbed by the receding atom because of Doppler effect. Hence the atom will not change in this case.
- When lasers are sent in from all the different directions, the atoms can get cold very quickly.
- This is called laser trapping, and the trapped atoms form an optical molass (光学粘胶).

Magnetic Trapping



- Problem: Laser cooling can cool the atoms down to 10μK, because atoms can spontaneously emit the absorbed photon. This is still too hot for BEC.
- Solution: Evaporative cooling
- The atoms behave as tiny compasses. They can be pulled by magnetic fields.
- A magnetic field can be designed to push the atoms inwards from both sides, forming a magnetic trap.

Evaporative Cooling



ùPrinciple: Evaporation takes heat. A cup of tea gets cool after steam escapes, because faster atoms escape from the cup, leaving behind the slower ones.

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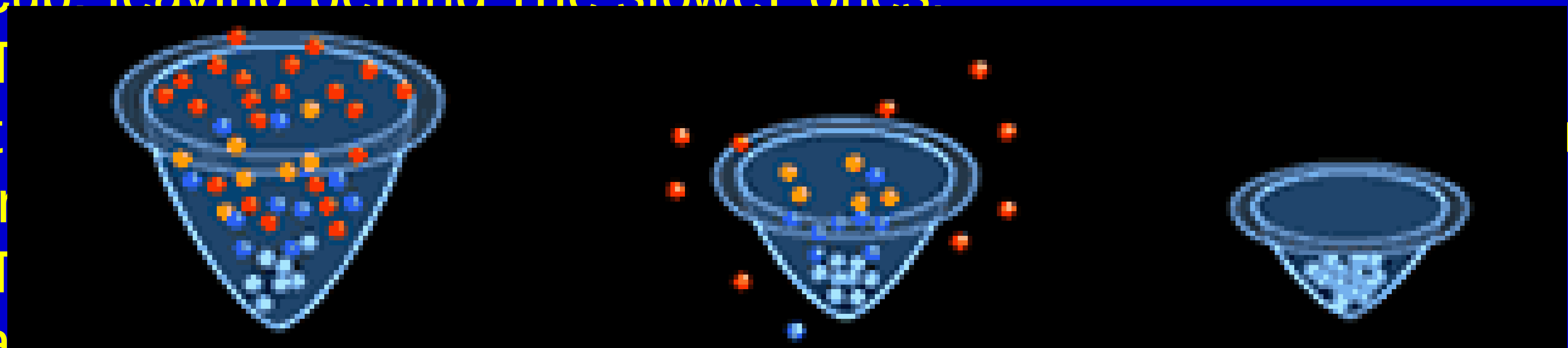
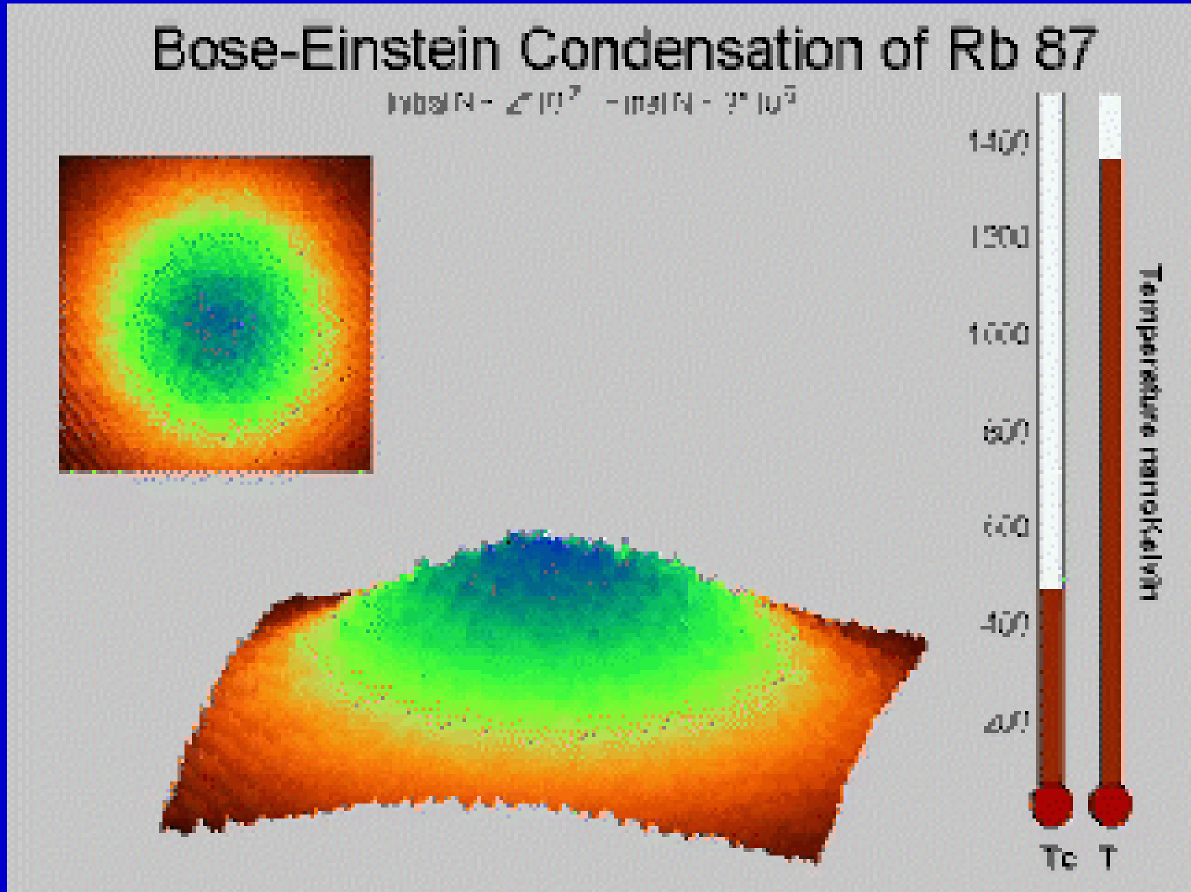


ùT

animation


Bose-Einstein Condensation of Rb 87
Temperature nanoKelvin
Tc
T

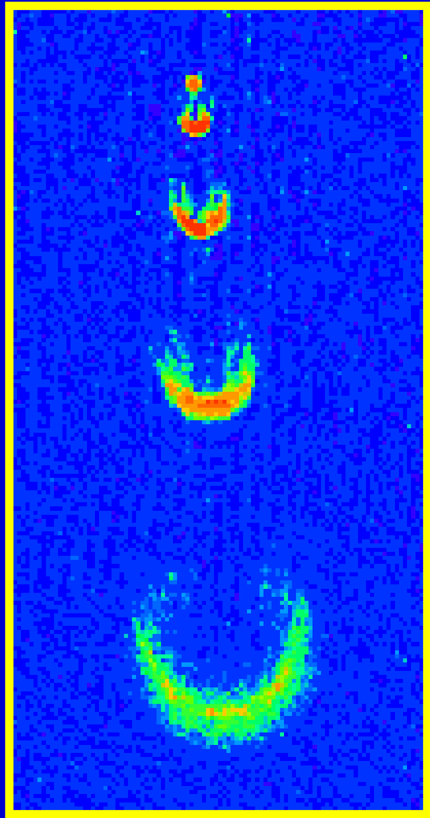
What Is BEC Made?

BEC结果

- Atom Laser
- Oscillations
- Interference Pattern
- Vortices
- ……

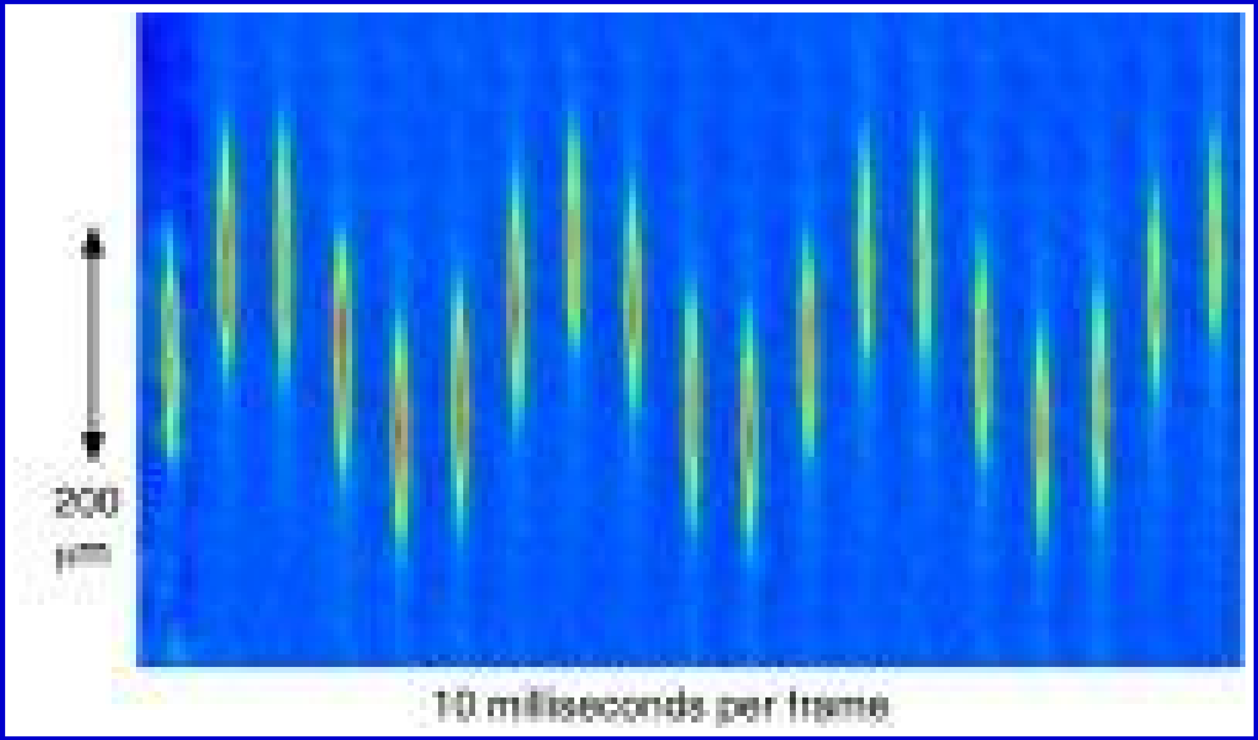
Atom Laser

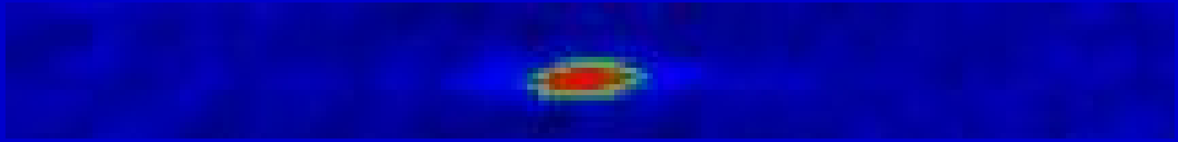
- Laser of light: all the photons are exactly the same in colour, direction and phase (positions of peaks and valleys).
- Laser of atoms: all the atoms in the condensate are exactly the same.



Oscillations

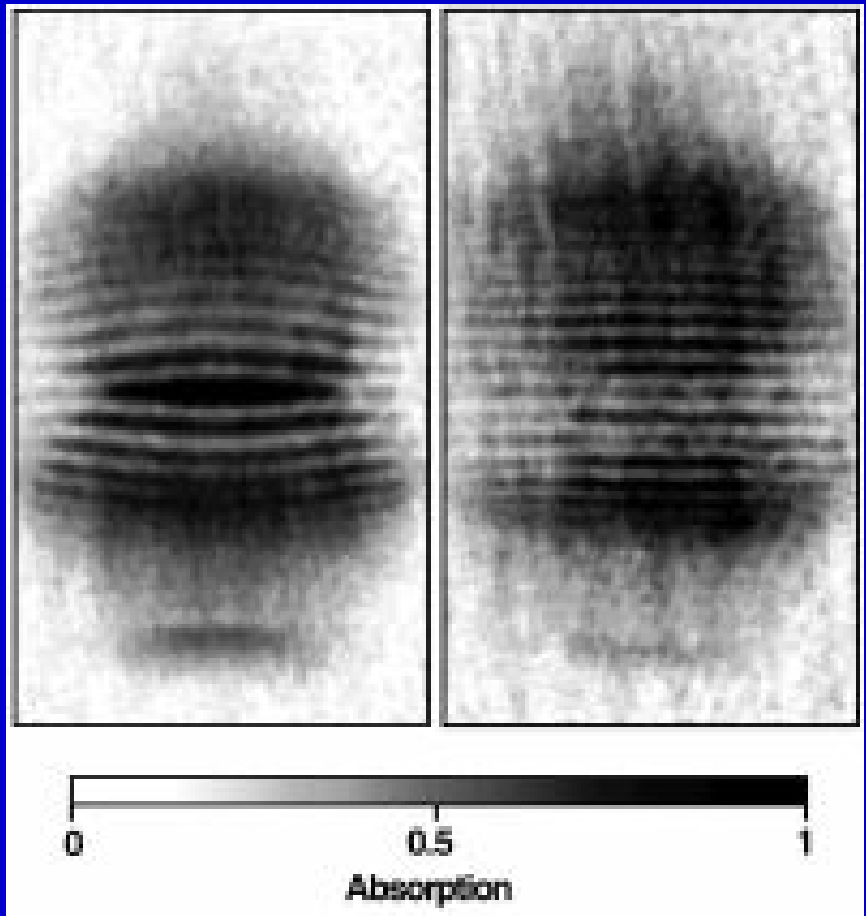
Note the "shape" motion and "sloshing" motion.

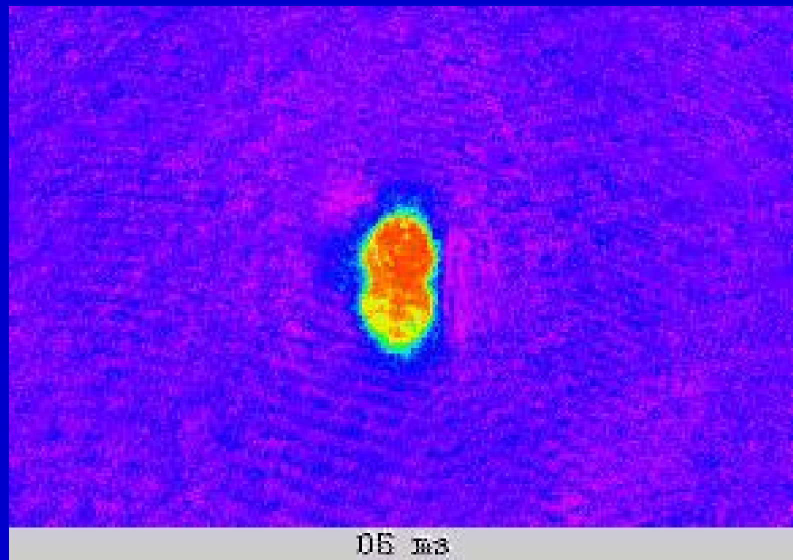


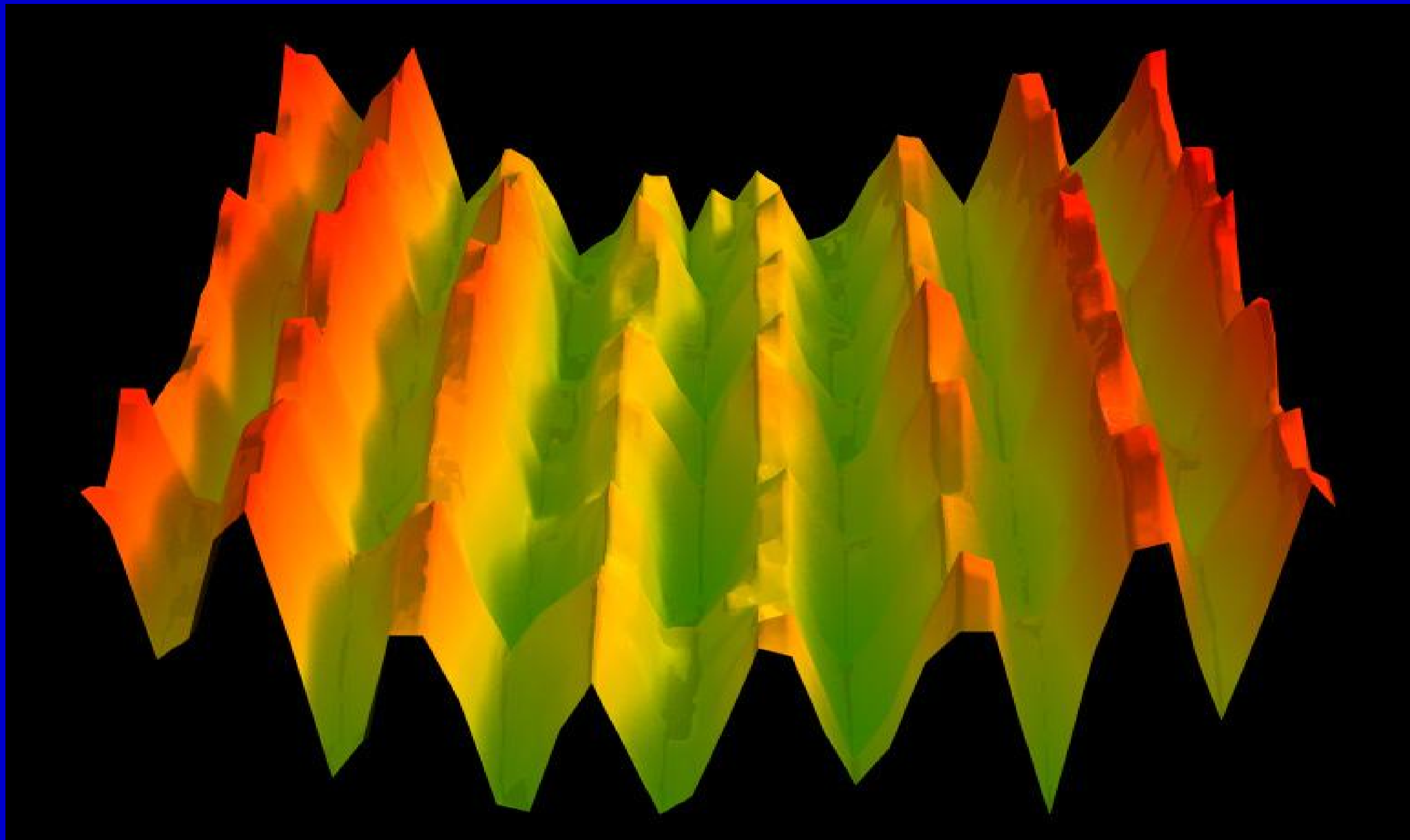


Interference Pattern

- When two Bose-Einstein condensates spread out, the interference pattern reveals their wave nature.





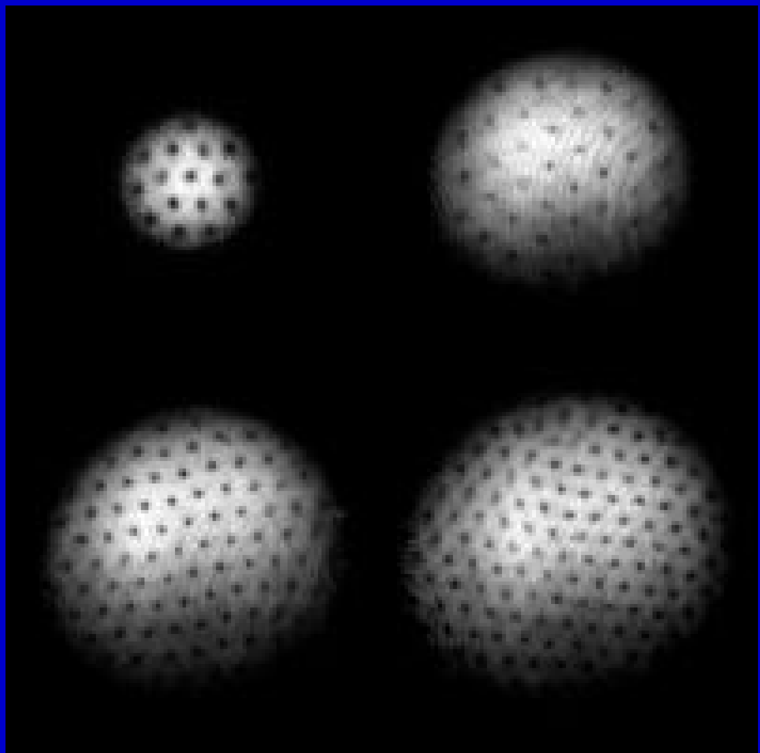


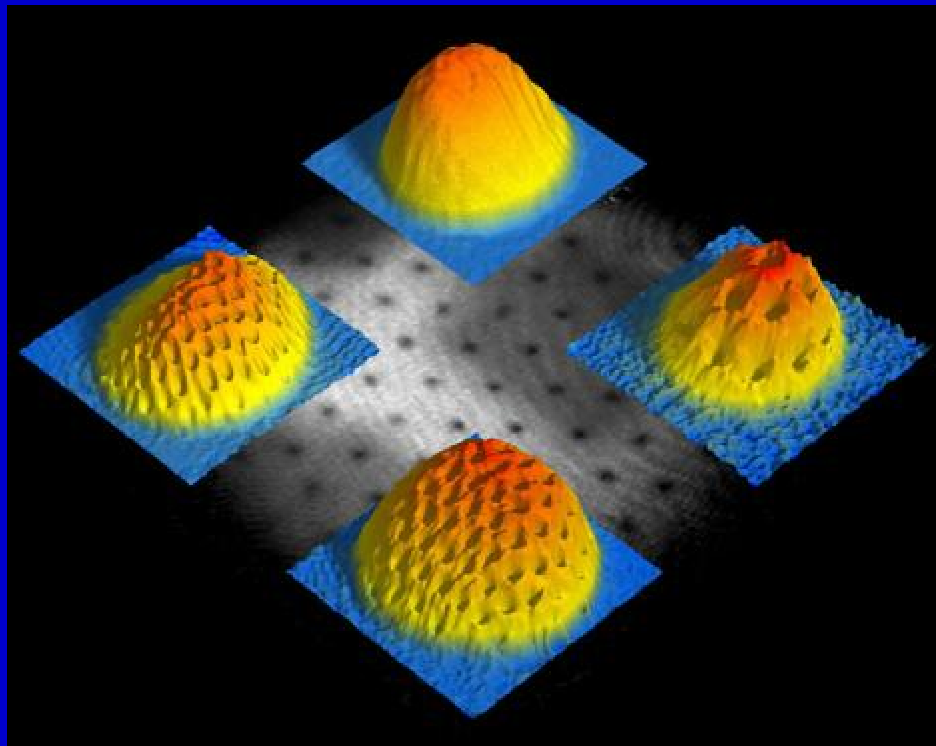
Matter waves Interference

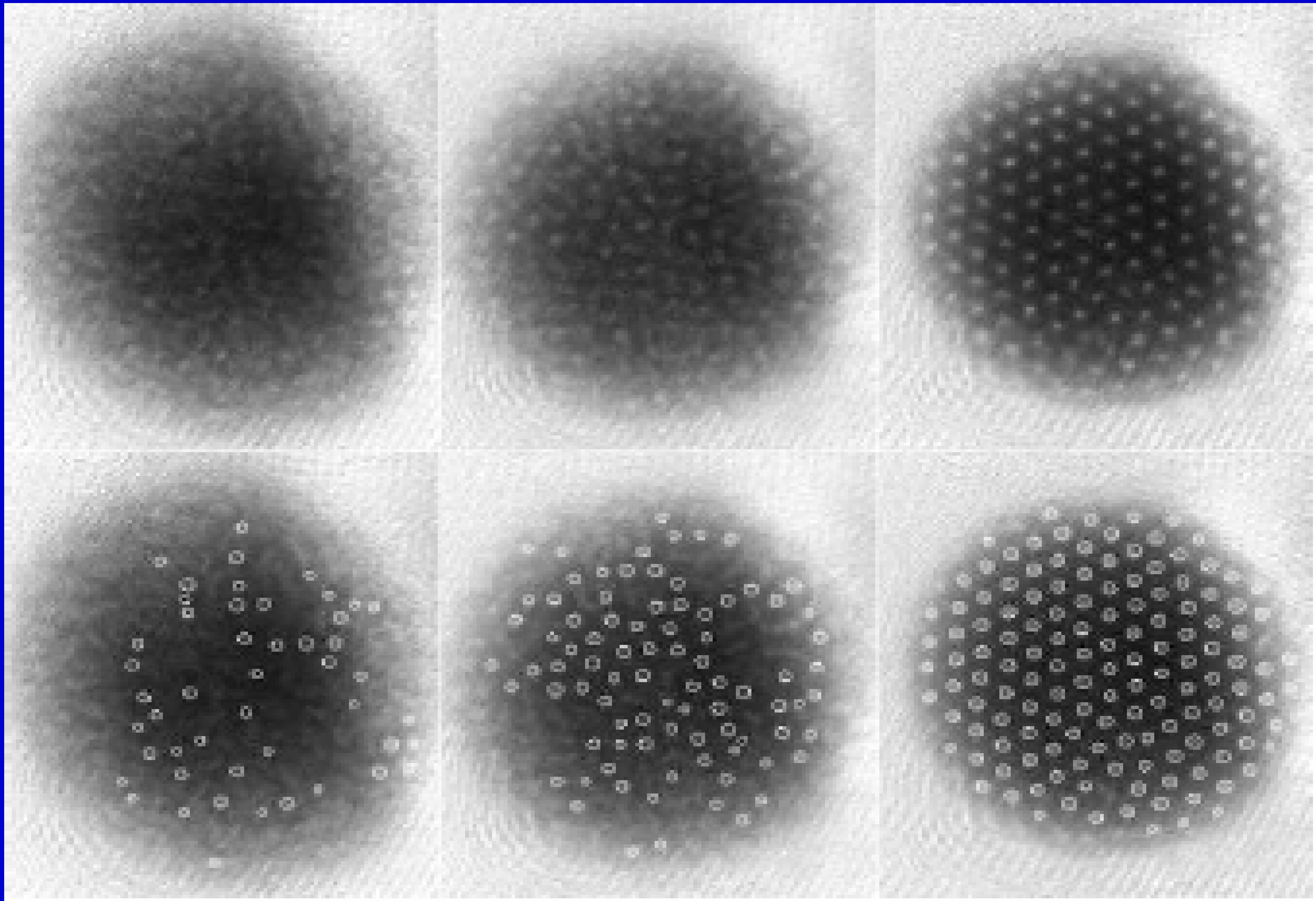
(MIT group, 1997)

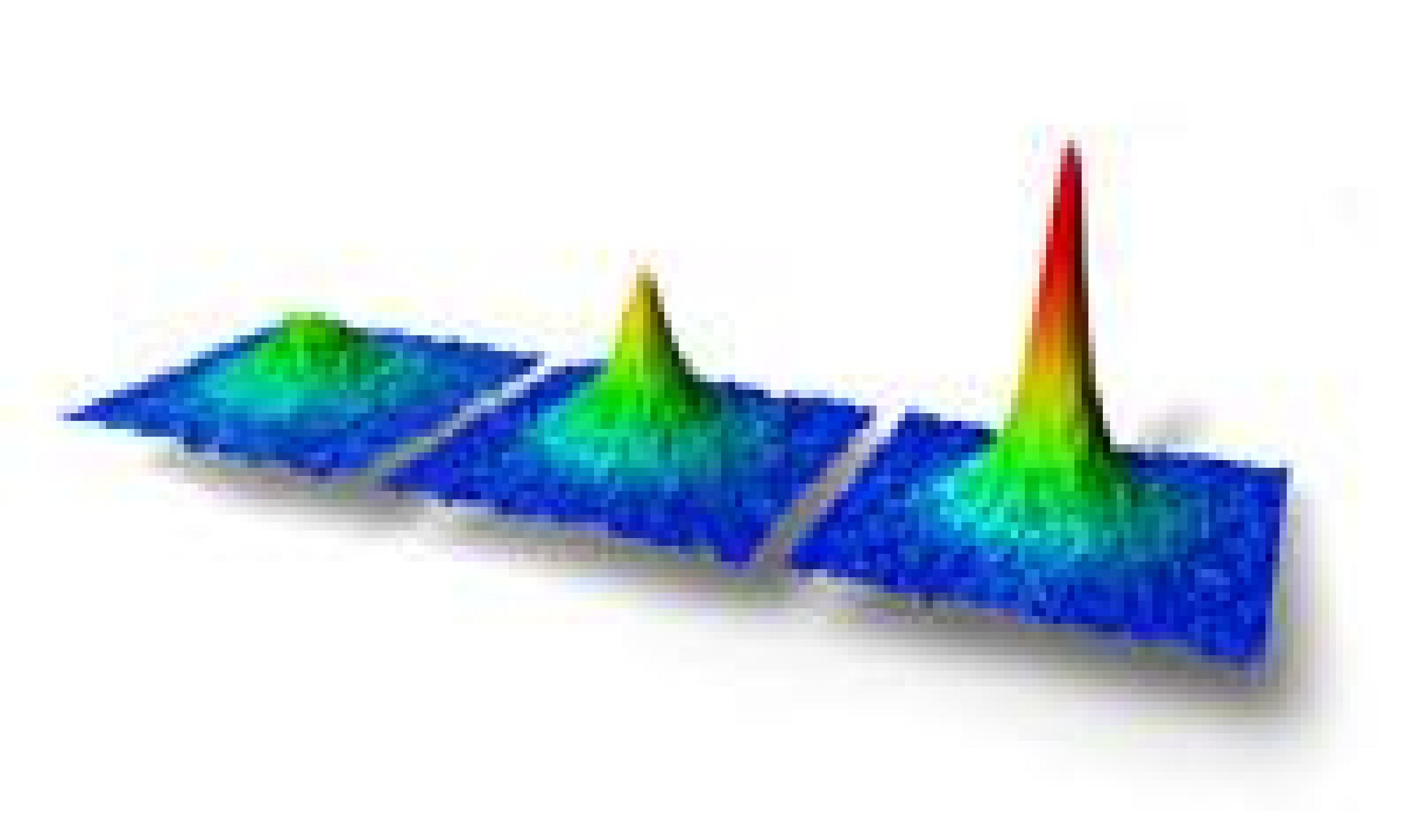
快速旋转BEC中的涡旋晶格

When the condensate is rotated, vortices appear. The angular momentum of each of them has a discrete value.



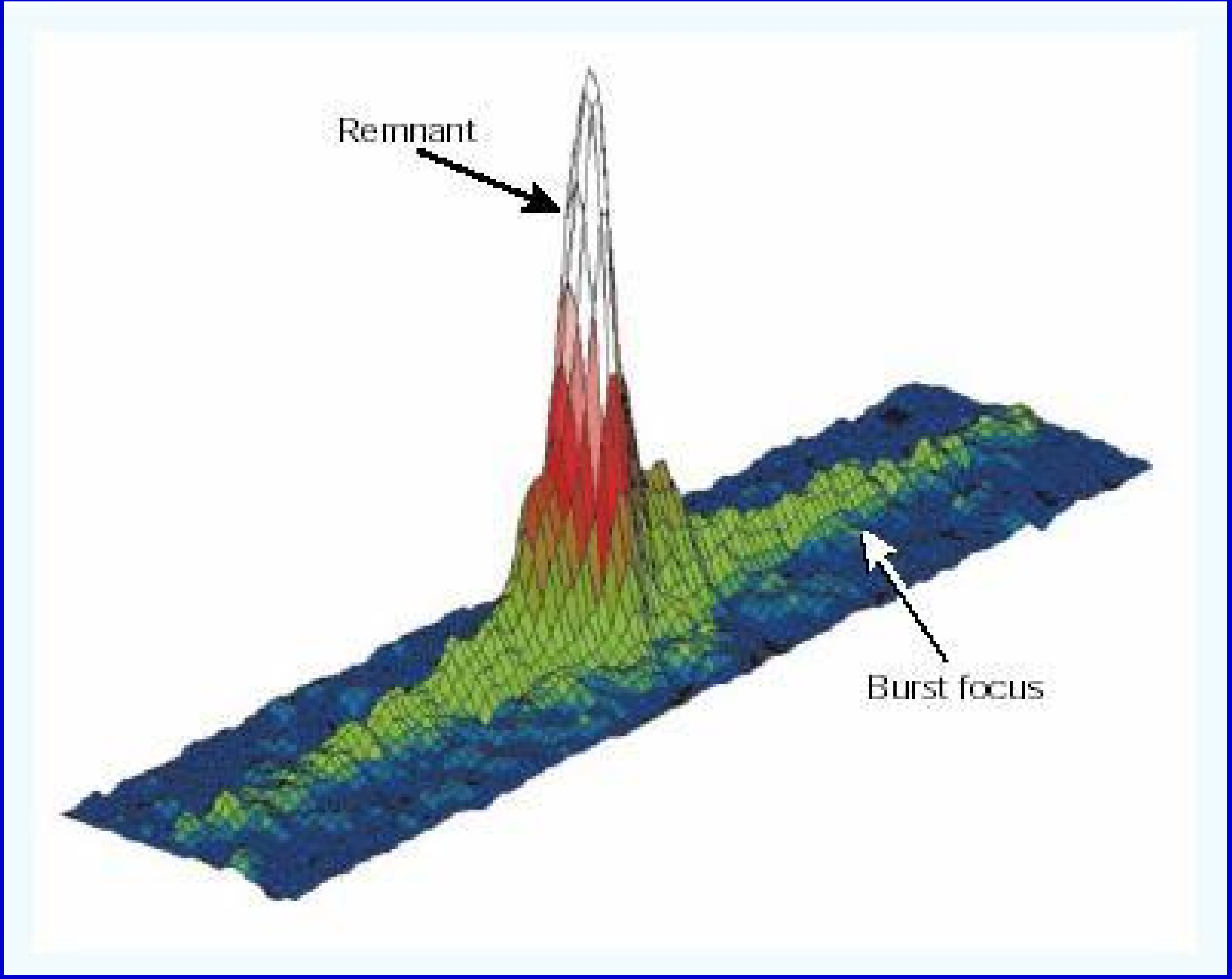






Bose condensate of molecules
(JILA, Innsbruck, MIT, ENS 2003)

玻色爆发 (Bosenova)

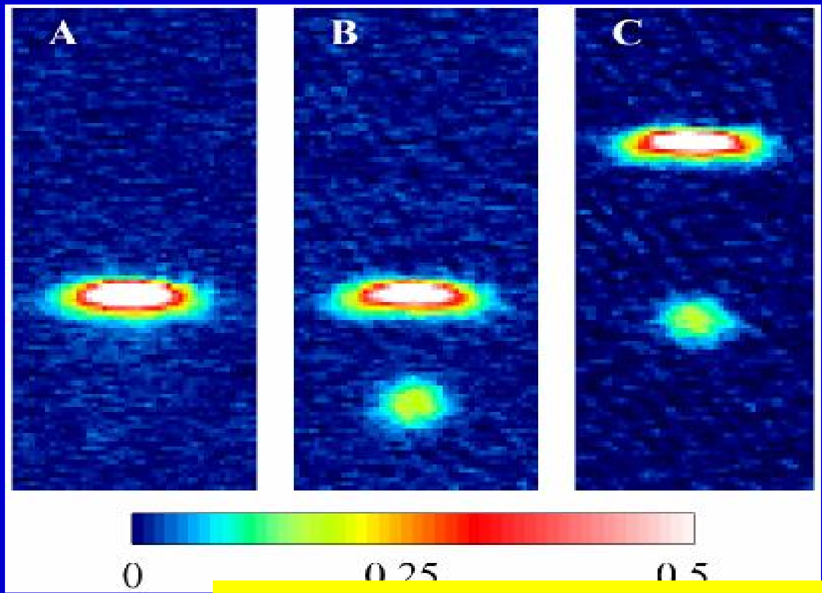


BEC的应用

- 原子光学
- 原子激光
- 原子刻蚀
- 原子钟
- 高精密度测量
- 光学晶格中的BEC
- 模拟研究量子多体动力学
- 量子信息学
- 超新星爆炸和黑洞

Creation of ultracold molecules

Ultracold Cs_2 molecules
(Stanford, Innsbruck, 2003)



Bose condensate of molecules
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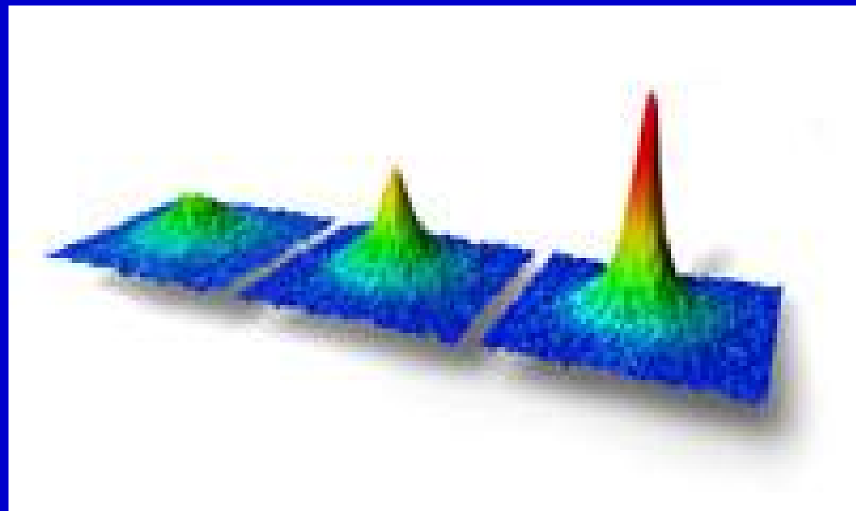
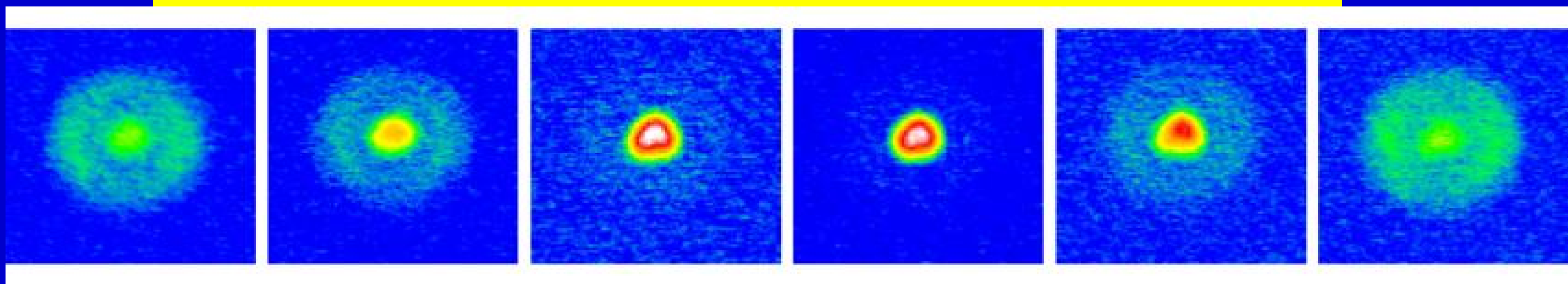


Stueckelberg oscillation (Innsbruck, 2005)

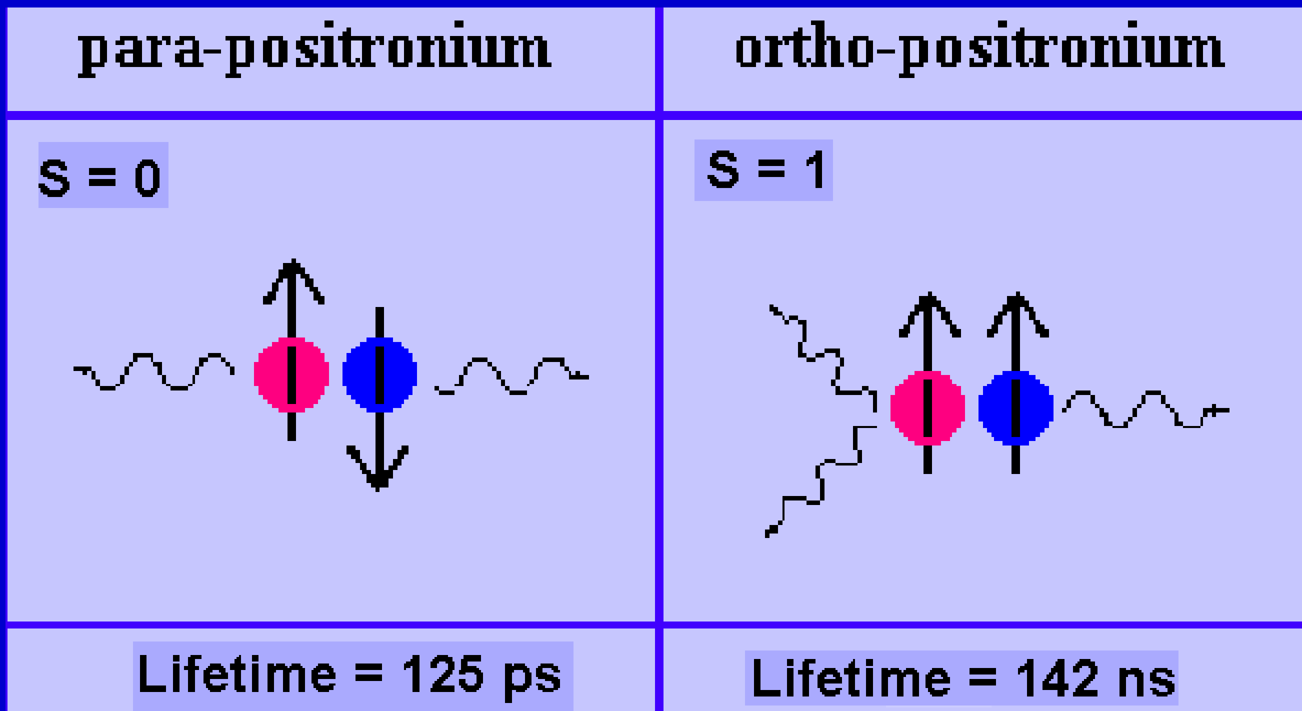


- **BE condensation has been observed for ^{4}He, ^{21}Na, ^{38}K etc., at a very low temperature (<μK) by Laser cooling.**

二、什么是Positronium BEC

Positronium (Ps) atom

- Bound state of a positron and an electron
- Binding energy of Ps atom is -6.8 eV
- Lightest Bose atom
- Mass ~1/1000 times smaller than m_H



BEC of Ps atom

Advantage : m_{Ps} is 10^{-4} order small than m_K or m_{Na} thus one expect the condensation at much higher temperature

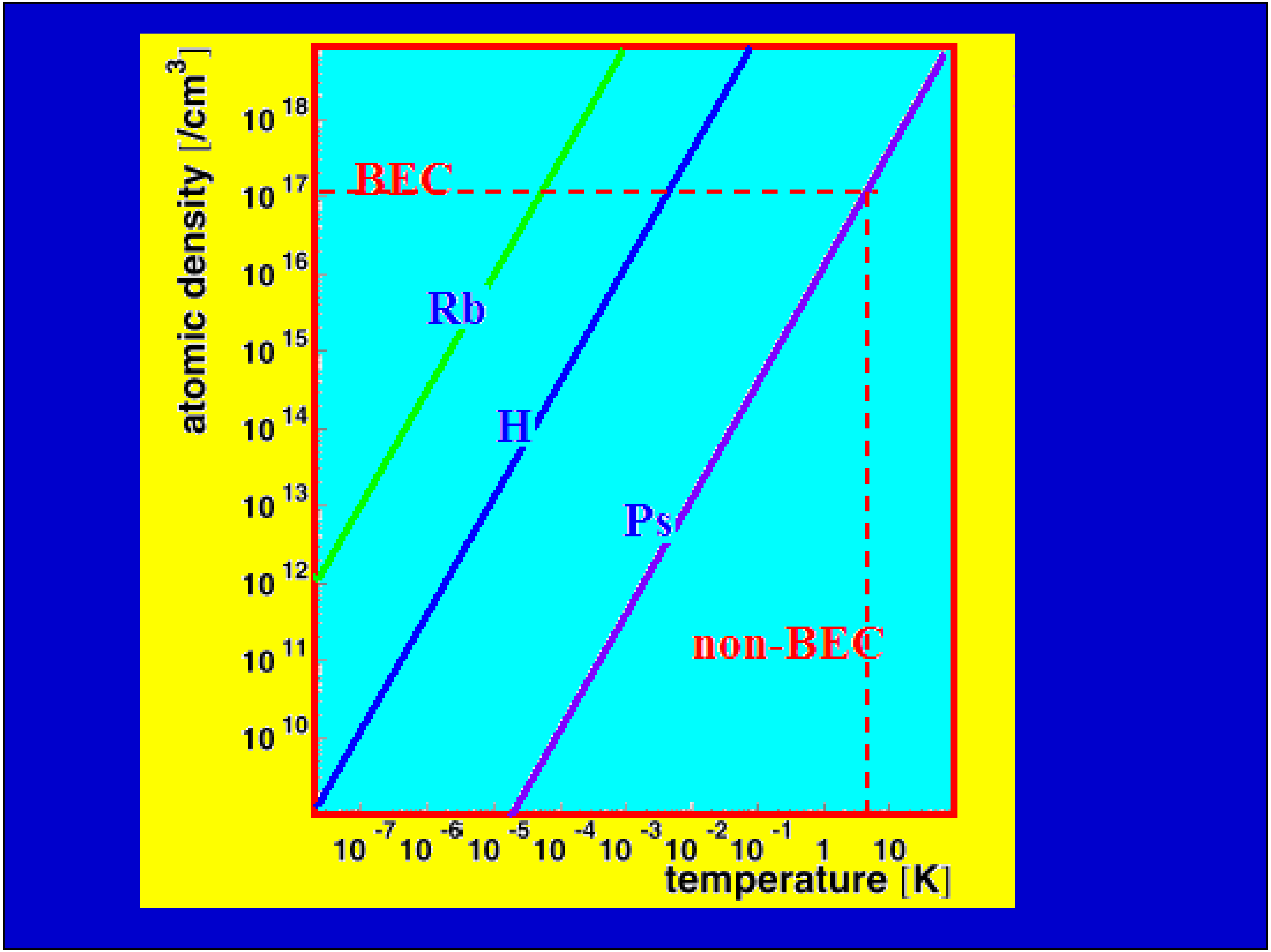
Limits : To achieve higher critical density of Ps atom. Lifetime of Ps atom is very small.

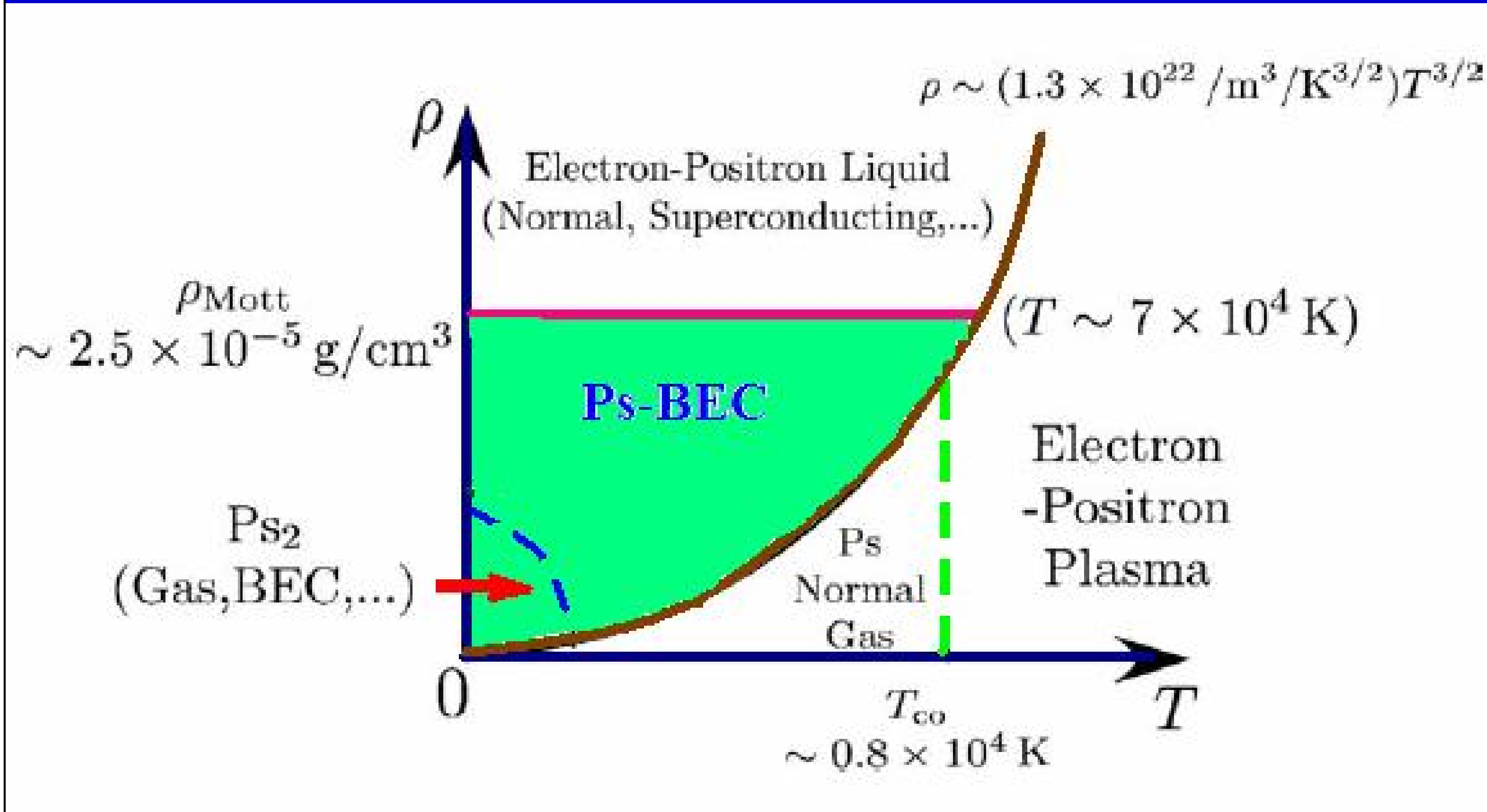
Condition for Ps BEC

For non-interacting Bose particles the critical density ρ_c above which the BE condensation occur at a critical temperature T_c is given by

$$\rho_c \lambda_d^3 = \rho_c [h/(2\pi mkT_c)^{1/2}]^3 = 2.65$$

λ_d **= de-Broglie wave length**


atomic density [/cm^3]
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
BEC
Rb
H
Ps
non-BEC
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10
temperature [K]



- Schematic phase diagram for Ps and electron–positron many-body system

511 keV γ-ray Laser!
GRASER

- At BEC : all the positronium atoms are in the same momentum state.
- All the positronium annihilation g-photons are coherent.
- Thus the 511 keV positronium annihilation g-photons behave like a **Gamma Ray Laser (GRASER)** .

One can use these 511 keV g-ray Laser to:

- initiate fusion reaction for electric power production
- destroy distant objects, If the Power > 10MJ !!!

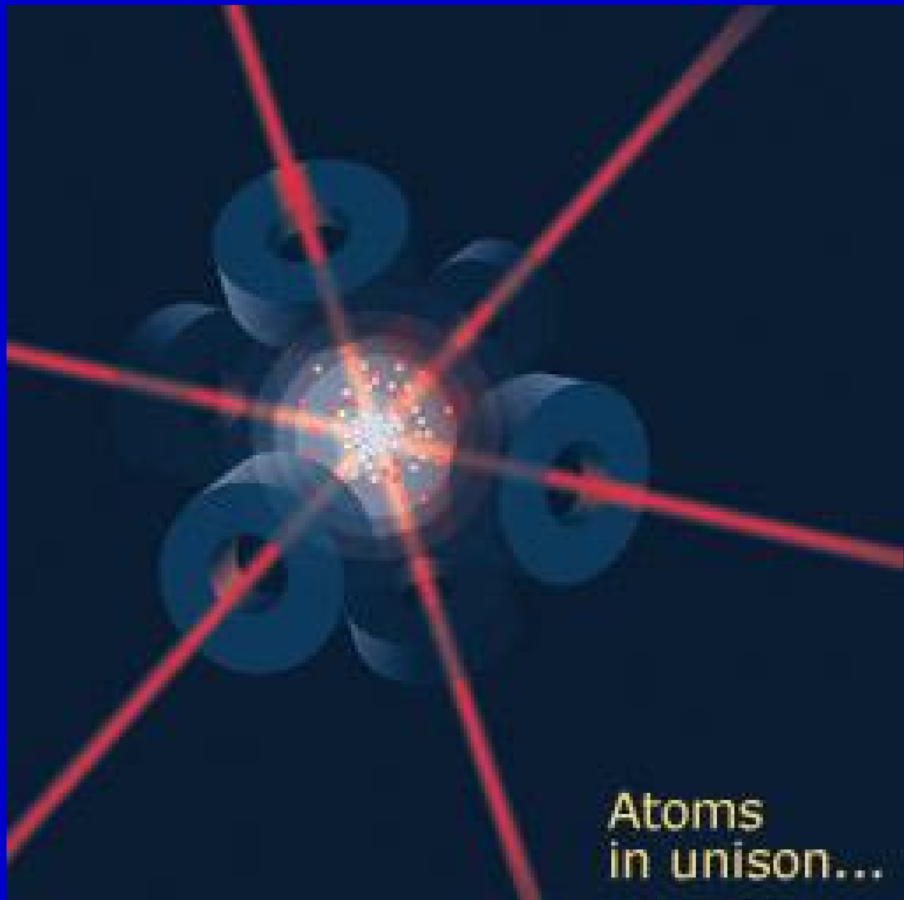
起动聚变反应

An intense burst of annihilation photons would enable us to achieve extremely high temperatures in a short time, would be useful in the maintenance of nuclear weapons and possibly as a substitute for the fission source ordinarily used to start a fusion reaction.

杀伤性武器

- This could be the basis of a clean bomb or more preferably a fusion power plant.
- Unlike visible photons, annihilation photons have a several cm absorption length and would impart their energy to a relatively large mass when impinging on a solid target.

三、o-Ps BEC历史与现状



Steps to wards the goal

- Setup a high intense positron beam facility with a suitable strong positron source.
- Creation of high number density p-Ps or o-Ps atom.
- By Laser cooling produce Bose-Einstein-condensation of these positronium atoms.

Setup a high intense positron beam facility

Nuclear Instruments and Methods in Physics Research A 532 (2004) 523–532

www

Intense source of slow positrons

P. Perez*, A. Rosowsky

DSM, Dapnia/SPP, C.E.A., Saclay, F-91191 Gif-sur-Yvette, France

Received 22 January 2004; received in revised form 5 May 2004; accepted 6 May 2004

Available online 8 July 2004

10MeV electron accelerator

10^{12}e+/s

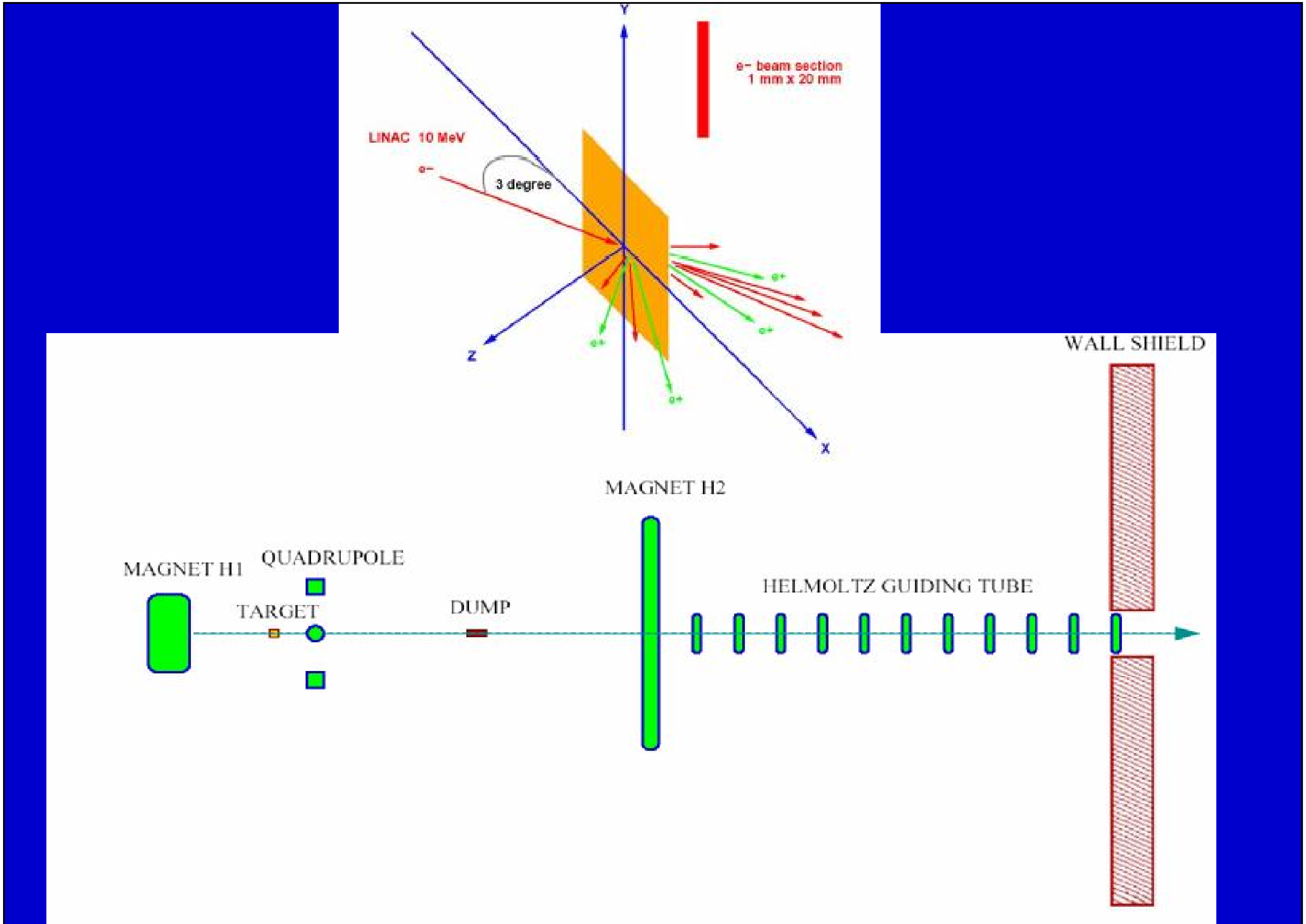


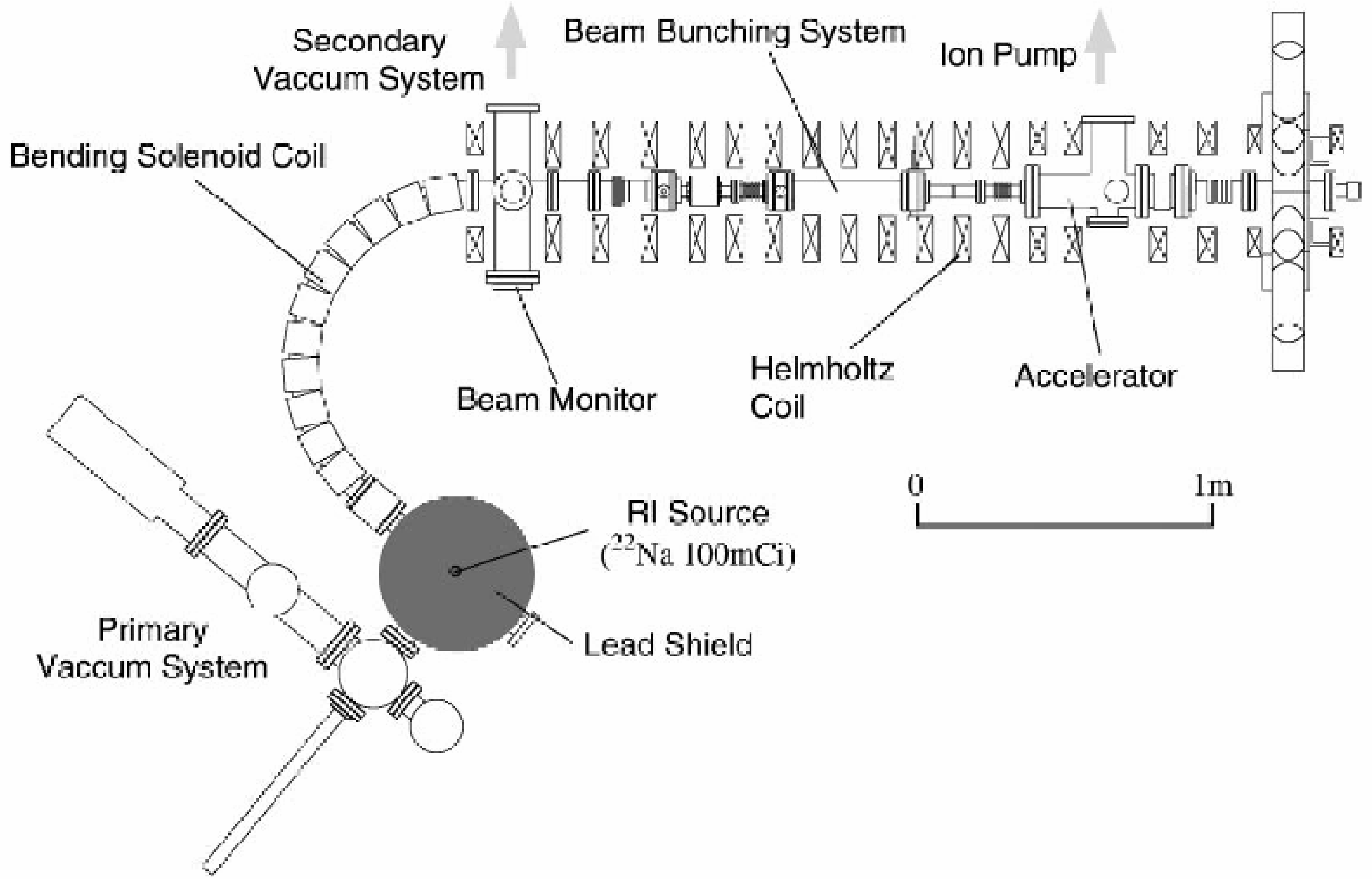
Fig. 7. Layout of the proposed magnetic collection system.

In Japan, the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba, is building an "Intense Slow Positron Beam Facility" with a 70MeV linac in order to produce 10^8 slow positrons per second.

In KEK, the new positron facility is based on a 25 MeV/1kW linac which should produce the same rate of positrons.

In *To*kyo Metropolitan University, TOPPS *To*kyo *P*olarized *P*ositron Beam *S*ystem is Based on 100mCi 22Na with 10^6 e+/s positron.

TOkyo metropolitan university Polarized Positron System- TOPPS



The Paul Scherrer Institute (PSI) has a ^{58}Co source of 500 mCi.

slow 10^{10} e+/s

In **Germeny,** the research reactor FRM-II will be used via neutron capture on cadmium, $^{113}Cd(n,\gamma)^{114}Cd$, to produce a flux of order 10^{10} slow positrons per second.

In Halle University, the EPOS complex is based on a 40 MeV/40 kW linac which is expected to deliver a flux of $8.5\ 10^{8}$ slow positrons per second.

USA

- USA: UC San Diego
- Lawrence Livermore (LLNL) which has a 100MeV linac of 45kW, with a dedicated extraction providing 10^{10} positrons per second
- The ORELA complex located in Oak Ridge consists of a linac of 180 MeV and 60 kW which produces 10^{8} slow positrons per second.
- There is also a High Flux Positron Beam in BNL.

Creation of high-number Density Positronium Atom

A microbeam (diameter ~ 1 mm) consisting of N $\geqslant 10^6$ e^+ at an energy of ~ 5 keV incident on the surface of a Si target, which has a small cavity of diameter (~ 1 mm) and a height (~ 0.1 mm).

e^+ of energy (~ 5 keV) stop in the Si at a depth of 100 nm, and about one-quarter of the incident e^+ will be reemitted as positronium (Ps) atom (energy ~ eV) into the cavity.

Ps atom at a density of 10^{17} per cc.

With such a density the Critical Temperature (T_c) of Bose-Einstein Condensation reaches to ~ 1 K.

PHYSICAL REVIEW B VOLUME 49, NUMBER 1

Possibilities for Bose condensation of positronium

P. M. Platzman and A. P. Mills, Jr.
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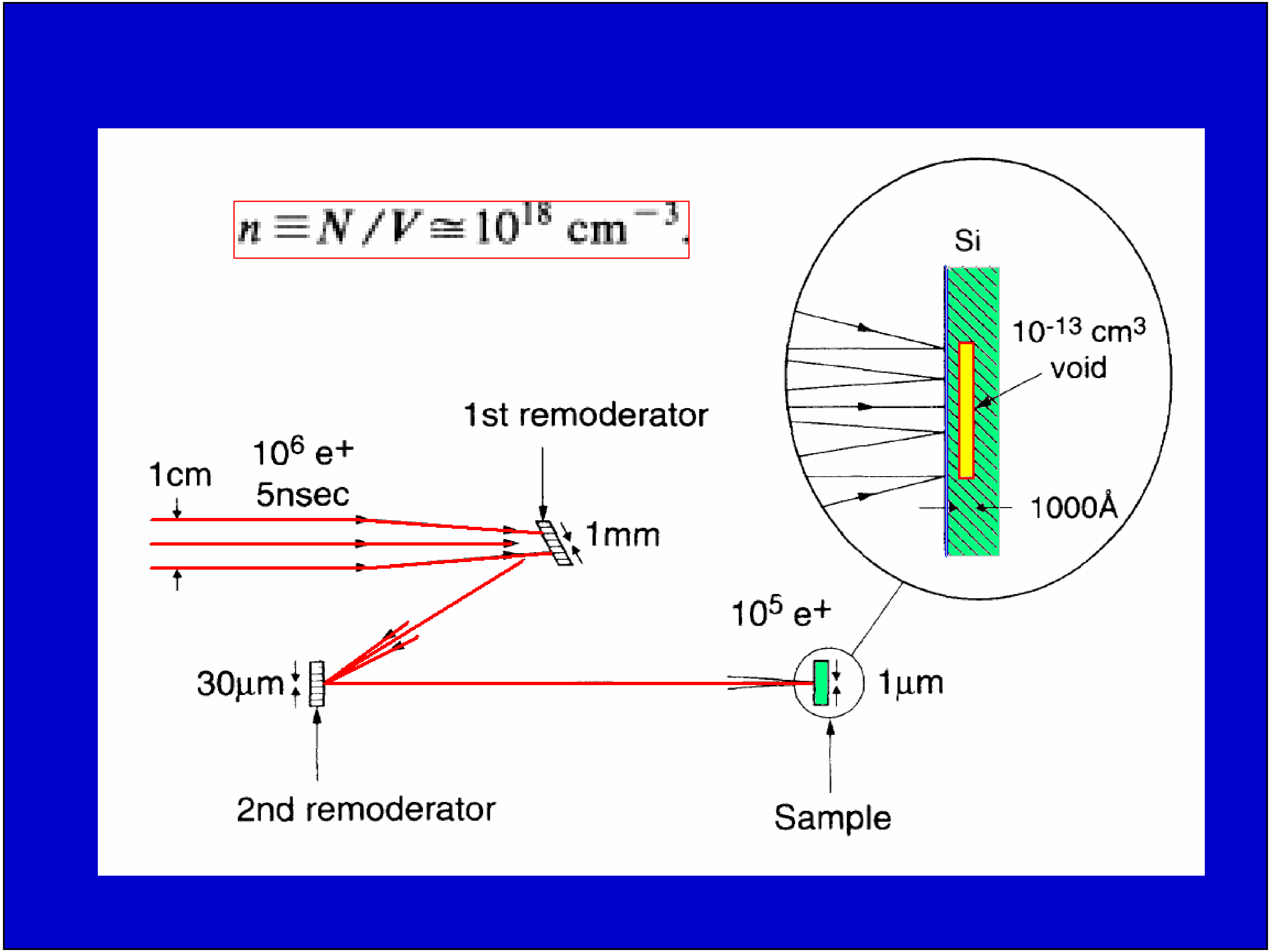
(Received 18 June 1993; revised manuscript received 2 September 1993)



$n \equiv N / V \cong 10^{18}\ \mathrm{cm}^{-3}$.
Si
10^{-13} cm^3
void
1000Å
1st remoderator
10^6 e+
5nsec
1cm
1mm
10^5 e+
30µm
1µm
2nd remoderator
Sample

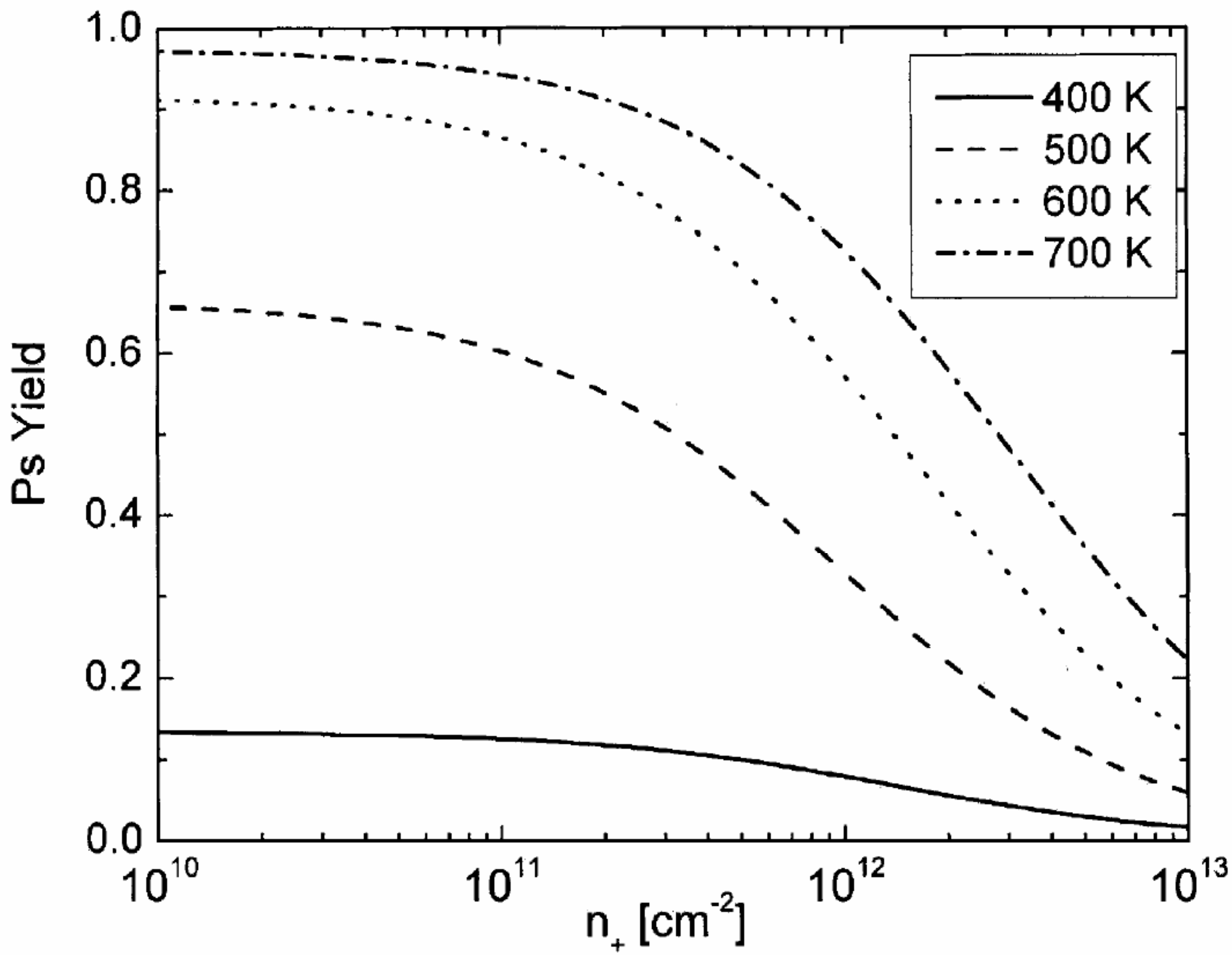


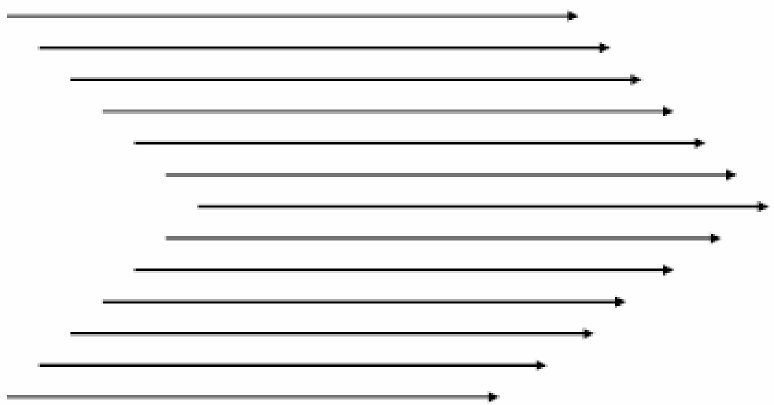
Fig. 3. Ps yield versus surface positron density n_+ at various temperatures.

Ps chemistry

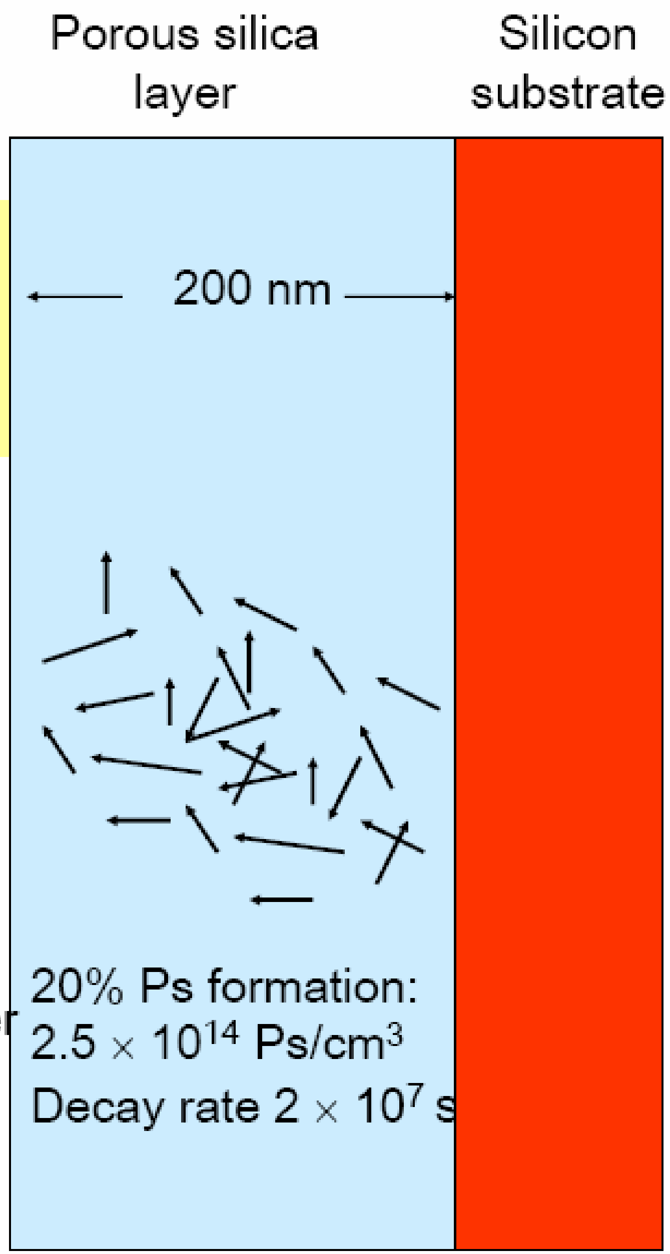
Ps-Ps spin exchange cross section

Spin exchange rate

$n\sigma v$ = 2.5 × 10^{14} cm^{-3} × 10^{-15} cm^{2} × 10^{7} cm/s = 2.5 ×10^{6} s^{-1}



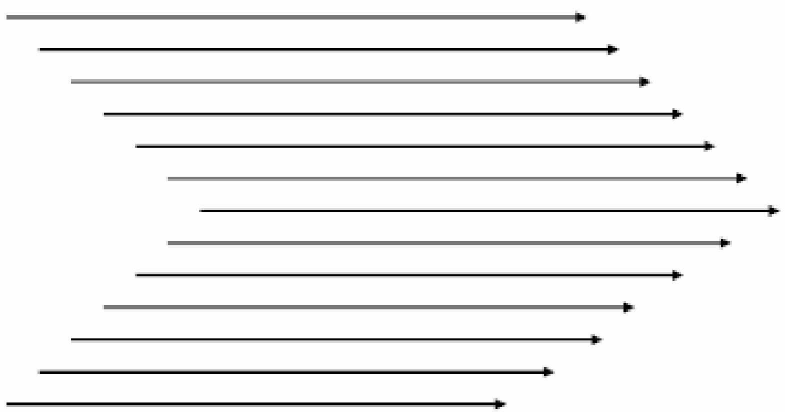
15 ns Pulse of 10^{7} e^{+} 0.2 mm diameter = 2.5×10^{10} e^{+}/cm^{2}



BEC of positronium

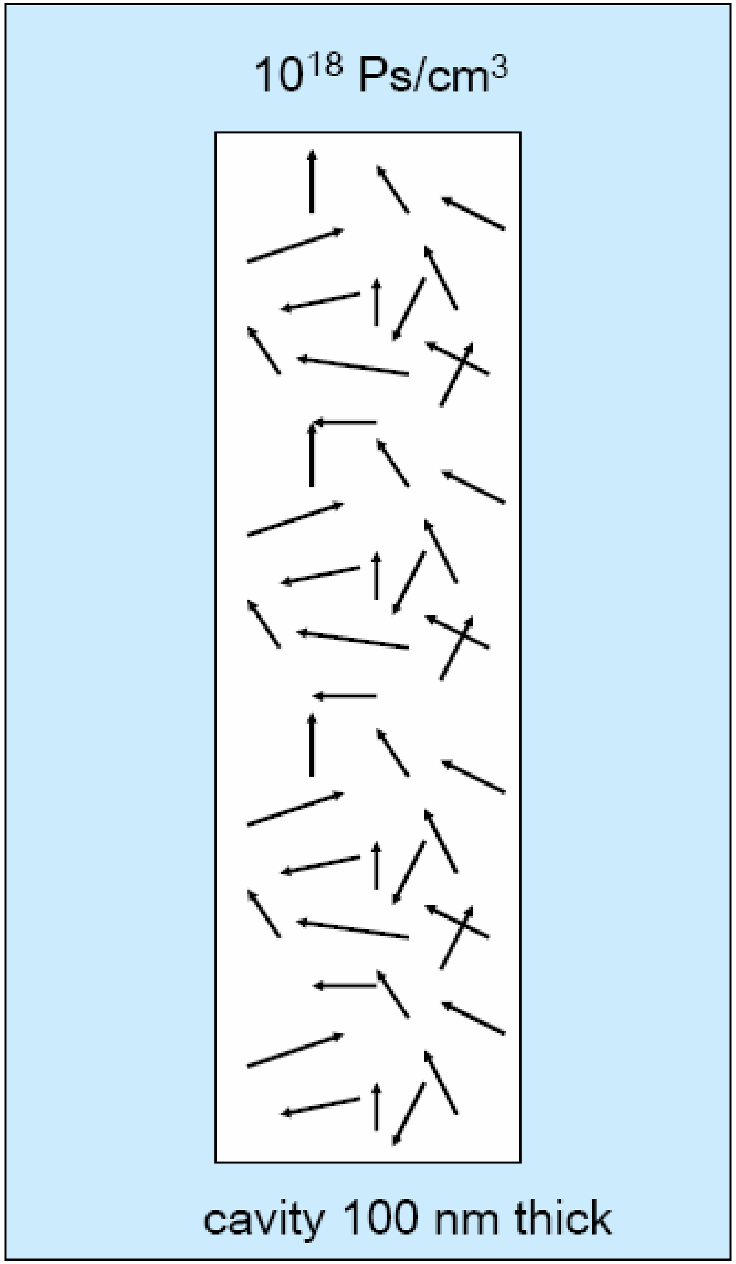
BEC critical temperature

$T_C = 15\ \mathrm{K} \times [\mathrm{density}/10^{18}\ \mathrm{cm}^{-3}]^{2/3}$

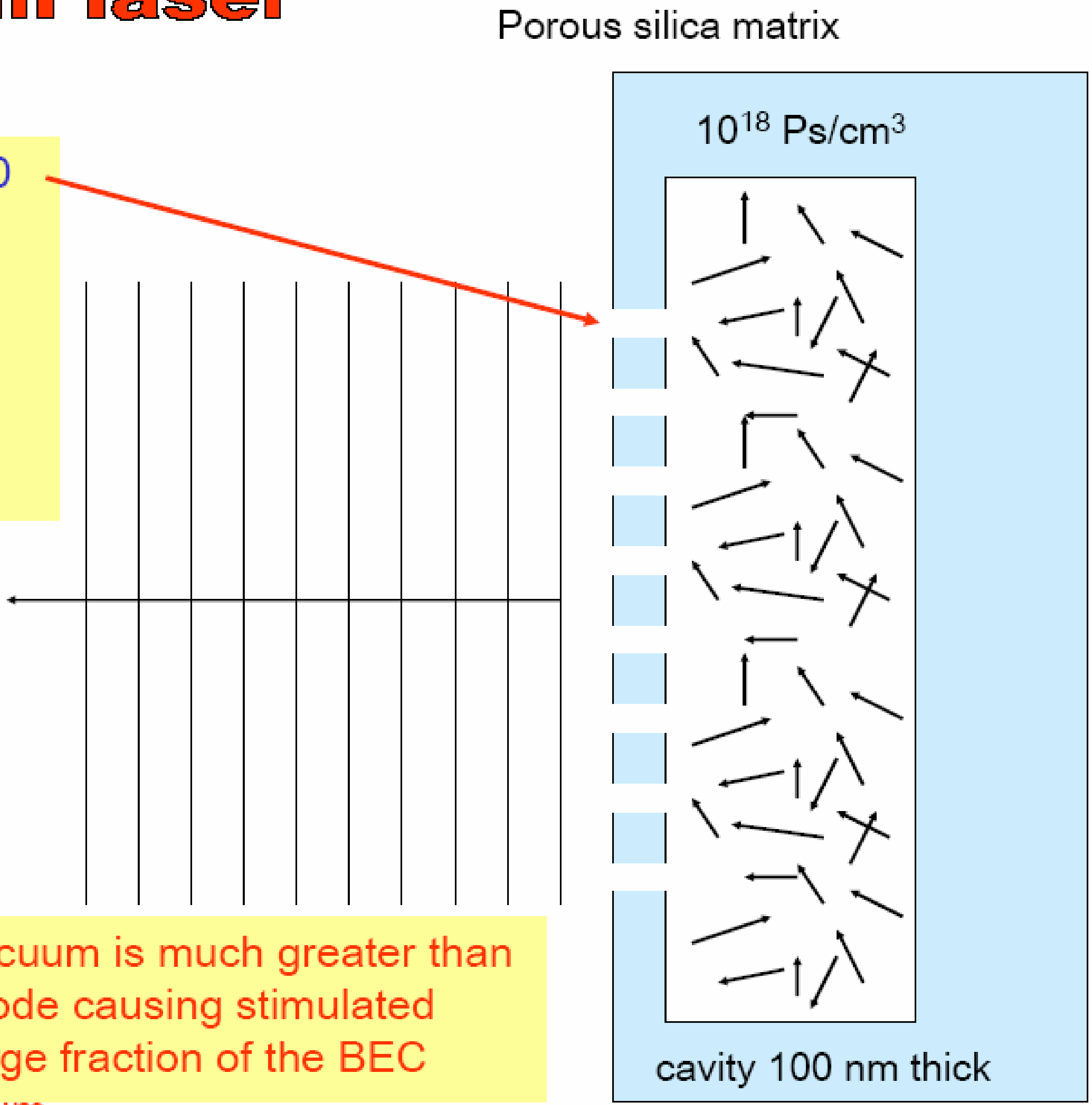


1 ns Pulse of 10^7 e^+ 5 μm diameter
= 4×10^{12} e^+/cm^2

Porous silica matrix



Ps atom laser



Holes smaller than 10 nm deBroglie wavelength

BEC Ps tunnels into vacuum and makes *plane wave* monoenergetic Ps beam

Ps Density in vacuum is much greater than one atom per mode causing stimulated emission of a large fraction of the BEC atoms into vacuum

BEC annihilation gamma ray laser

Compton Wavelength standard

Linewidth of the annihilation laser: $\Delta\lambda/\lambda = \Delta E_{FWHM}/E = \pi\alpha^{5} < 6.5\text{x}10^{-11}$.

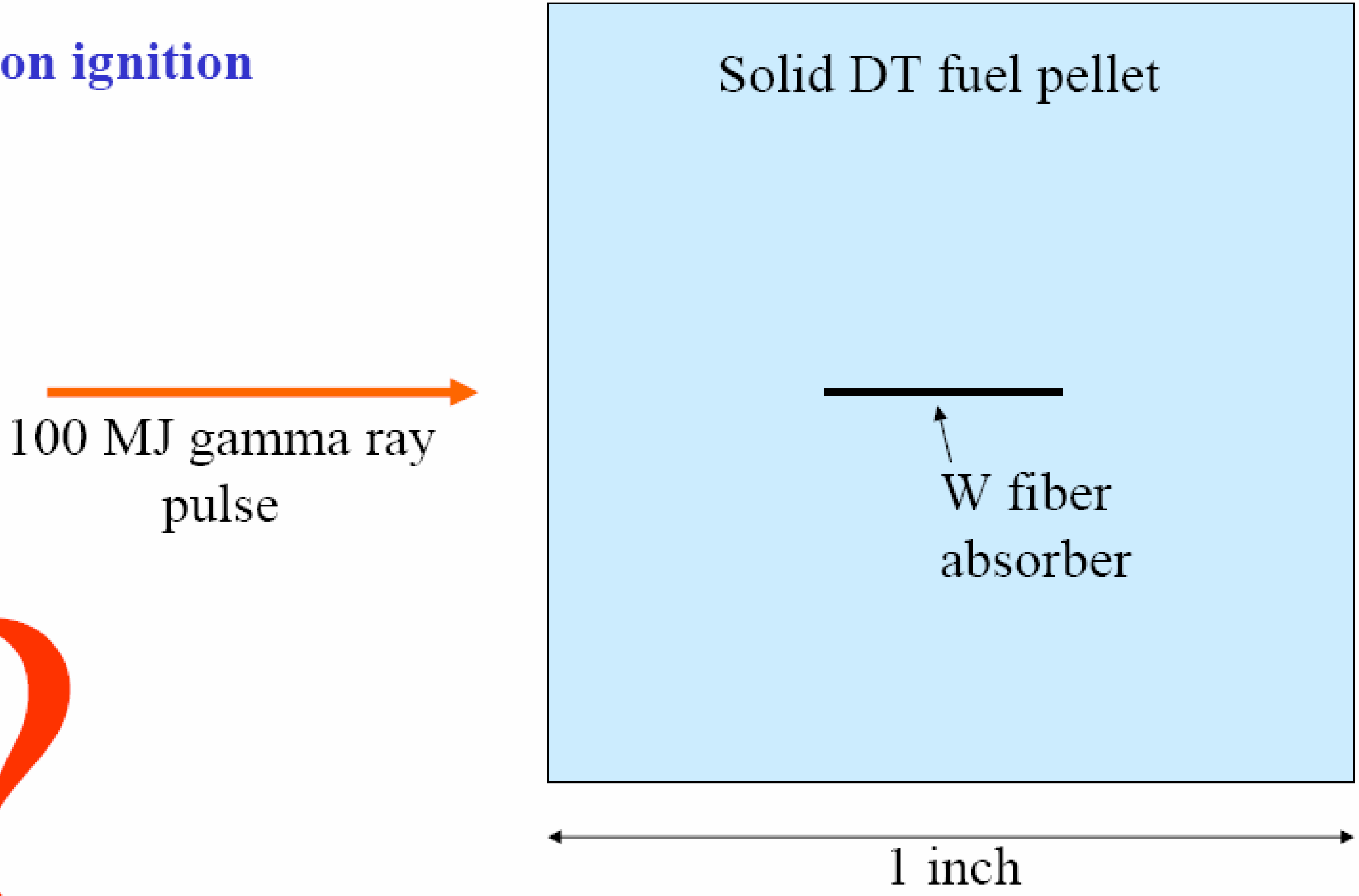
A combined measurement of the infinite mass Rydberg, R_{∞} and λ_{A} could yield a value for the product,

$$R_{\infty}\lambda_{C}/2\pi = 1/\alpha^{4}$$

with precision improved by four orders of magnitude.

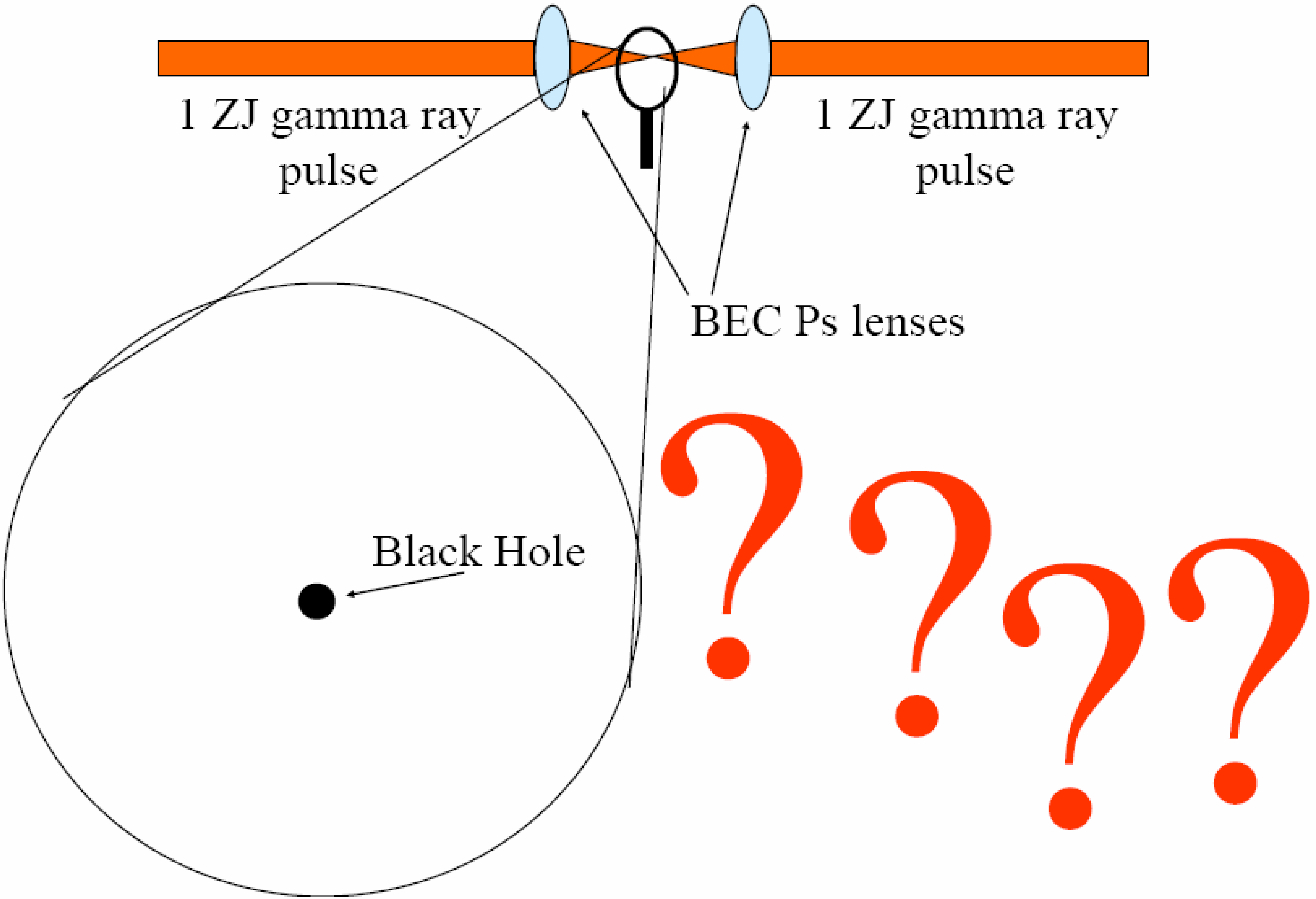
BEC annihilation gamma ray laser

Fusion ignition



?

BEC annihilation gamma ray laser



Ps-Ps spin exchange experiment

Experimental configuration

(1) $PbWO_4$ & XP2020 single-shot γ-ray detector

Agilent 6 GHz digital oscilloscope

(2)

20 mCi Na-22 source

Solid Ne moderator

Surko positron trap and accumulator

Velocity buncher

Pulsed magnet beam compressor

1 pulse per minute

(3)

15 ns Pulse of 10^7 e^+ 0.2 mm diameter: $= 2.5\times10^{10}$ e^+/cm^2

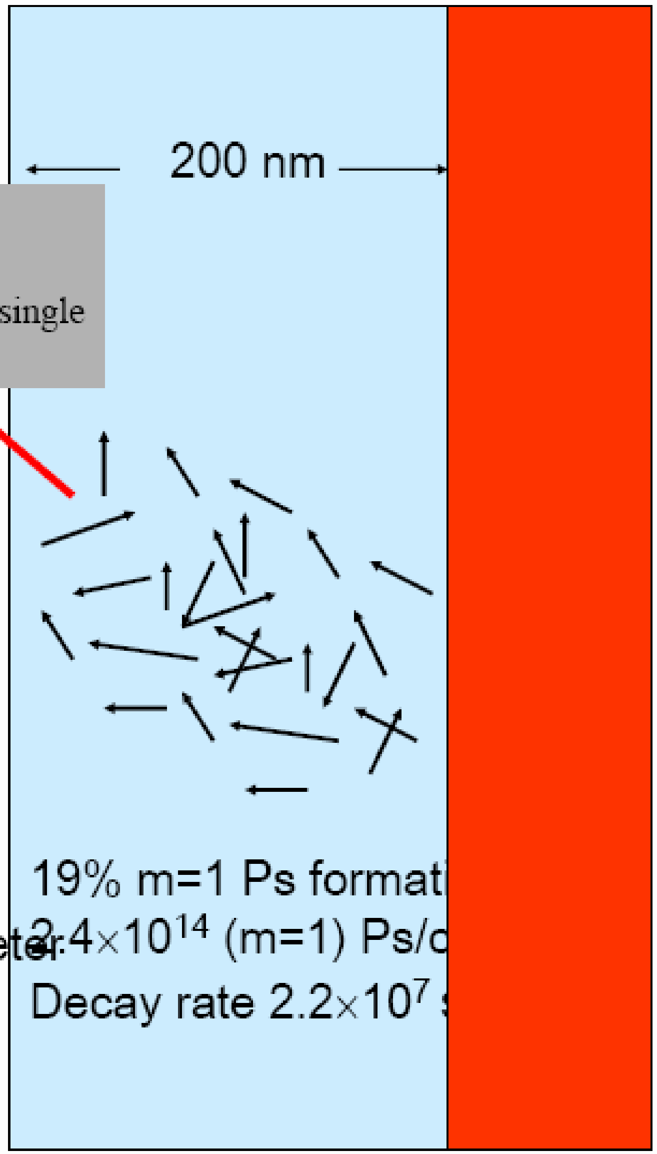
(4)

(5)

Millions of annihilation photons in a single burst

Porous silica layer

Silicon substrate



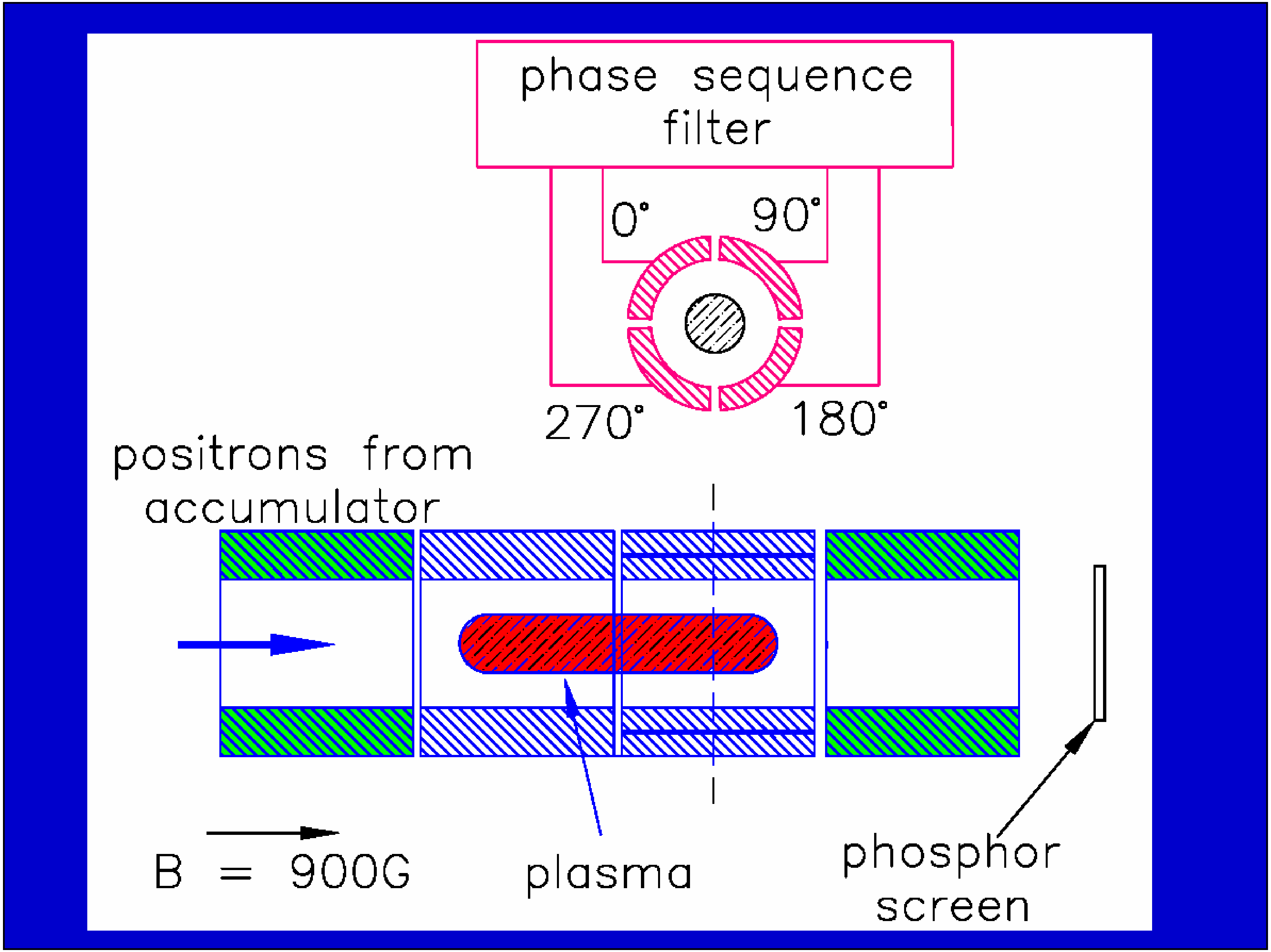
A Multicell Trap to Confine Large Numbers of Positrons

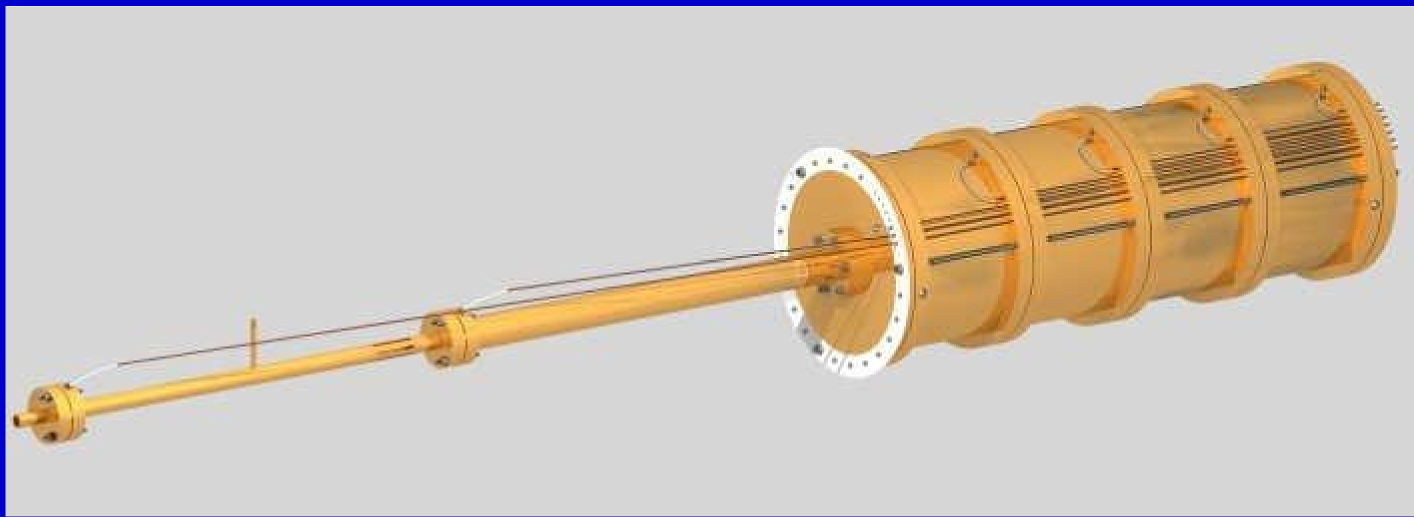
C. M. Surko[1] and R. G. Greaves[2]

[1] Department of Physics, University of California, San Diego

La Jolla, CA 92093, USA

[2] First Point Scientific, Inc. Agoura Hills, CA 91301, USA


phase sequence filter
0°
90°
270°
180°
positrons from accumulator
B = 900G
plasma
phosphor screen



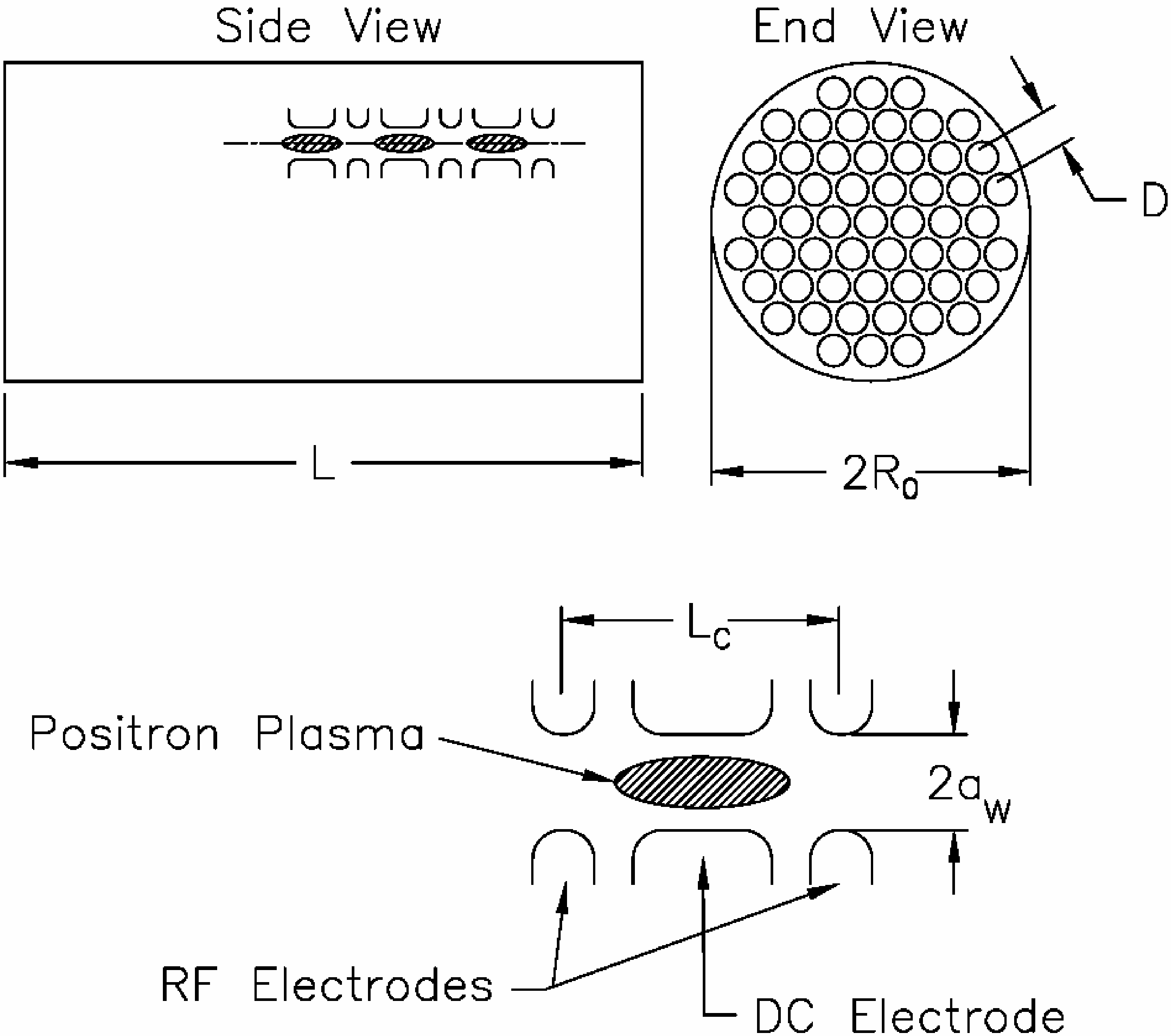
The Brillouin Limit

- The limiting density *nB*, commonly referred to as the Brillouin limit (Davidson, 1990), is given (in cgs units) by

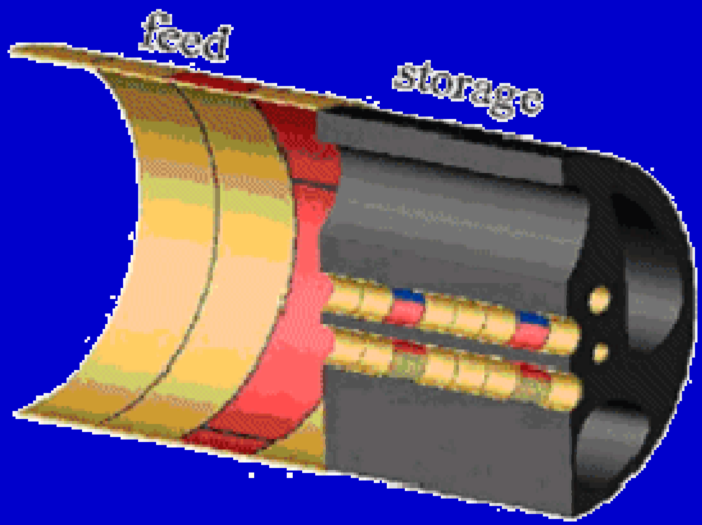
$$n_B = \frac{B^2}{4\pi mc^2}$$

For positrons

$$n_B = 5\times 10^{12}\left(\frac{B}{1\mathrm{T}}\right)^2 \ [\mathrm{cm}^{-3}]$$



Side View
End View
L
D
2R0
Lc
Positron Plasma
2aw
RF Electrodes
DC Electrode



- This will greatly increase the number of particles that can be trapped for a given confinement voltage. The current design goal is a 95 cell trap (5 cells in the B-field direction and 19 hexagonally close-packed cells in the transverse direction) capable of storing 10^{12} positrons for weeks.

PRL 95, 025002 (2005) PHYSICAL REVIEW LETTERS week ending 8 JULY 2005

New Source of Dense, Cryogenic Positron Plasmas

L. V. Jørgensen,[1,*] M. Amoretti,[2] G. Bonomi,[3] P. D. Bowe,[1] C. Canali,[2,4] C. Carraro,[2,4] C. L. Cesar,[5] M. Charlton,[1] M. Doser,[3] A. Fontana,[6,7] M. C. Fujiwara,[8,9] R. Funakoshi,[10] P. Genova,[6,7] J. S. Hangst,[11] R. S. Hayano,[10] A. Kellerbauer,[3] V. Lagomarsino,[2,4] R. Landua,[3] E. Lodi Rizzini,[12] M. Macrì,[2] N. Madsen,[11] D. Mitchard,[1] P. Montagna,[6,7] A. Rotondi,[6,7] G. Testera,[2] A. Variola,[2] L. Venturelli,[12] D. P. van der Werf,[1] and Y. Yamazaki[9]

(ATHENA Collaboration)[†]

[1]*Department of Physics, University of Wales Swansea, Swansea SA2 8PP, United Kingdom*
[2]*Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy*

We have developed a new method, based on the ballistic transfer of preaccumulated plasmas, to obtain large and dense positron plasmas in a cryogenic environment. The method involves transferring plasmas emanating from a region with a low magnetic field (0.14 T) and relatively high pressure (10^{-9} mbar) into a 15 K Penning-Malmberg trap immersed in a 3 T magnetic field with a base pressure better than 10^{-13} mbar. The achieved positron accumulation rate in the high field cryogenic trap is more than one and a half orders of magnitude higher than the previous most efficient UHV compatible scheme. Subsequent stacking resulted in a plasma containing more than 1.2×10^9 positrons, which is a factor 4 higher than previously reported. Using a rotating wall electric field, plasmas containing about 20×10^6 positrons were compressed to a density of 2.6×10^{10} cm^{-3}. This is a factor of 6 improvement over earlier measurements.

Cooling of ps atom

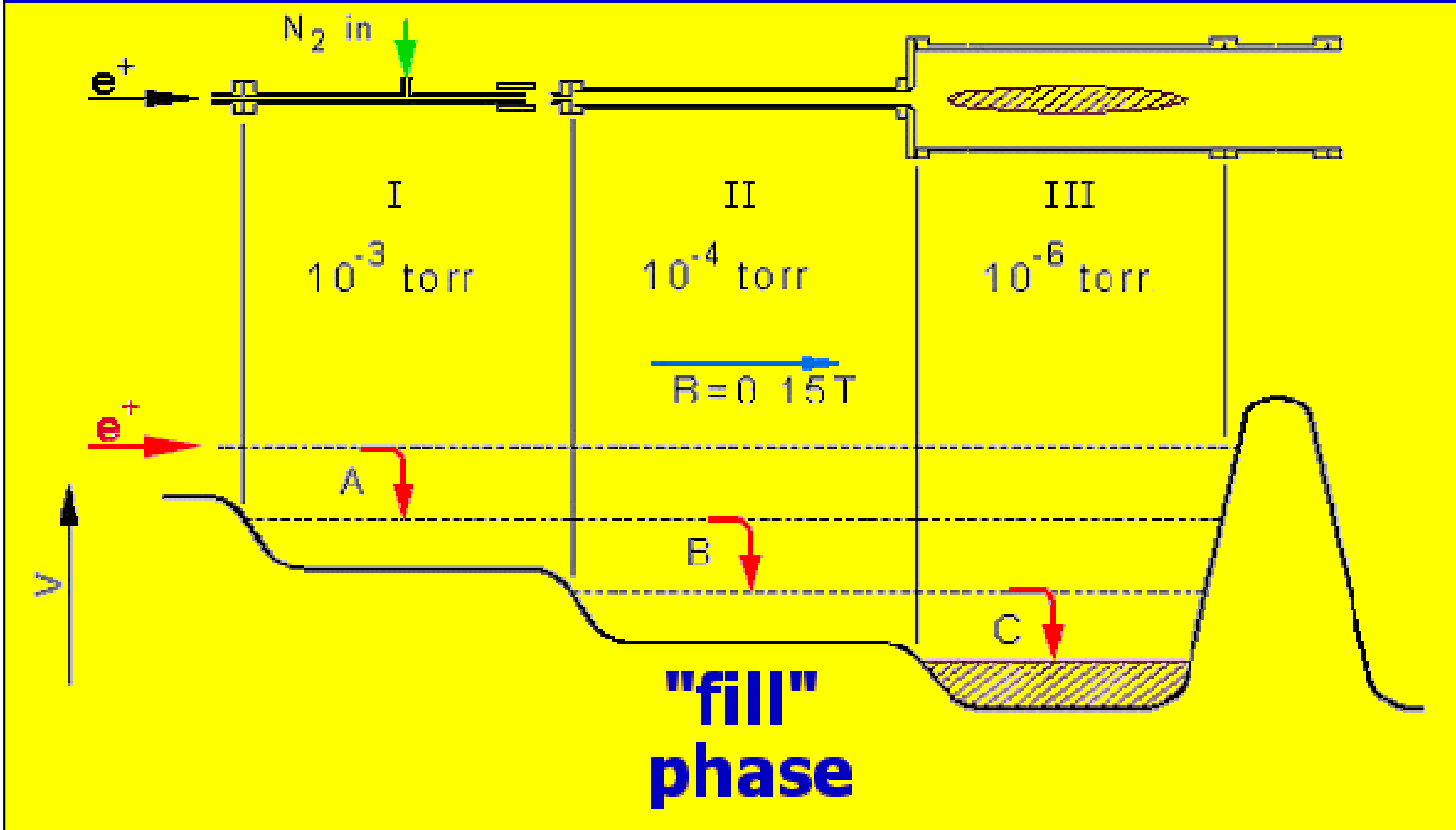
- Gas Cooling
- *Cyclotron cooling*
- *Sympathetic cooling*
- Laser cooling

一、Gas cooling

慢化后得到的是低能正电子，能量大约为1.5eV。采用三级逐步冷化技术，进一步减少正电子的能量。如图所示，三个区域的压强逐步降低，在第III区达到<1´10^{-8}torr。在不同的区域选择不同的减速气体，达到最优化的冷化效果。

第一阶段：

The cooling gas is selected to have a large cross section for positron energy loss, but a small cross section for positronium atom formation。



N2 in
e+
I
10-3 torr
II
10-4 torr
III
10-6 torr
B=0 15T
e+
A
B
C
V
"fill"
phase

三步冷却法示意图

第二步

- At energies in the 0.05 to several eV range, vibrational transitions in molecules are used, and below 0.05 eV, rotational transitions in molecules and momentum-transfer collisions in atoms are used to cool the positrons. The most efficient gas for buffer-gas trapping has proven to be molecular nitrogen, which has a large, resonant cross section。

第三步

- At lower energies, where vibrational excitation is important, cross sections have been measured for only a few molecules. However, positron-cooling rates have been measured for several molecules; SF_6 and CF_4 are particularly effective in this energy range.
- The current version of buffer-gas positron traps typically uses a mixture of N_2 and CF_4 in the final trapping stage for rapid cooling.

- 经**3**个阶段冷却后估计大约**30%**的注入正电子可以输运并冷却到极低的能量，约在**meV**量级，形成正电子等离子体被约束在势阱中。

295 K = 0.038 eV

二、Cyclotron cooling

- A convenient method to cool positrons is cyclotron radiation in a strong magnetic field. The cyclotron-cooling rate for electron mass particles is approximately

$$\Gamma c = B^2/4,$$

where B is in tesla and Γc is in s^{-1}. The characteristic radiation cooling time, $1/\Gamma c$ of positrons in a 5 T field is 0.16s.

- Above are limited to producing a temperature equal to the temperature of the environment ~e.g., 4 K for cyclotron cooling in a trap cooled to liquid helium temperature!.

三、*Sympathetic cooling*

- A technique has been developed to reach temperatures significantly below the ambient by sympathetic cooling of the positrons with laser-cooled ions, simultaneously confined in the same trap with the positrons. This technique recently demonstrated a high-density positron plasma (4×10^{9} cm^{-3}) at <5 K in a room temperature trap. The technique has the potential to produce positrons with parallel energies less than 100 mK.

ELSEVIER

Nuclear Instruments and Methods in Physics Research B 192 (2002) 117–127

NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

Sympathetically laser-cooled positrons ☆

B.M. Jelenković [a,b], A.S. Newbury [a,c], J.J. Bollinger [a,*], T.B. Mitchell [a,d], W.M. Itano [a]

[a] *Time and Frequency Division, National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA*
[b] *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Zemun, Belgrade, Yugoslavia*
[c] *Ball Aerospace, Boulder, CO 80301, USA*
[d] *Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA*

Abstract

We present results on trapping and cooling of positrons in a Penning trap. Positrons from a 2 mCi ^{22}Na source travel along the axis of a 6 T magnet and through the trap after which they strike a Cu reflection moderator crystal. Up to a few thousand positrons are trapped and lose energy through Coulomb collisions (sympathetic cooling) with laser-cooled ^{9}Be$^+$. By imaging the ^{9}Be$^+$ laser-induced fluorescence, we observe centrifugal separation of the ^{9}Be$^+$ ions and positrons, with the positrons coalescing into a column along the trap axis. This indicates the positrons have the same rotation frequency and comparable density ($\sim 4 \times 10^9$ cm^{-3}) as the ^{9}Be$^+$ ions, and places an upper limit of approximately 5 K on the positron temperature of motion parallel to the magnetic field. We estimate the number of trapped positrons from the volume of this column and from the annihilation radiation when the positrons are ejected from the trap. The measured positron lifetime is >8 days in our room-temperature vacuum of 10^{-8} Pa. Published by Elsevier Science B.V.

A Laser-Cooled, High Density Positron Plasma§

B.M. Jelenković†, A.S. Newbury*, J.J. Bollinger, T.B.Mitchell‡ and W.M. Itano

Time and Frequency Division, NIST, Boulder, CO 80305

Abstract. We present results on trapping and cooling of positrons in a Penning trap. Up to a few thousand positrons are trapped and sympathetically cooled through Coulomb collisions (sympathetic cooling) with laser-cooled $^9Be^+$ ions. By imaging the $^9Be^+$ laser-induced fluorescence, we observe centrifugal separation of the $^9Be^+$ ions and the positrons, with the positrons coalescing into a column along the trap axis. This indicates the positrons have the same rotation frequency and comparable density ($\sim 4 \times 10^9$ cm^{-3}) as the $^9Be^+$ ions, and places an upper limit of approximately 5 K on the positron temperature of motion parallel to the magnetic field. The measured positron lifetime is > 8 days in our room temperature vacuum of 10^{-8} Pa.

PHYSICAL REVIEW A **67**, 063406 (2003)

Sympathetically cooled and compressed positron plasma

B. M. Jelenković,[1,2] A. S. Newbury,[1,*] J. J. Bollinger,[1,†] W. M. Itano,[1] and T. B. Mitchell[3]
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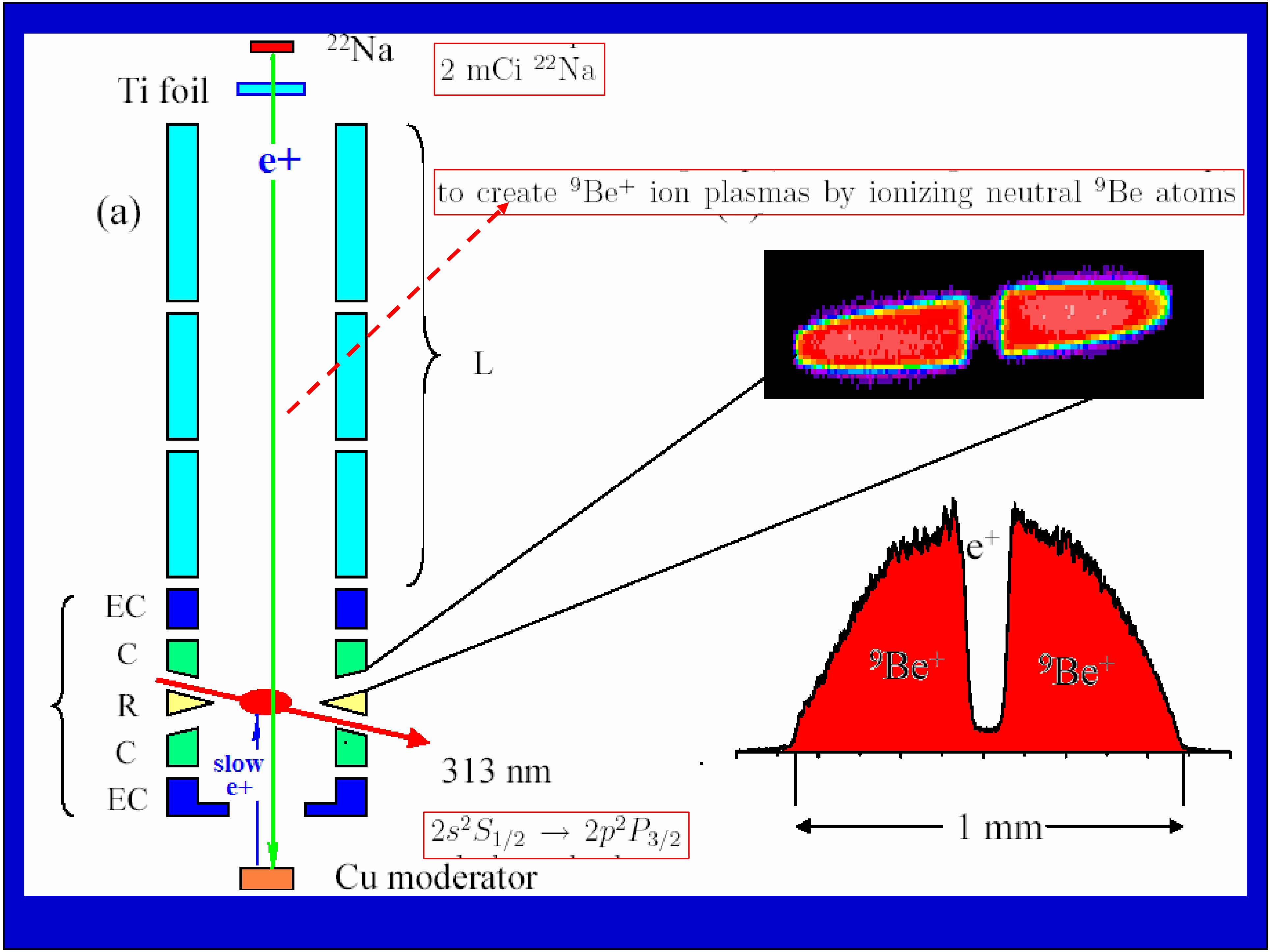
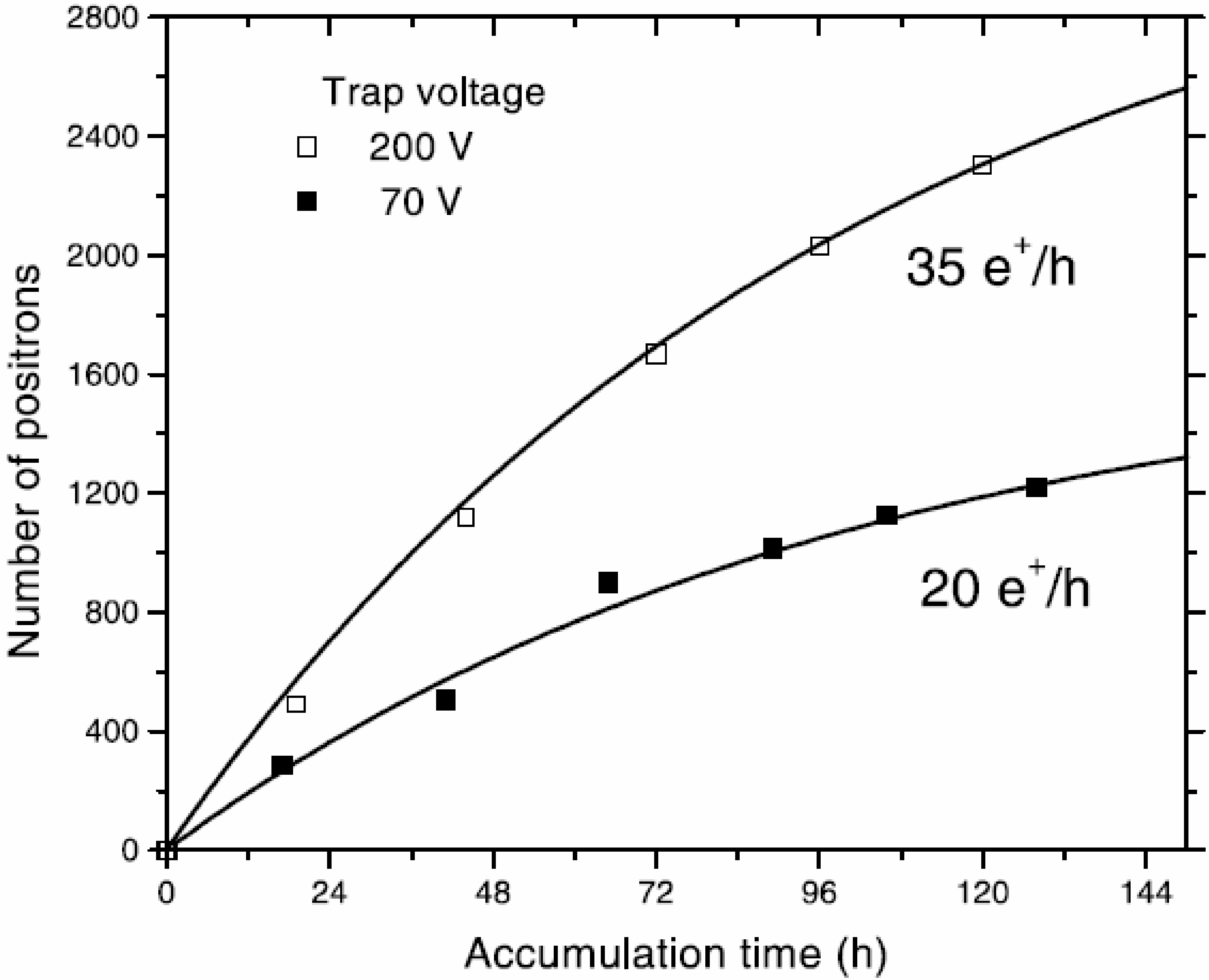
[2]*Institute of Physics, University of Belgrade, Belgrade, Yugoslavia*
[3]*Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA*

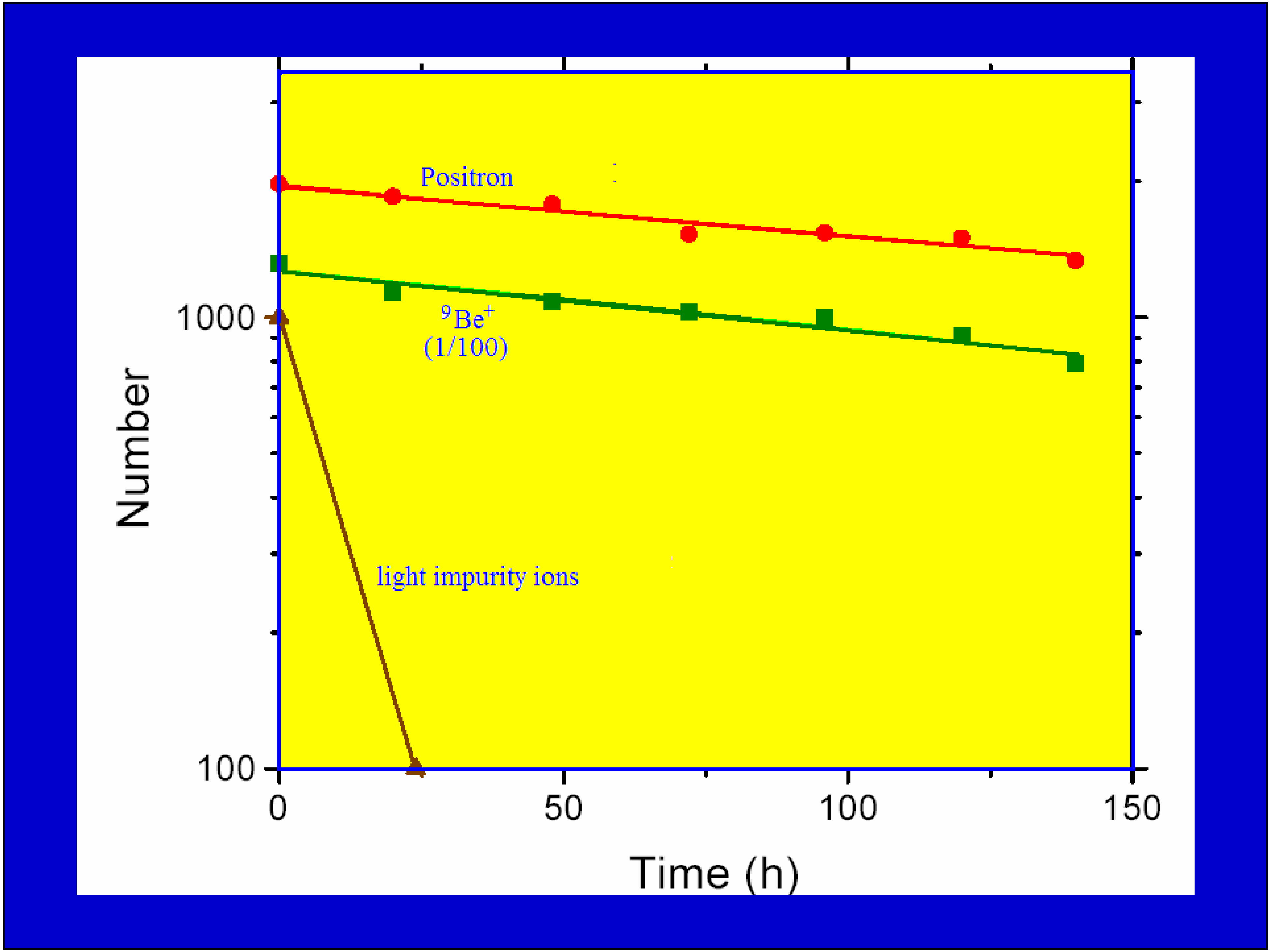
(Received 27 February 2003; published 18 June 2003)

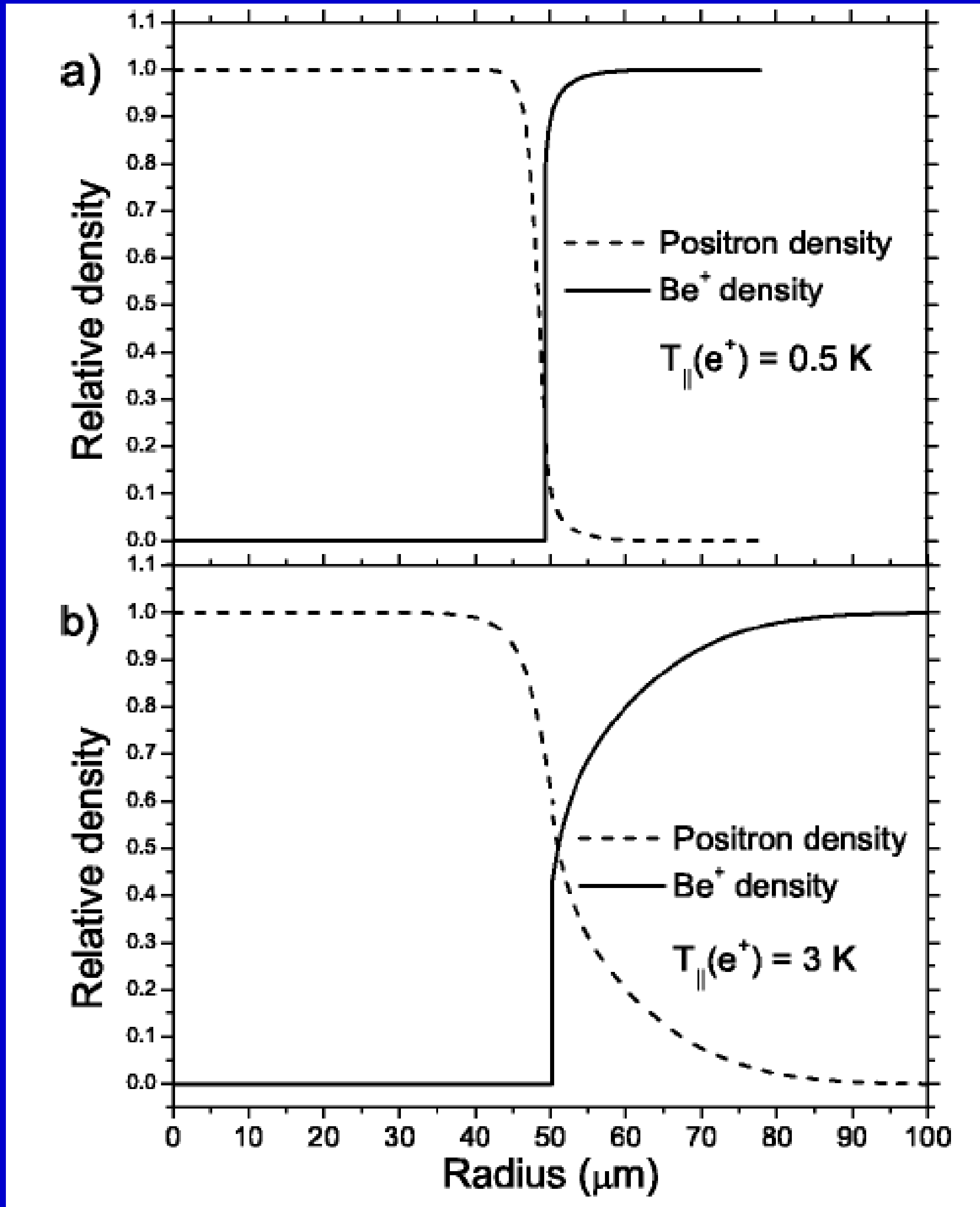
We report sympathetic cooling and compression of a few thousand positrons by laser-cooled $^9Be^+$ ions in a Penning ion trap. The observed centrifugal separation of the two species implies approximate rigid rotation of the positrons and $^9Be^+$ ions, and a positron density comparable to the $^9Be^+$ ion density of $\gtrsim 4\times 10^9$ cm^{-3}. We use the sharpness of the separation to place a 5-K upper limit on the positron temperature of motion parallel to the magnetic field. The positron lifetime is greater than two weeks in our room-temperature Penning trap.


22Na
2 mCi 22Na
Ti foil
e+
(a)
to create 9Be+ ion plasmas by ionizing neutral 9Be atoms
L
EC
C
R
C
EC
slow e+
313 nm
2s2S1/2 → 2p2P3/2
Cu moderator
e+
9Be+
9Be+
1 mm



Trap voltage
200 V
70 V
35 e+/h
20 e+/h
Number of positrons
Accumulation time (h)
0
400
800
1200
1600
2000
2400
2800
0
24
48
72
96
120
144


Positron
$^9Be^+$
(1/100)
light impurity ions
Number
1000
100
0
50
100
150
Time (h)


a)
b)
Relative density
Relative density
Positron density
Be+ density
T||(e+) = 0.5 K
Positron density
Be+ density
T||(e+) = 3 K
Radius (μm)

NIM B
Beam Interactions with Materials & Atoms
235 (2005) 504–508

Simultaneous cooling of highly charged ions with electrons and positrons

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Available online 24 May 2005

四、Laser cooling

Laser cooling of positronium

E.P. Liang C.D. Dermer

Optics Communications
Volume 65, Issue 6 , 15 March 1988, 419-424

J. Phys. B: At. Mol. Opt. Phys. **23** (1990) 329–336. Printed in the UK

Optical saturation of the 1^3S–2^3P transition in positronium

K P Ziock†, C D Dermer†, R H Howell†, F Magnotta† and K M Jones‡
† Physics Department, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
‡ Williams College, Williamstown, MA 01267, USA

PHYSICAL REVIEW A, VOLUME 62, 023405

Simulation of a method for forming a laser-cooled positron plasma

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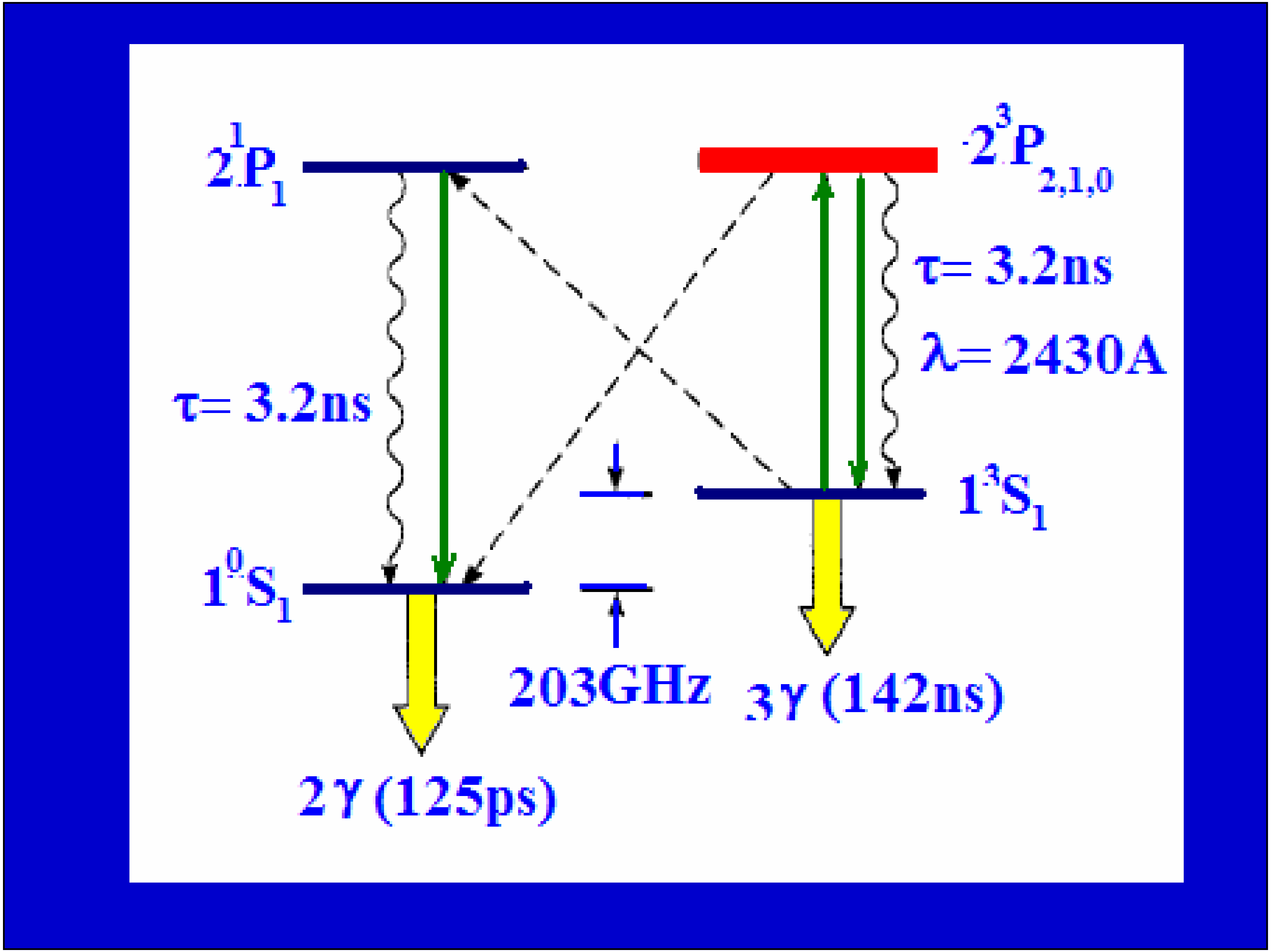
Laser cooling of ortho-Ps

Doppler cooling of o-Ps through

- 1s à 2p excitation of Ps
- transition energy = 5.2 eV
- lifetime = 3.2 ns
- Decay of 2p (excited state) to the 1s (groundstate) by emission of 243 nm photons
- One excitation cycle is 6.4 ns.
- Residual temperature of o-Ps ~ 0.6K, one photon recoil limit.


2^1P_1
$2^3P_{2,1,0}$
τ= 3.2ns
τ= 3.2ns
λ= 2430A
1^3S_1
1^0S_1
203GHz
3γ (142ns)
2γ (125ps)

Study of Ortho-Positronium Laser Cooling

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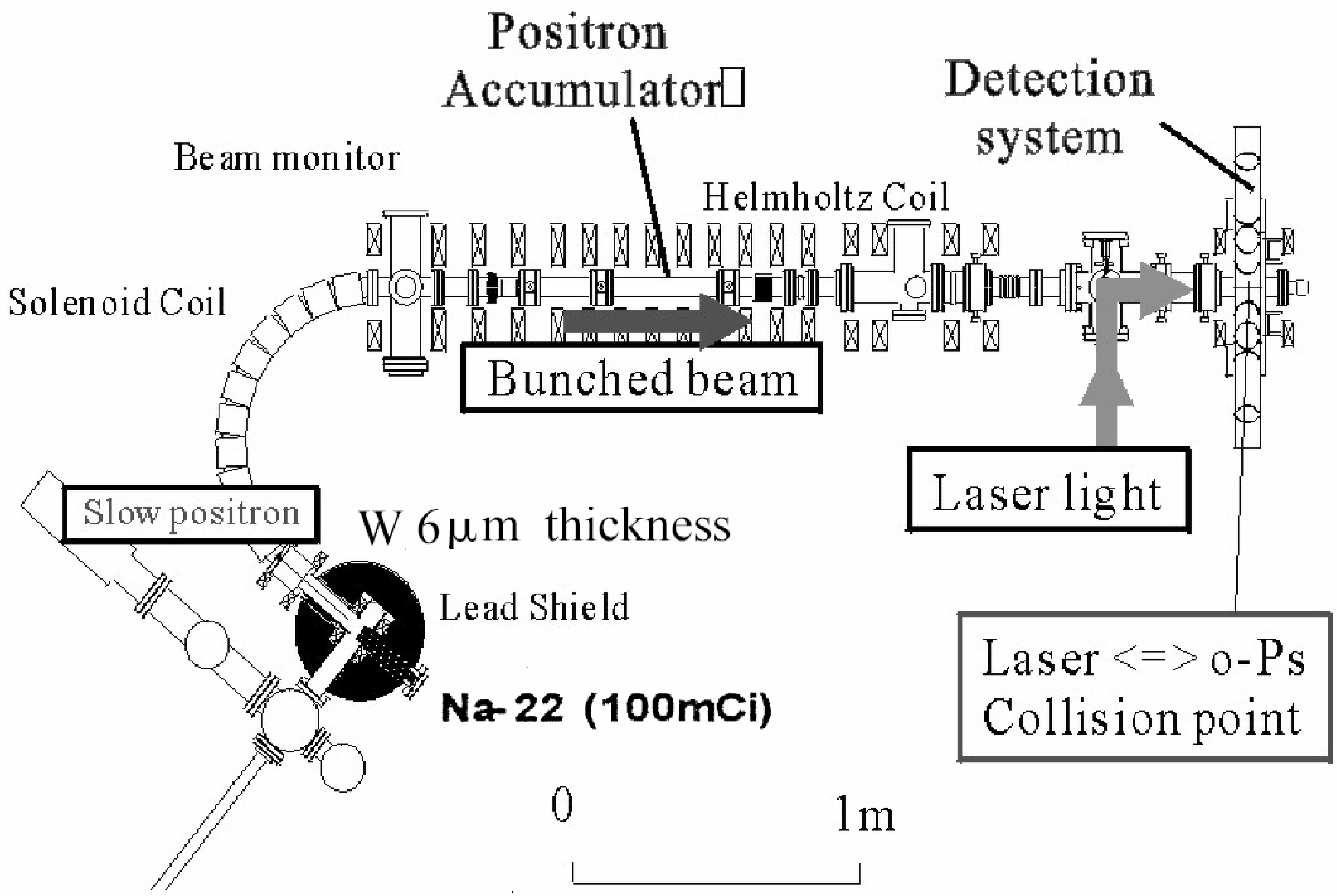
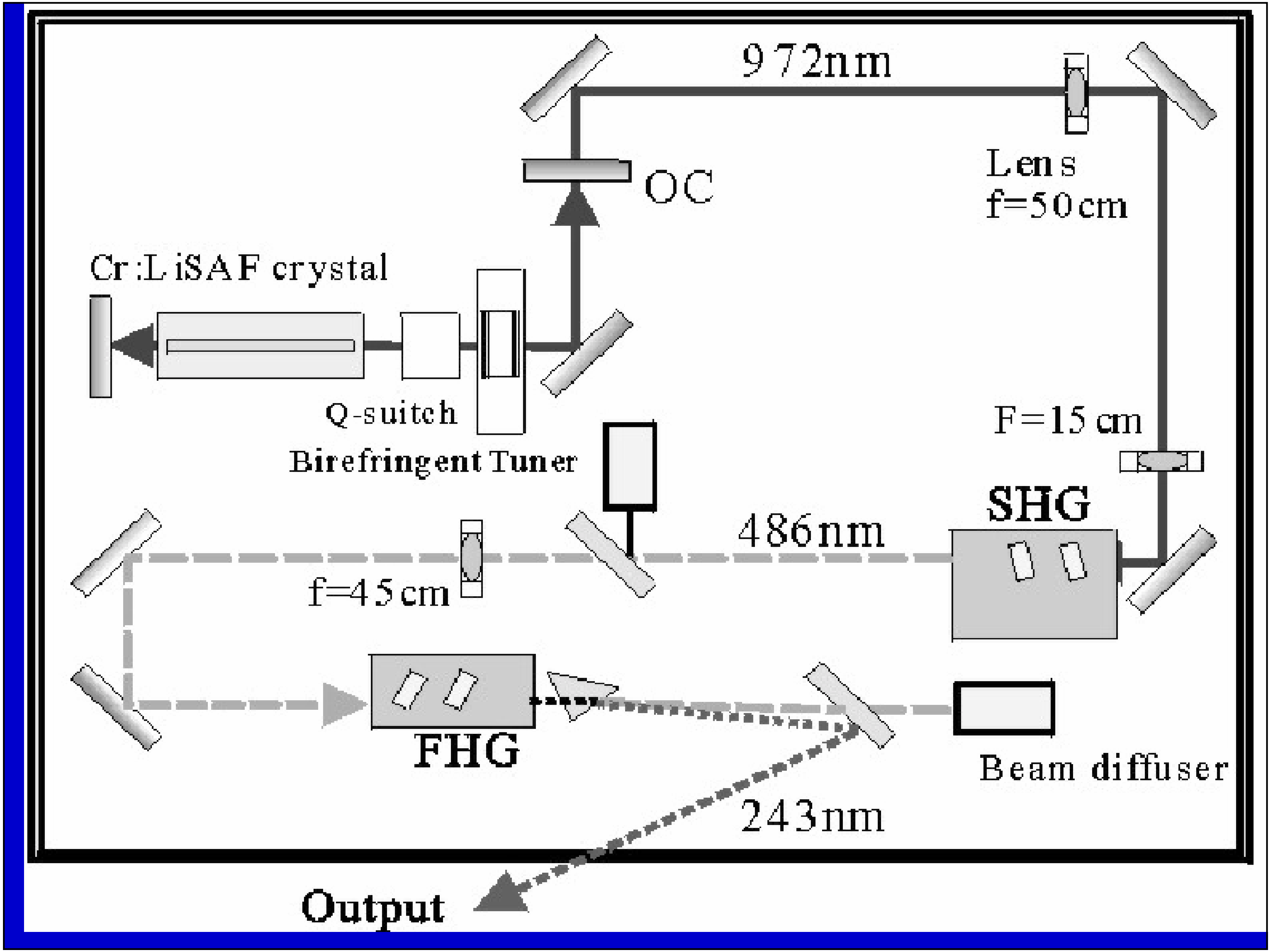
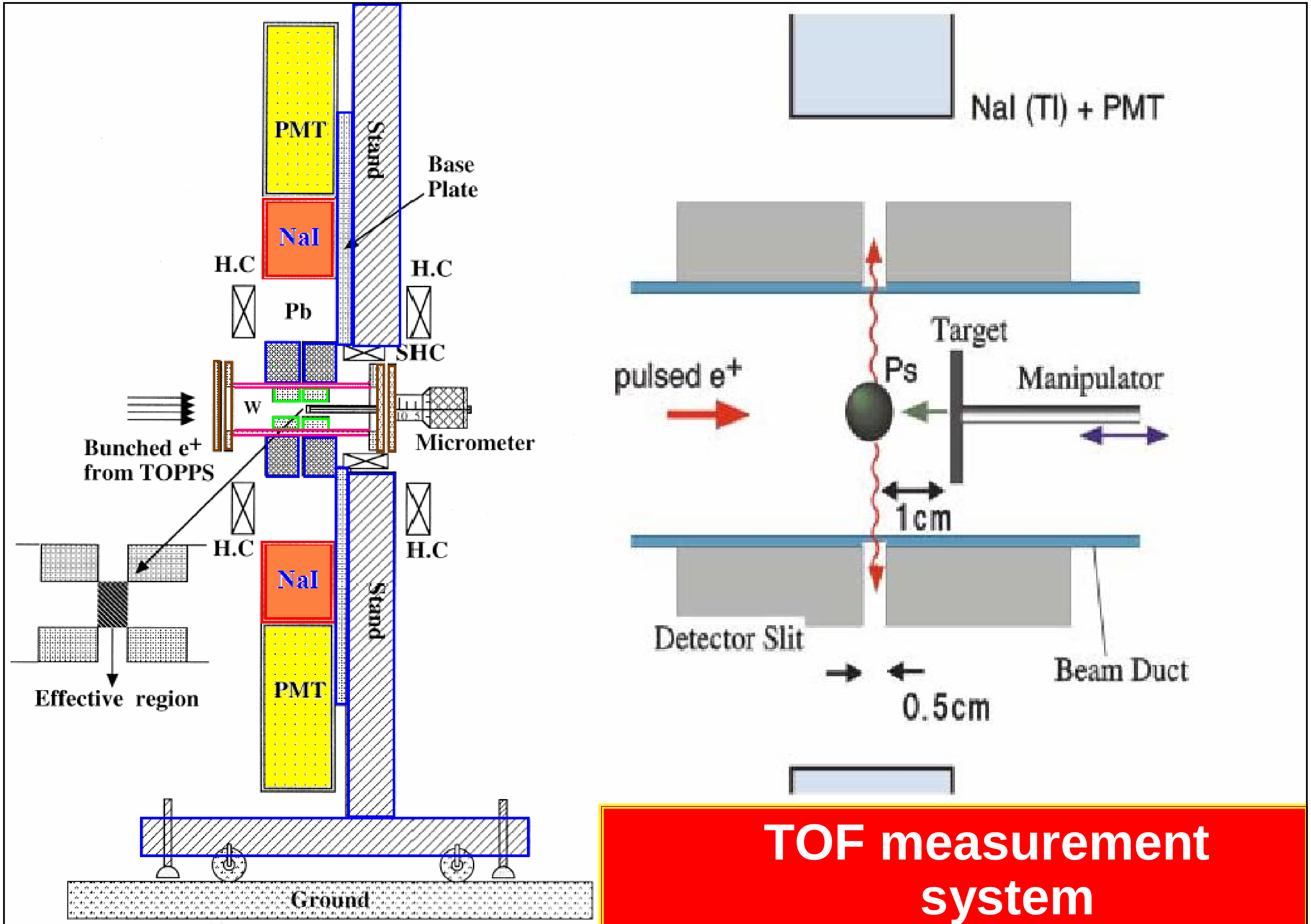


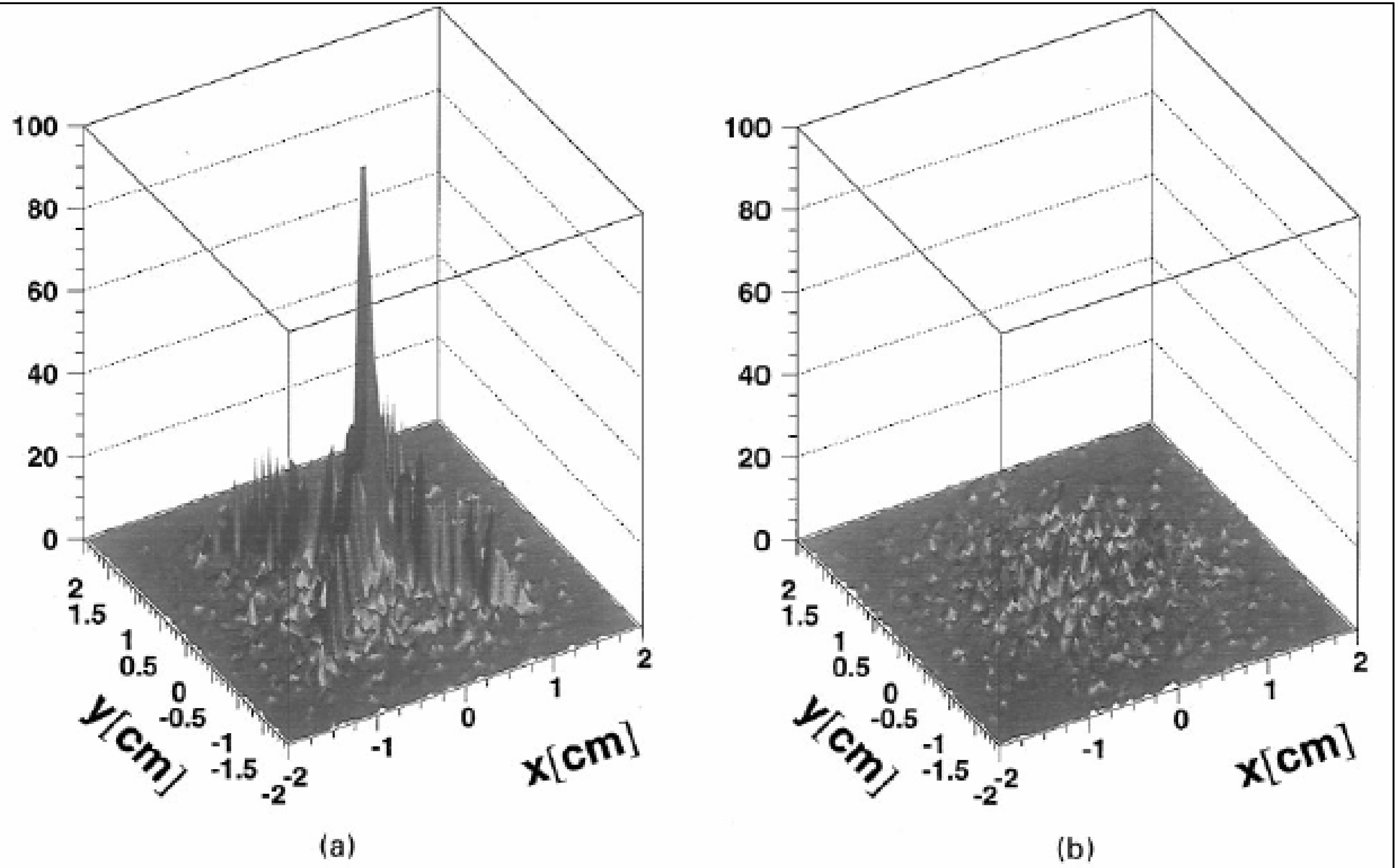
Fig.1 Schematic view of the e^+-beam line



972nm
OC
Lens
f=50cm
Cr:LiSAF crystal
Q-suitch
Birefringent Tuner
F=15 cm
SHG
486nm
f=45cm
FHG
Beam diffuser
243nm
Output



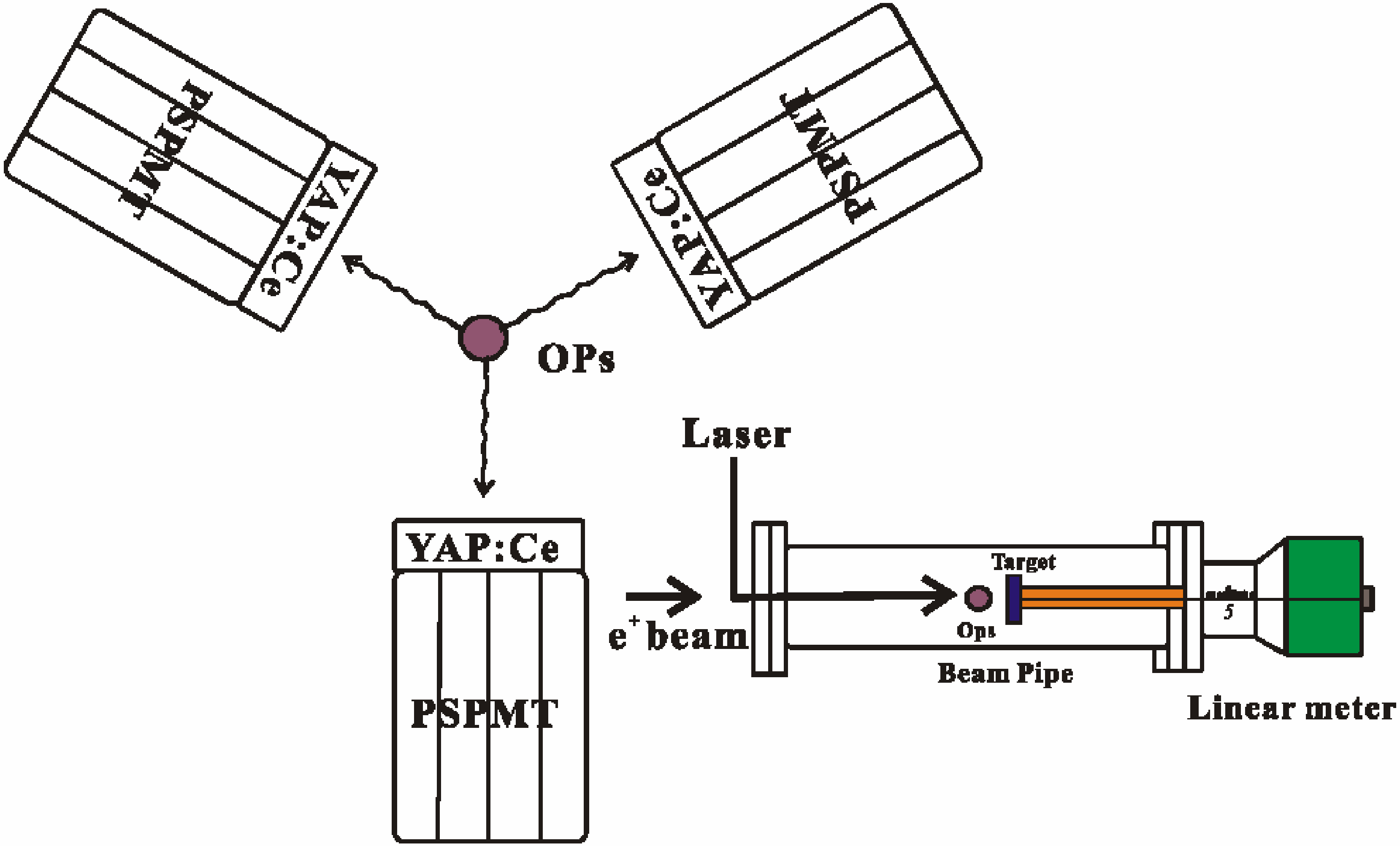
TOF measurement system



- Spatial distributions of *o*-Ps projected on the *x*-*y* plane at 220 ns for laser-on (a) and laser-off (b).

A cooling effect is clearly demonstrated in Fig. 6, where the large enhancement emerges around the original production point of Ps when the laser is switched on (Fig. 6(a)) whereas only the broad distribution is seen when the laser is not applied (Fig. 6(b)). It should be noted that 44% of initial *o*-Ps is contained in Fig. 6(a) whereas only 21% is available in Fig. 6(b). The Monte Carlo simulation has also shown that about 7% of *o*-Ps atoms initially produced are cooled down to 1 K within 220 ns, that is consistent with the calculation given in Section 1.

Basic Idea of Laser Cooled oPs detection system



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Positronium in low temperature mesoporous films

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We investigate the formation and annihilation of ortho-positronium atoms (o-Ps), the spins parallel electron (e^-)–positron (e^+) bound state, in mesoporous films from 400 to 50 K. At room temperature up to 20% of the implanted e^+ end up as o-Ps which self-annihilates (the bound e^+ and e^- annihilate); this is 50% of the formed o-Ps. One would expect self-annihilation to be suppressed at lower temperatures since, although o-Ps trapped in pores of diameter $\phi > 1$ nm, found in these films, is more likely to self-annihilate, several effects could decrease o-Ps formation and/or o-Ps trapping in a pore. Instead we find that at 50 K the amount of e^+ ending up as self-annihilating o-Ps is up to 19% greater than predicted if *no* suppressing effects played a role. Copious amounts of o-Ps atoms self-annihilate at 50 K (up to 30% of implanted e^+, 75% of formed o-Ps). This amount was found to increase even further down to 10 K making these films ideal substrates in which to confine large amounts of collisionally cooled, self-annihilating o-Ps for the eventual realization of an o-Ps Bose Einstein condensate (BEC).

Thank you!