Laser spectroscopy experiments for QED tests at strong electromagnetic fields

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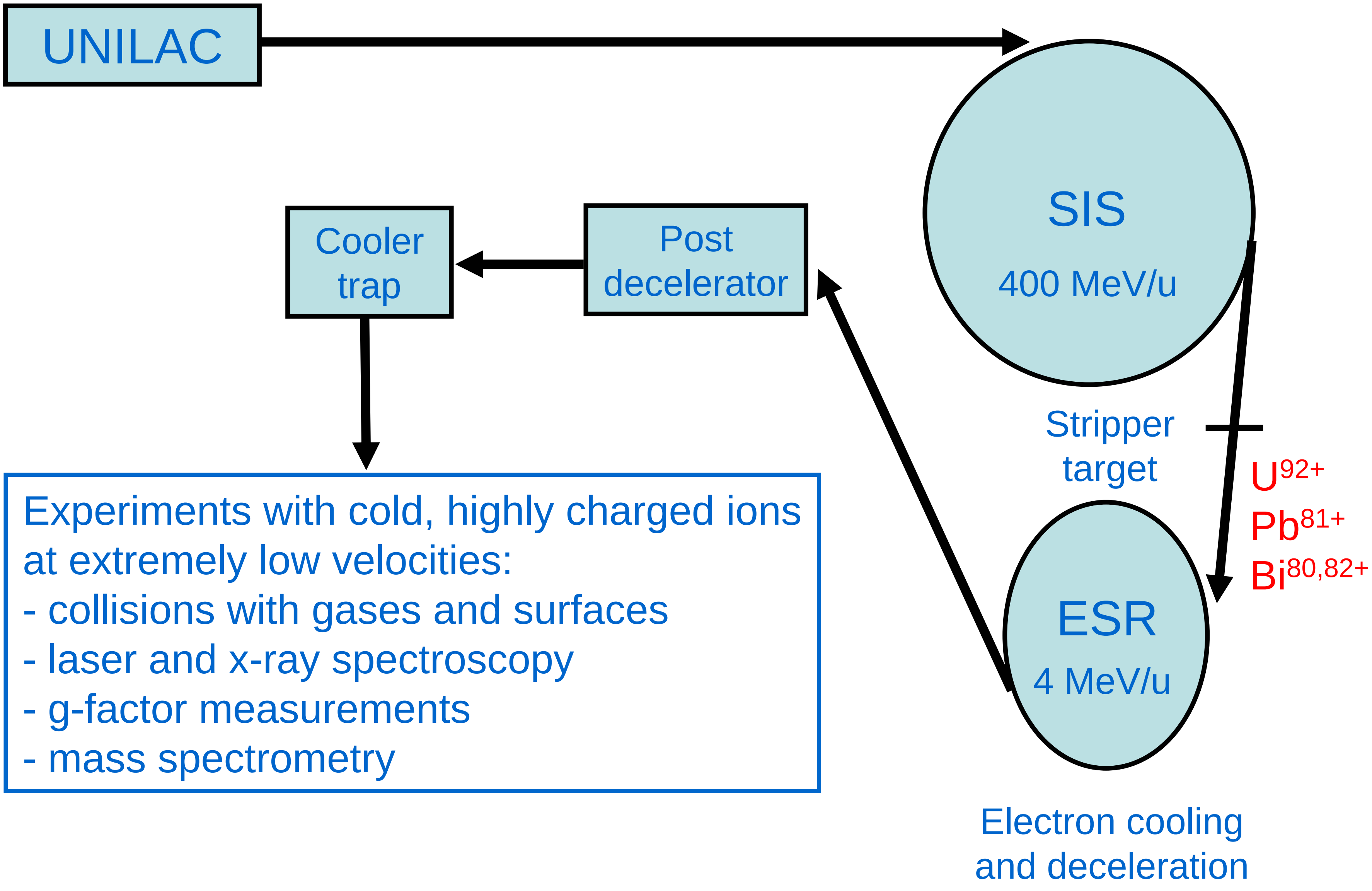
David Church (Texas)

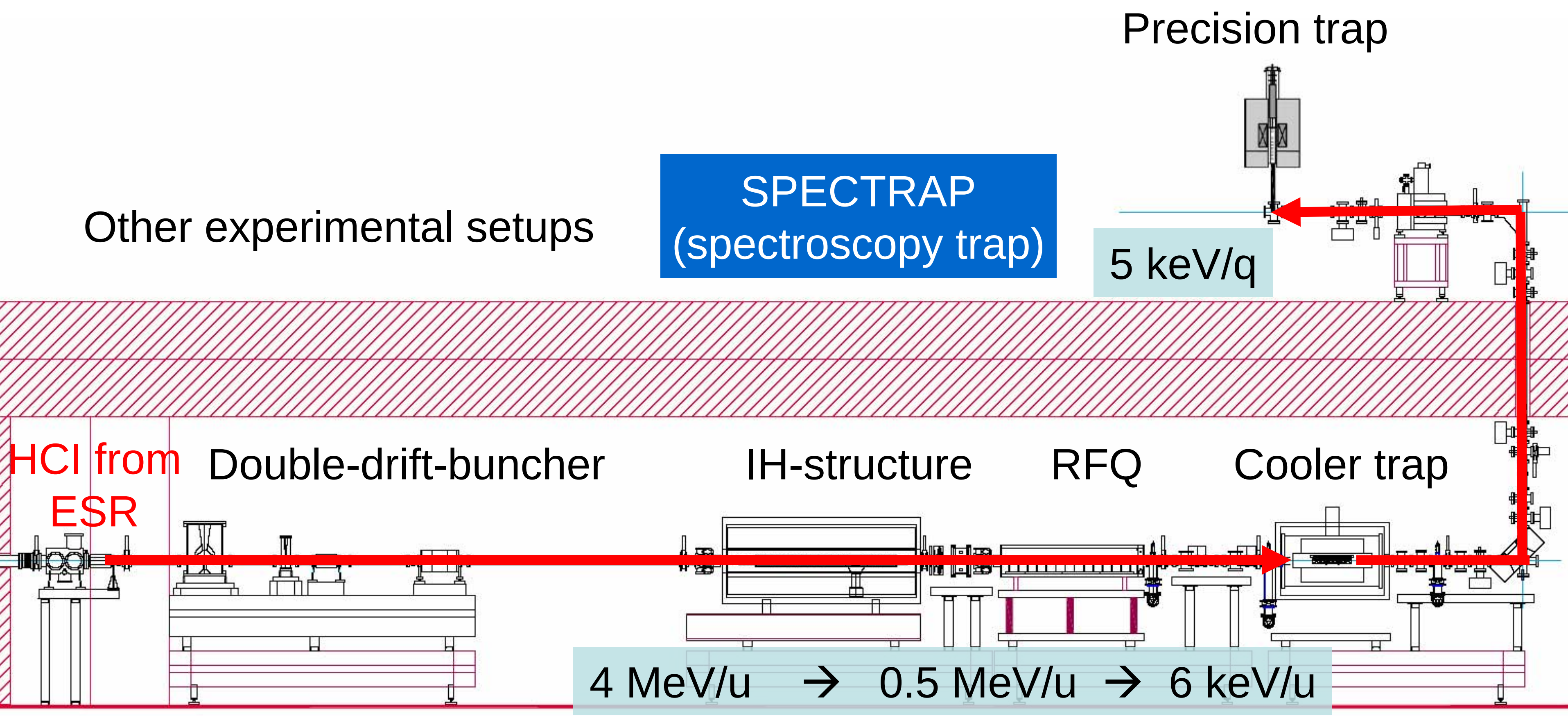
5.02.2008

The HITRAP project (overview)



HITRAP re-injection channel at GSI

"An Ion Trap Facility for Experiments with Highly-Charged Ions"



Laser spectroscopy of highly charged ions

- Test of QED at extreme fields (10^{16} V/cm and 10^{4} T)
- Use hydrogen- and lithium-like ions
- Measure (1s, 2s) ground state hyperfine splittings
- Need experimental resolution of ~10^{-6}

- HFS wavelengths Z>70 in visible → laser spectroscopy
- Use standard laser systems
- Use Penning trap, resistive cooling and rotating wall technique for trapping, cooling and compression of ion cloud, respectively

→ Estimated experimental resolution ~10^{-7}

→ Test of (higher order) QED to a few percent

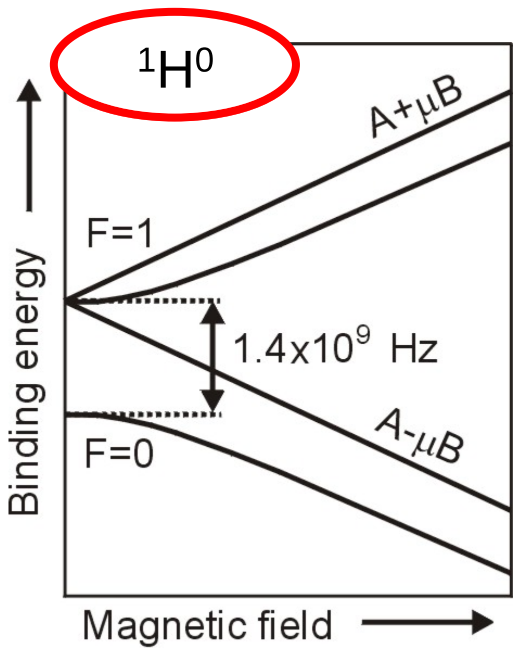
→ Experiments to be performed in 2009-2010

Hyperfine splitting in hydrogen-like ions

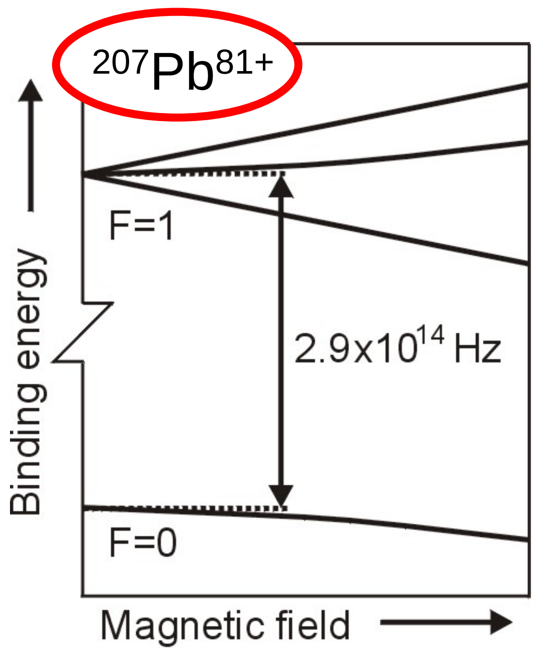
$$E_{HFS} = \frac{4}{3}\alpha(Z\alpha)^3 g_I \frac{m_e}{m_p}\frac{2I+1}{2} m_e c^2 A_{1s}(1-\delta_{1s})$$

$$g_I = \mu/(\mu_N I) \qquad \kappa = \sqrt{1-(Z\alpha)^2} \qquad A_{1s} = \frac{1}{\kappa(2\kappa-1)}$$

Hydrogen-like $^{207}Pb^{81+}$ (1s) $^2S_{1/2}$ (I=1/2, F=0 → F=1)
Above calculation gives λ=970(40) nm
Full calculation yields λ=1020(4) nm
Experiment gives λ=1019.7(2) nm (and τ=50 ms)



Zeeman splitting is 2.8×10^{10} Hz at B=1 T



Hydrogen- and lithium-like ions

Similar calculations for H-like and Li-like ions

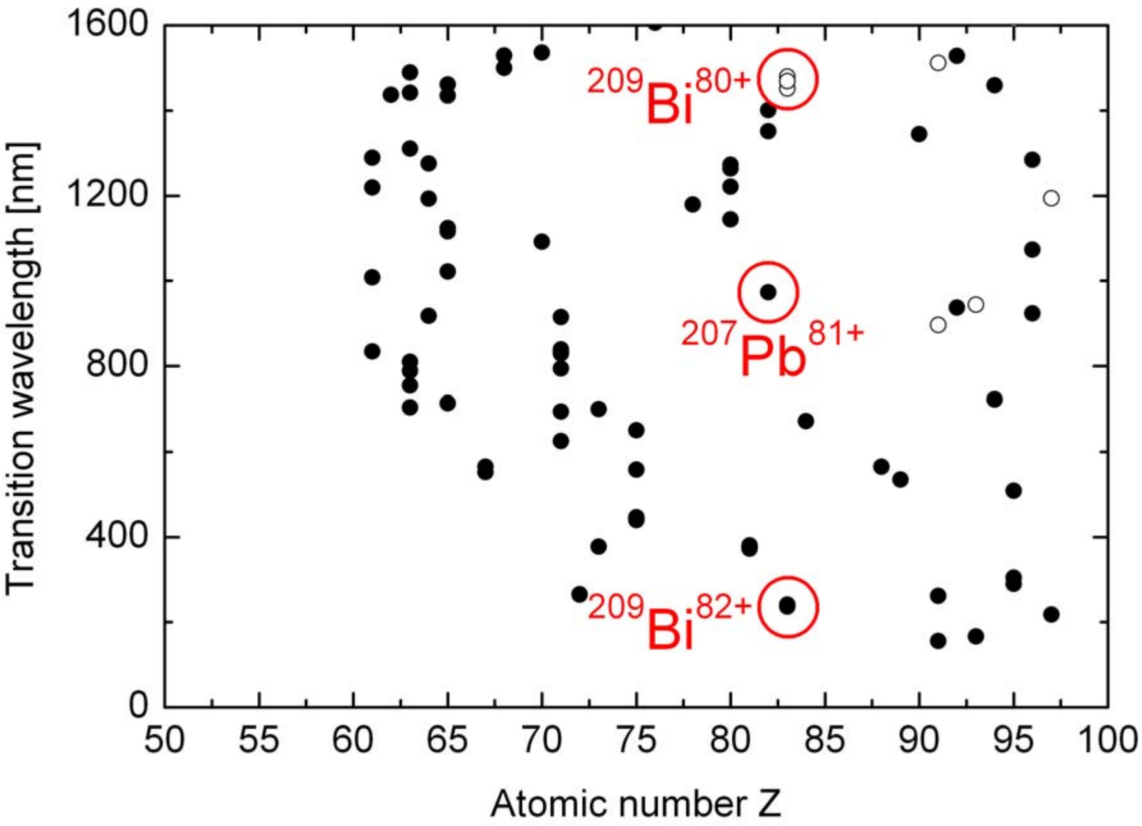
Lithium-like $^{209}Bi^{80+}$ $(1s^2 2s)$ $^2S_{1/2}$ (I=9/2, F=4 → F=5)

Simple calculation gives λ=1448(50) nm

Full calculation yields λ=1555.4(4) nm (797 meV)

Experiment gives λ=1512(48) nm (820 meV)

λ=1567(10) nm (791 meV)



How to extract the QED information?

$$\Delta E^{(1s)} = \Delta E^{(1s)}_{\text{Dirac}}(1 - \varepsilon^{(1s)}) + \Delta E^{(1s)}_{\text{QED}}$$

$$\Delta E^{(2s)} = \Delta E^{(2s)}_{\text{Dirac}}(1 - \varepsilon^{(2s)}) + \Delta E_{\text{int}}(1 - \varepsilon^{(\text{int})})$$
$$+ \Delta E^{(2s)}_{\text{QED}} + \Delta E_{\text{int-QED}}$$

The ratio $\dfrac{\varepsilon^{(2s)}}{\varepsilon^{(1s)}} = f(\alpha Z)$ hardly depends on the nuclear structure!
(ε is the Bohr-Weisskopf effect)

$$\Delta' E = \Delta E^{(2s)} - \xi \Delta E^{(1s)}$$

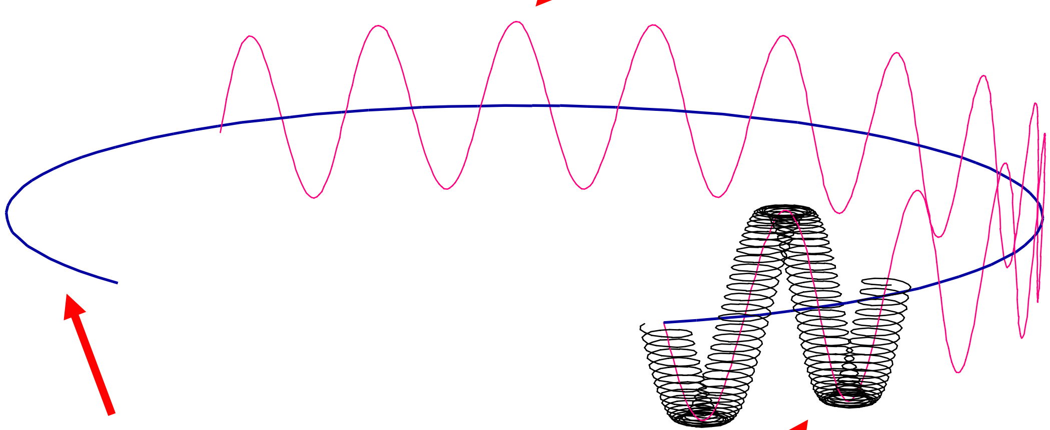
$$\Delta' E = \Delta' E_{\text{non-QED}} + \Delta' E_{\text{QED}}$$

V.M. Shabaev, Phys. Rev. Lett. **86**, 3959 (2001).

The Penning trap

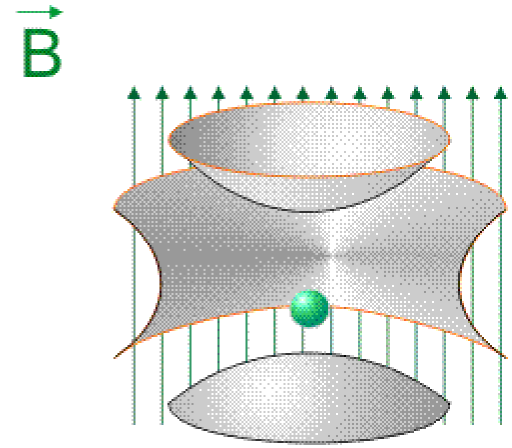
Electric ~ 10 V
Magnetic ~ 1 T

axial confinement
by electric field
(axial freq. ω_z)
~250 kHz

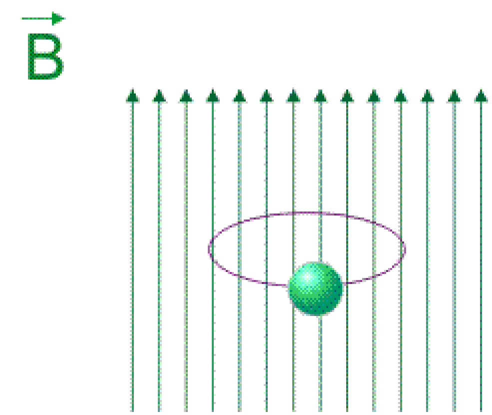


Ex**B** drift about
trap centre
(magnetron freq. ω_m)
~ 50 kHz

radial confinement
by magnetic field
(cyclotron freq. ω_c)
~ 500 kHz

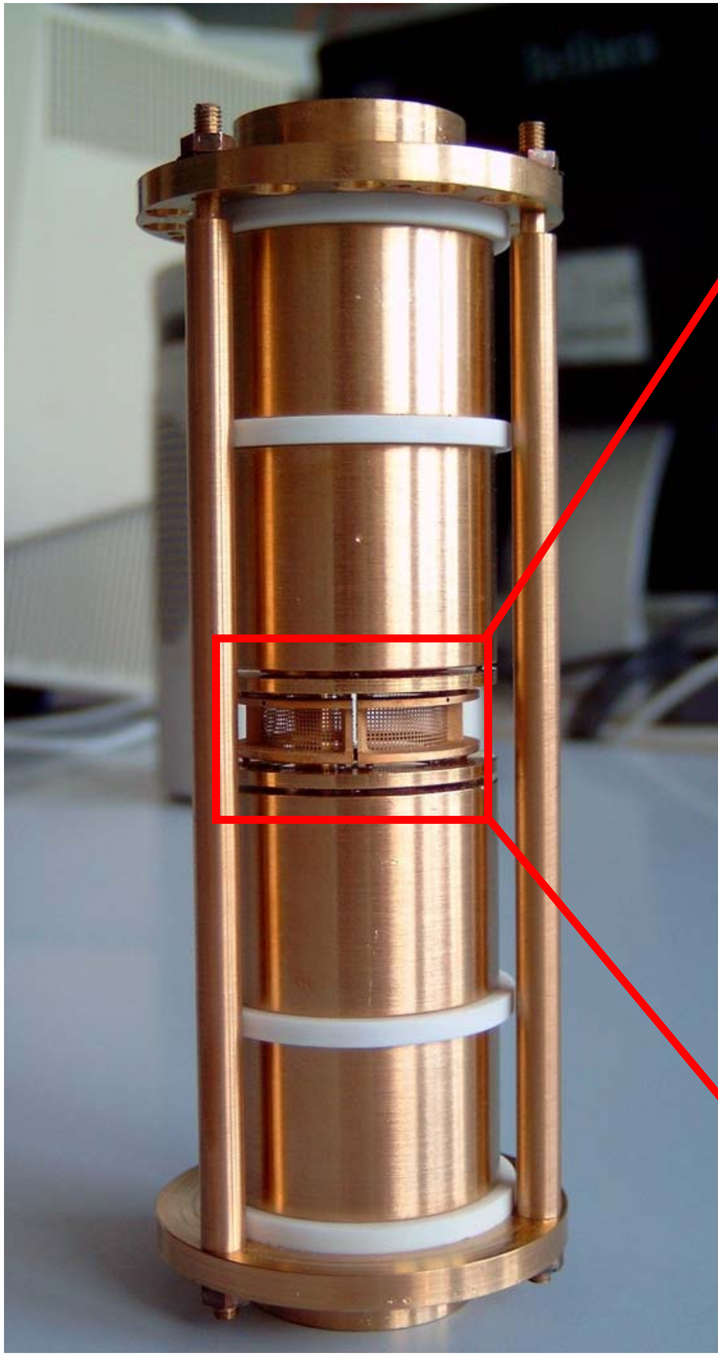


PLUS

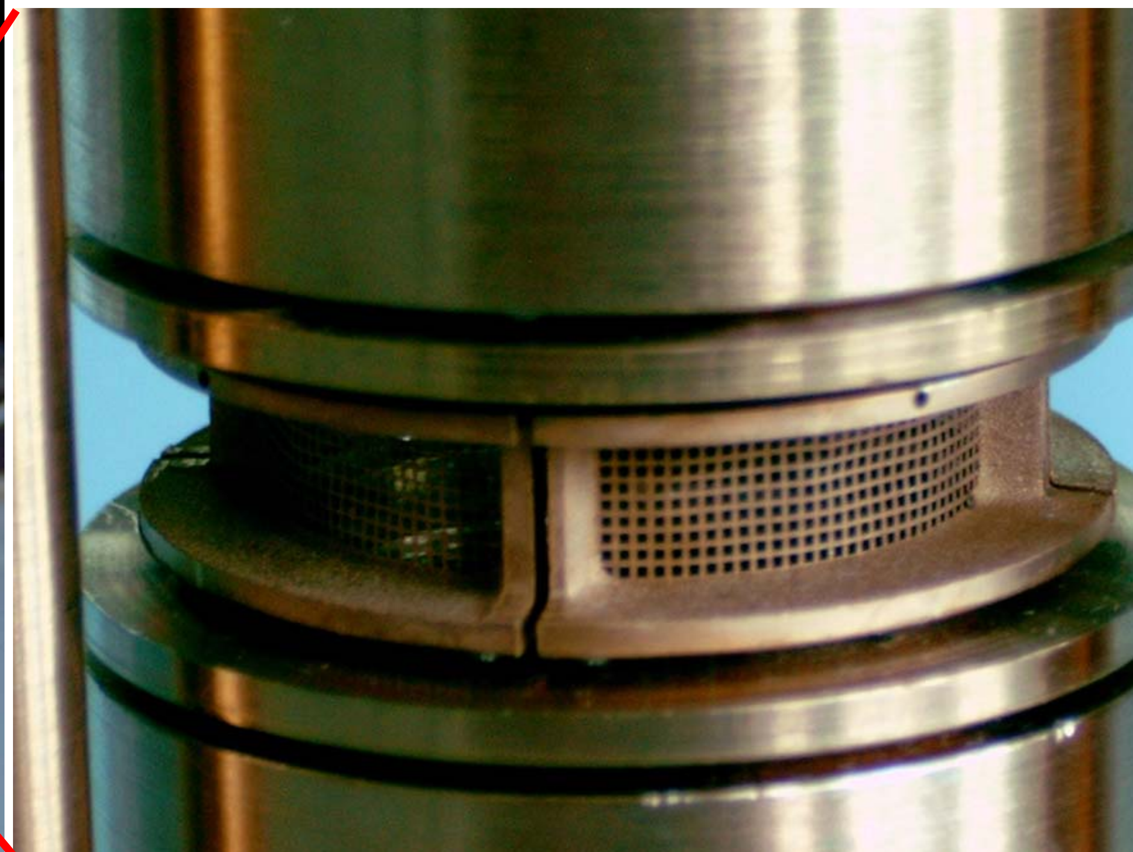


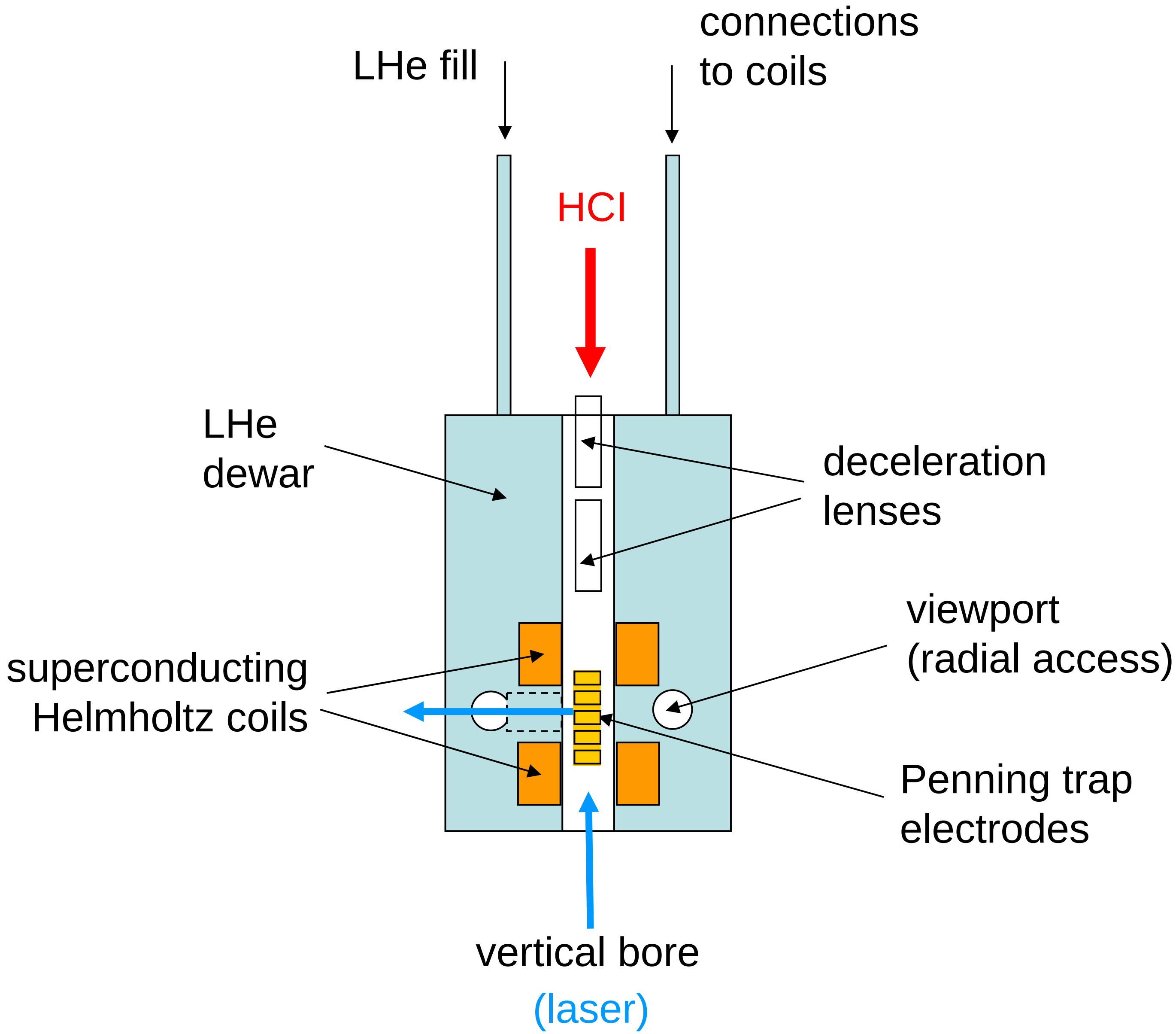
Imperial College London

OFHC trap electrodes



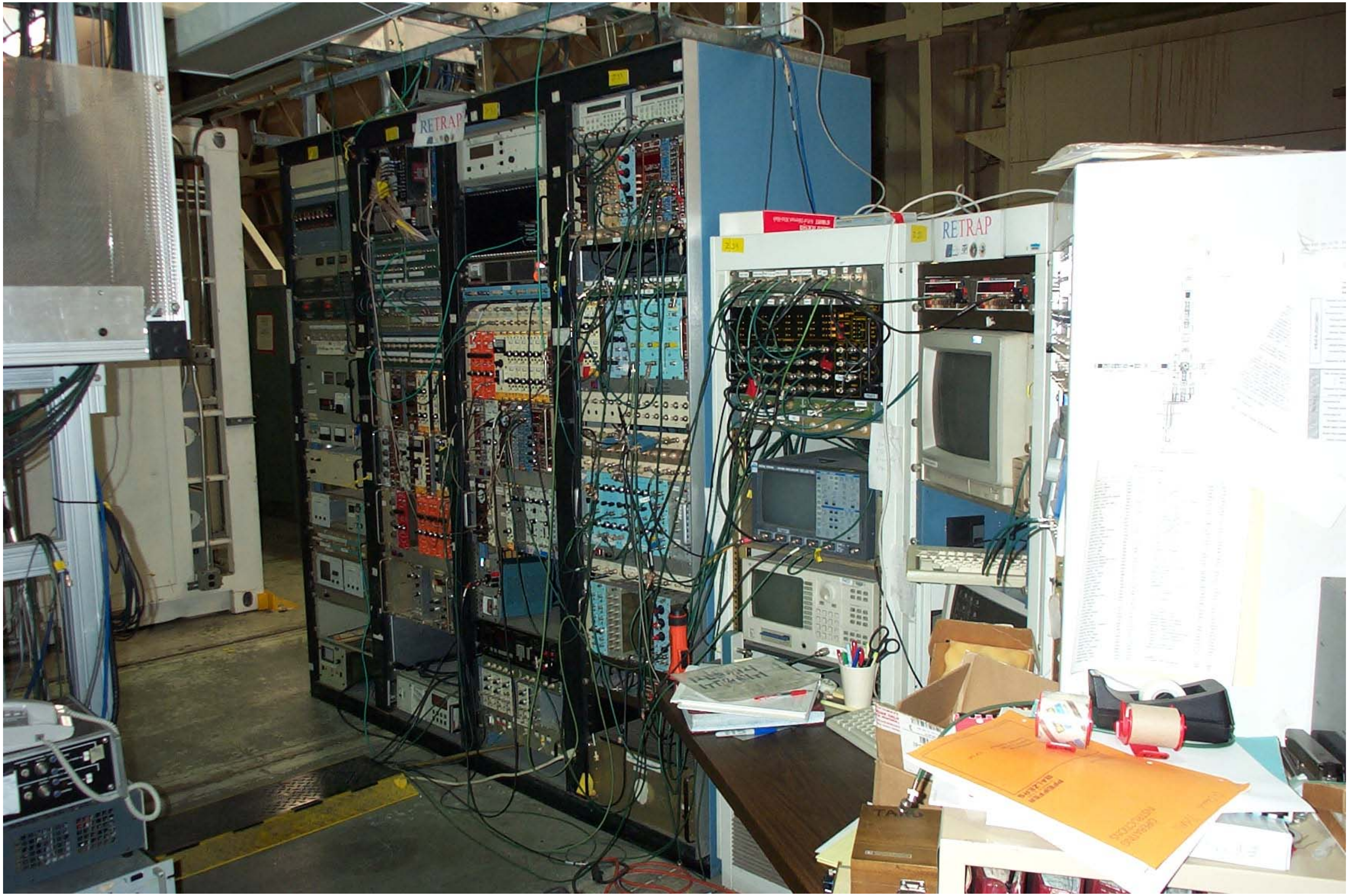
after gold plating it always looks better



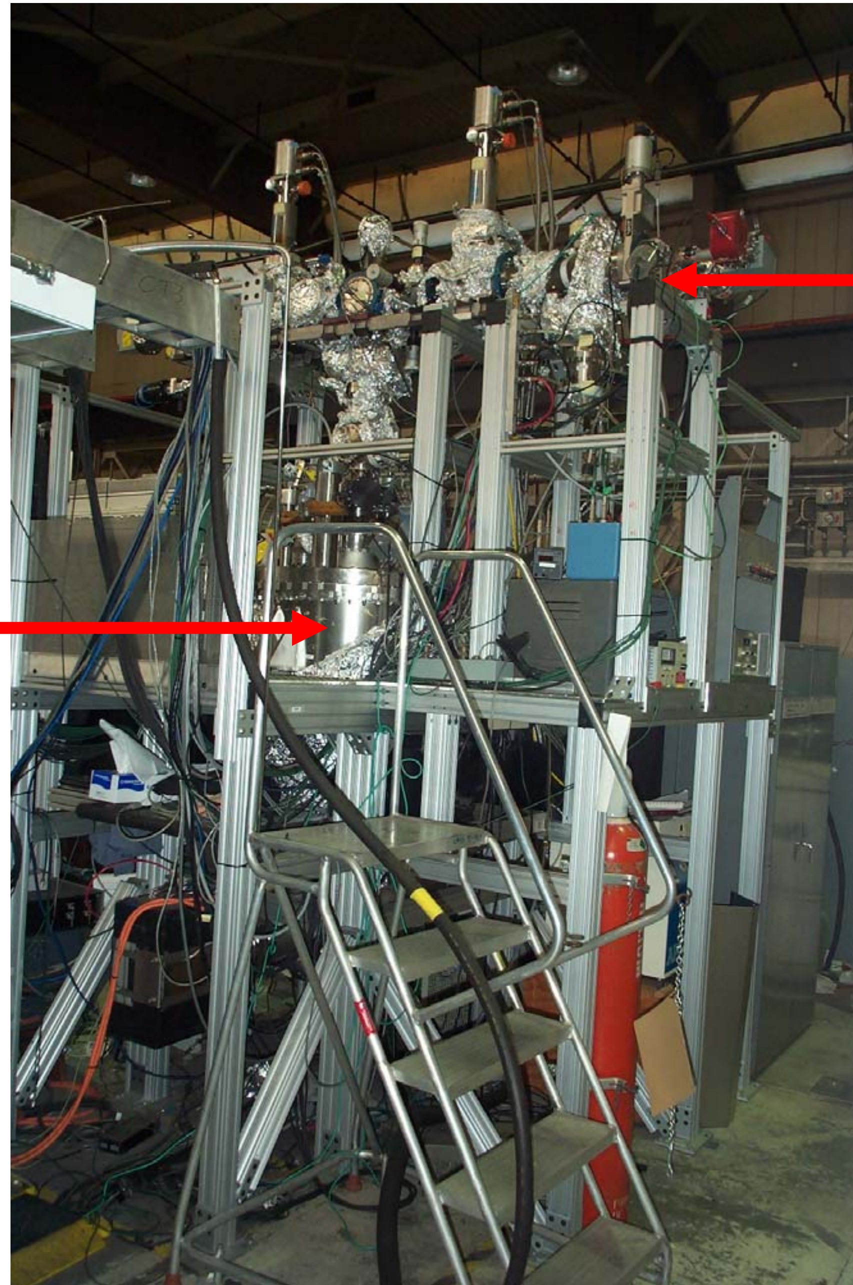

LHe fill
connections
to coils
HCI
LHe
dewar
deceleration
lenses
viewport
(radial access)
superconducting
Helmholtz coils
Penning trap
electrodes
vertical bore
(laser)

RETRAP in Berkeley Lab (USA)

electronic racks



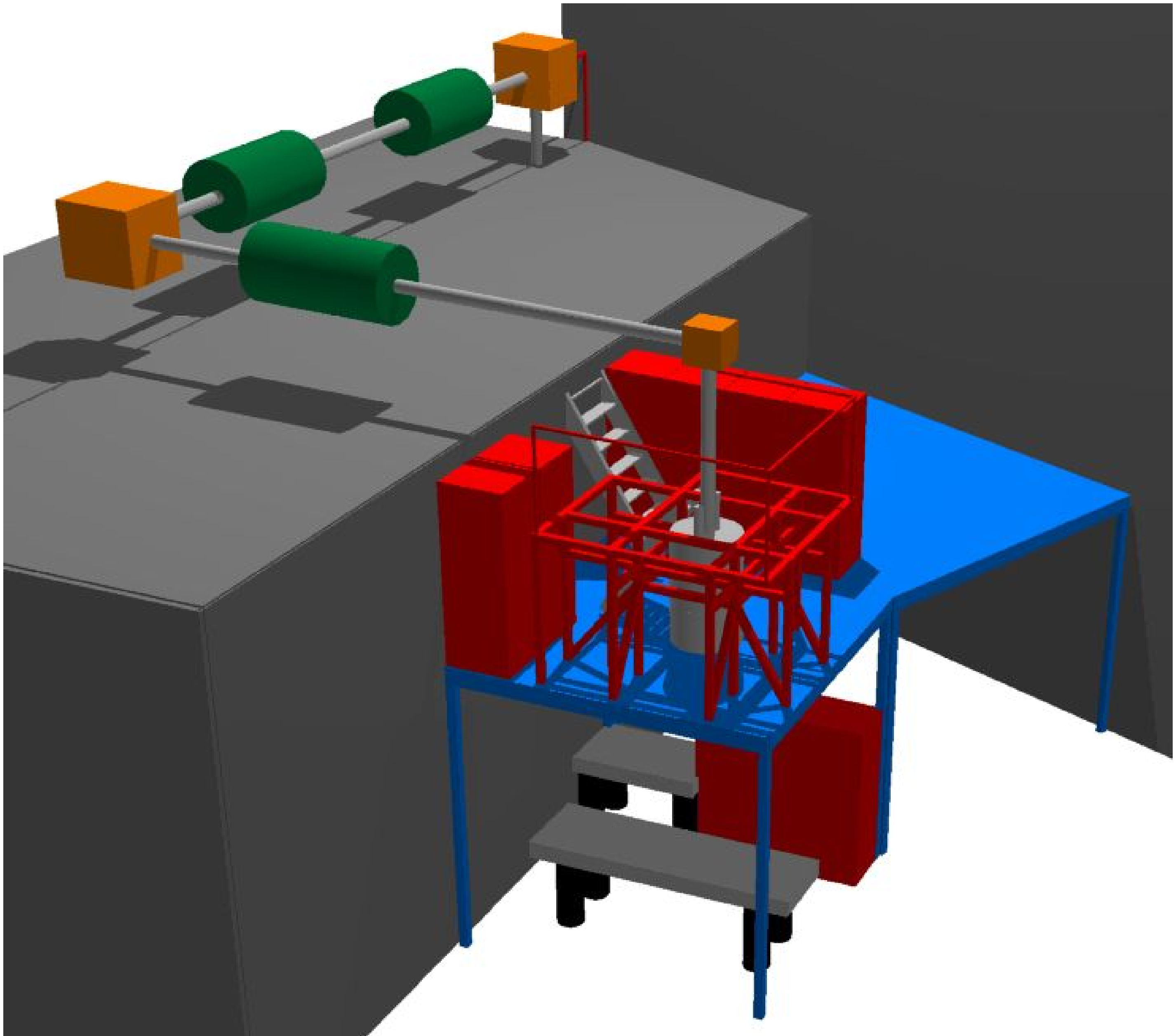
RETRAP magnet and beamline



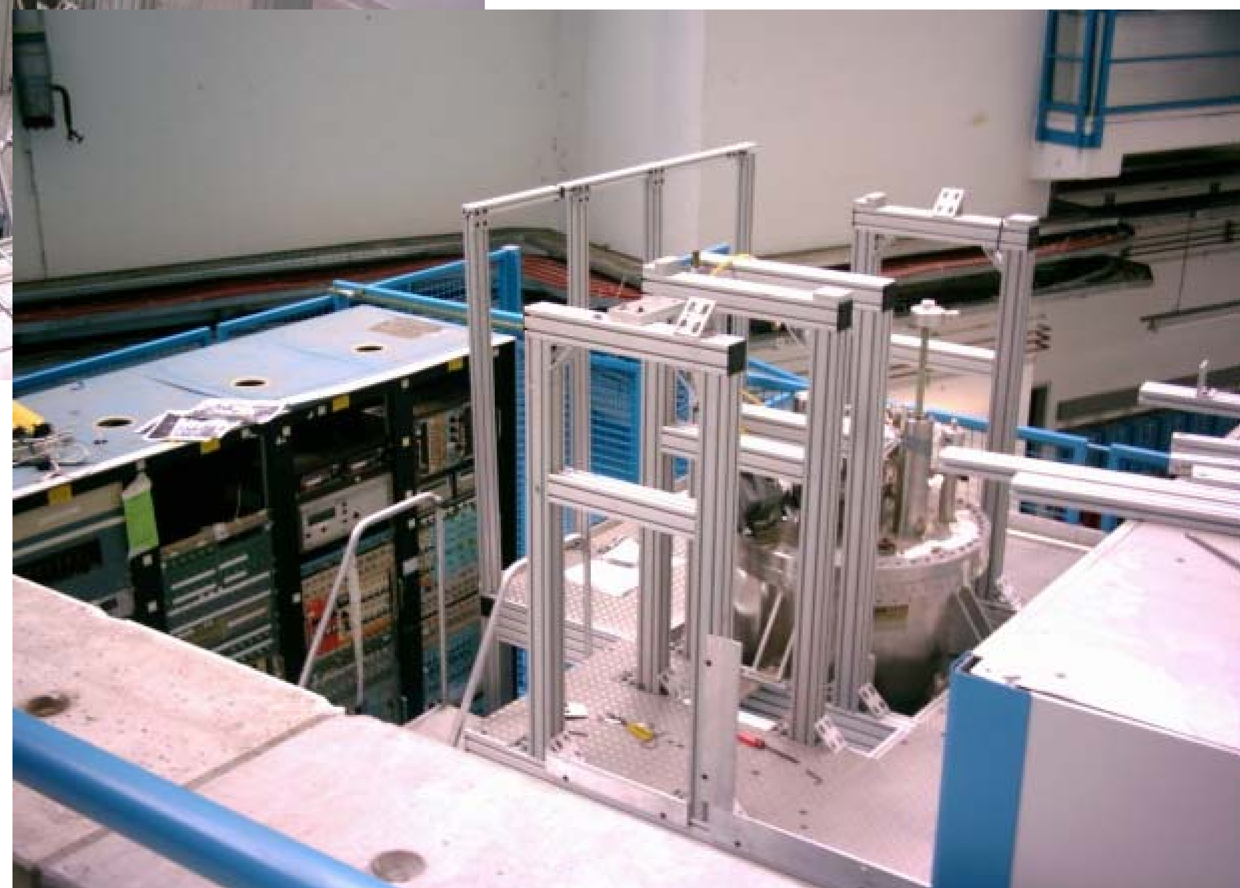
Beamline

Superconducting
Magnet

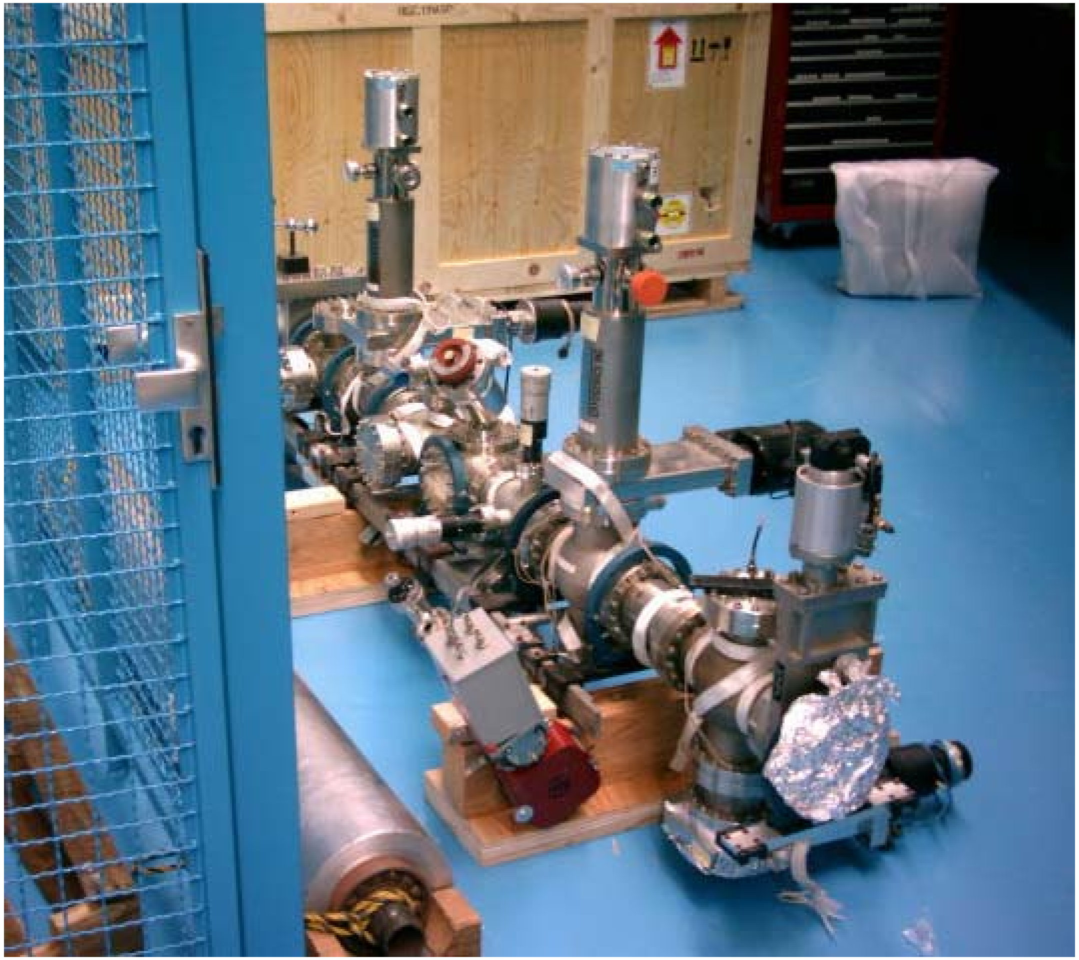
RETRAP @ HITRAP – Step 4



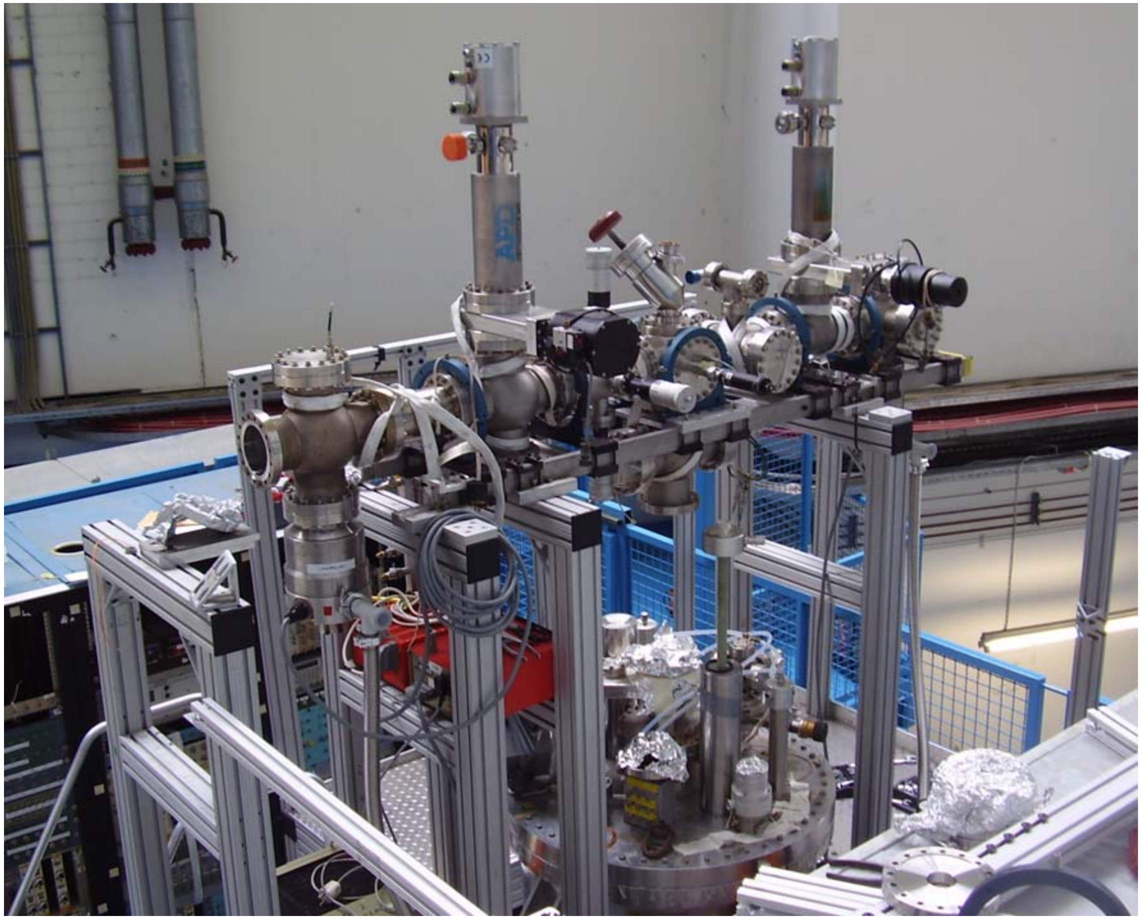
August 2007



August 2007



August / September 2007



Stairs to platform
(September 2007)

HITRAP "Wanne" (December 2007)

(higher) cage surrounding SPECTRAP (December 2007)

"Podestfläche" - access for cryogen dewars (December 2007)

stairs to HITRAP facility (December 2007)

another view on the new cage (December 2007)

Timeline for experiments

time

2008: installation and tests at the HITRAP facilty

$^{207}Pb^{+}$, $^{2}P_{1/2}$ → $^{2}P_{3/2}$ (I=1/2, λ~710 nm) → magnetic moment

2009: measurements of ground state HFS in

$^{209}Bi^{80+}$ (~1555 nm) → 635 nm @ 400 MeV/u in the ESR

2010: measurements of ground state HFS in

$^{207}Pb^{81+}$ (~1020 nm), and in

$^{209}Bi^{82+}$ (~244 nm) and $^{209}Bi^{80+}$ (~1555 nm) → QED test (% level)

Thank you!

EXTRA SLIDES

Next steps:

still in December 2007

see if the helium dewar is still intact → vacuum test

- -

fix the broken welds (LHe heat shield + LN2 turret)

insert (new) trap

re-assemble the magnet system March 2008?

test the vacuum of the system

first tests with LN2

tests with LHe and charging of the magnet

Laser systems which could be used:

- Ar^+ pumped dye laser, tunable 200 - 700 nm
- Ti:Sapphire laser, tunable 700 - 990 nm

asked for in BMMF proposal (Gerhard Birkle, TUD)

- New Focus TLB 6326, tunable 1470 - 1545 nm
- Coherent Verdi pumplaser (18W)
- Upgrade and frequency stabilisation Coherent 899
- Technoscan frequencydoubler
- Optics...

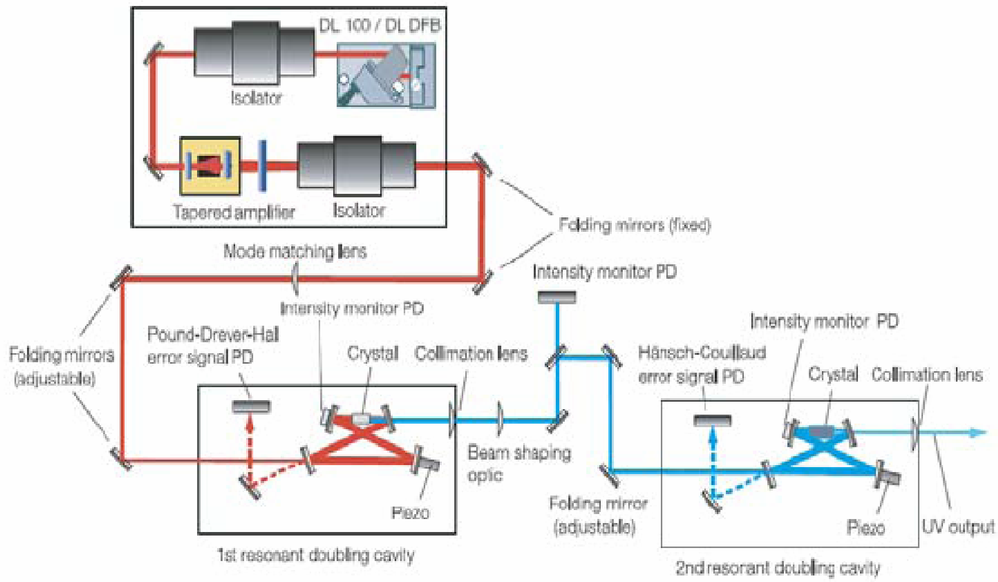
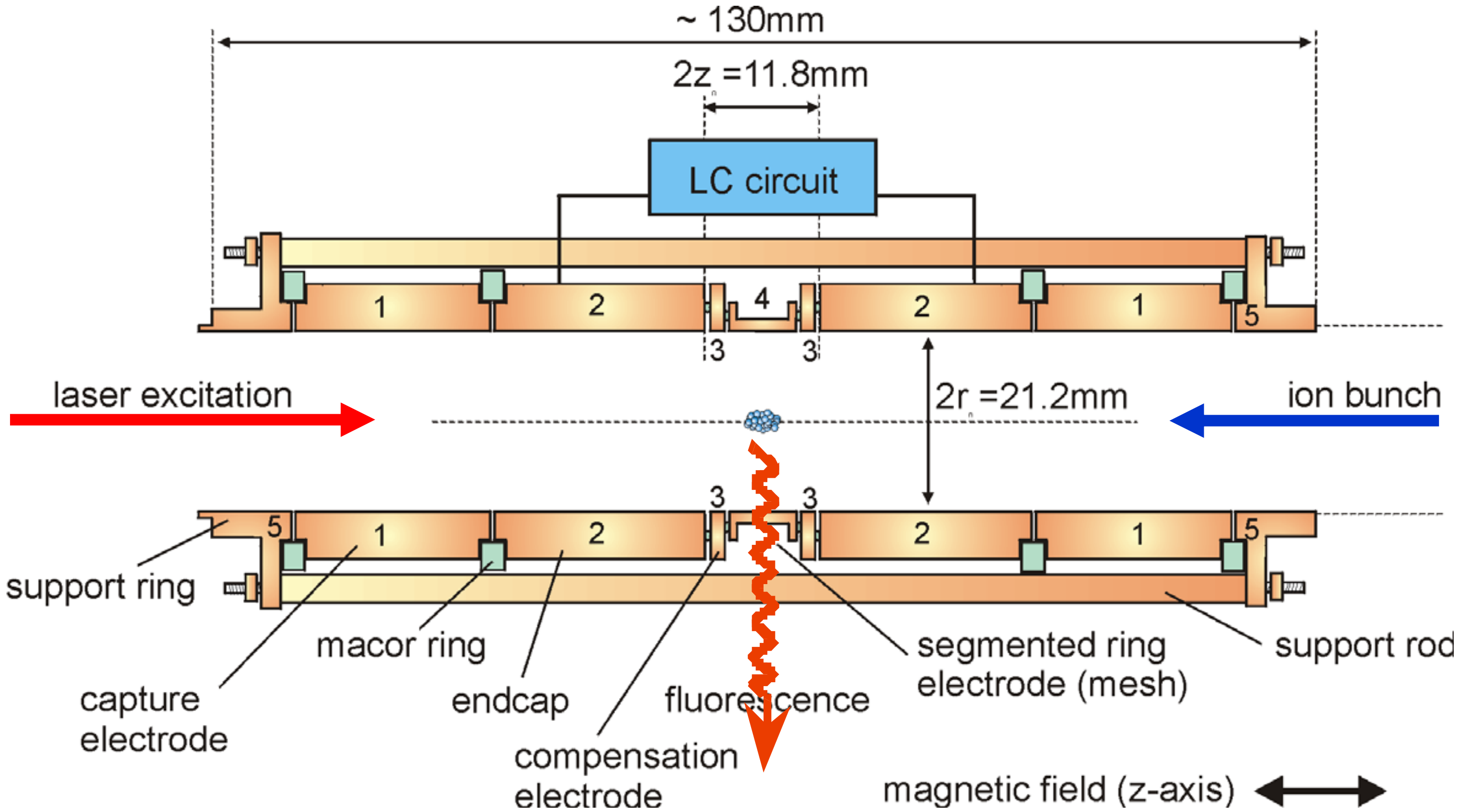


Abb. 5: Schema des Lasersystems zur Erzeugung von UV-Licht bei 243,9 nm. Das Ausgangslicht eines MOPA-Systems wird durch zweifache Frequenzverdopplung in UV-Licht konvertiert (Abb. basierend auf Angaben der Firma TOPTICA).

Der Hersteller spezifiziert eine Laserleistung von 15 mW im UV-Wellenlängenbereich von 241 nm bis 245 nm. Diese Ausgangsleistung ist mehr als ausreichend um die Spektroskopie an gefangenen $^{209}Bi^{+28}$ Ionen effizient durchführen zu können. Für die Spezifikation des modensprungfreien Durchstimmbereiches des Lasersystems im UV gibt der Hersteller 25 GHz an. Die Linienbreite des UV-Lichtes wird mit < 4 MHz über 5 Mikrosekunden vom Hersteller angegeben.

Neben dem UV-Licht verlässt auch ein Teilstrahl des infraroten Laserlichts (976nm) das Lasersystem. Dieser kann zur Frequenzdiagnose und zur Frequenzstabilisierung genutzt werden. Außerdem hat das Lasersystem alle elektronischen Steuereingänge, die nötig sind um sowohl die Frequenz des Laserlichtes zu stabilisieren, durchzustimmen, als auch die Laserleistung zu stabilisieren.

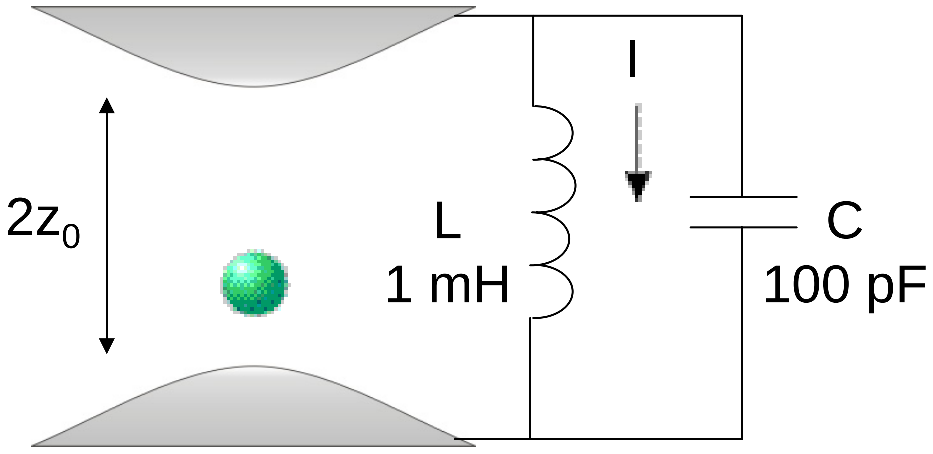
Cylindrical open-endcap Penning trap

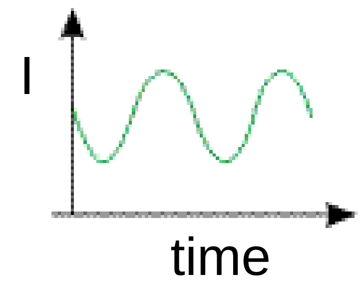


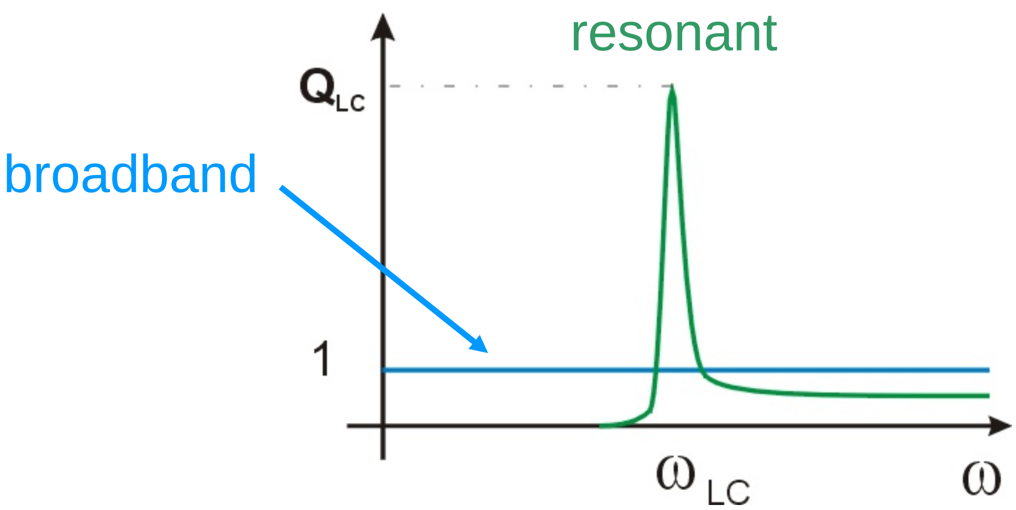
Technical specifications:

- Superconducting magnet → magnetic field ~1 T (ΔB~10^{-3} T)
- Resistive cooling → temperature ~10 K (cooling time ~20 s)
- Rotating wall technique → ion cloud d~3 mm, 10^5 ions (freq. ~1 MHz)
- Expected fluorescence ~4x10^3 counts/sec (background ~10^2 counts/sec)

Resistive cooling (electronic detection)







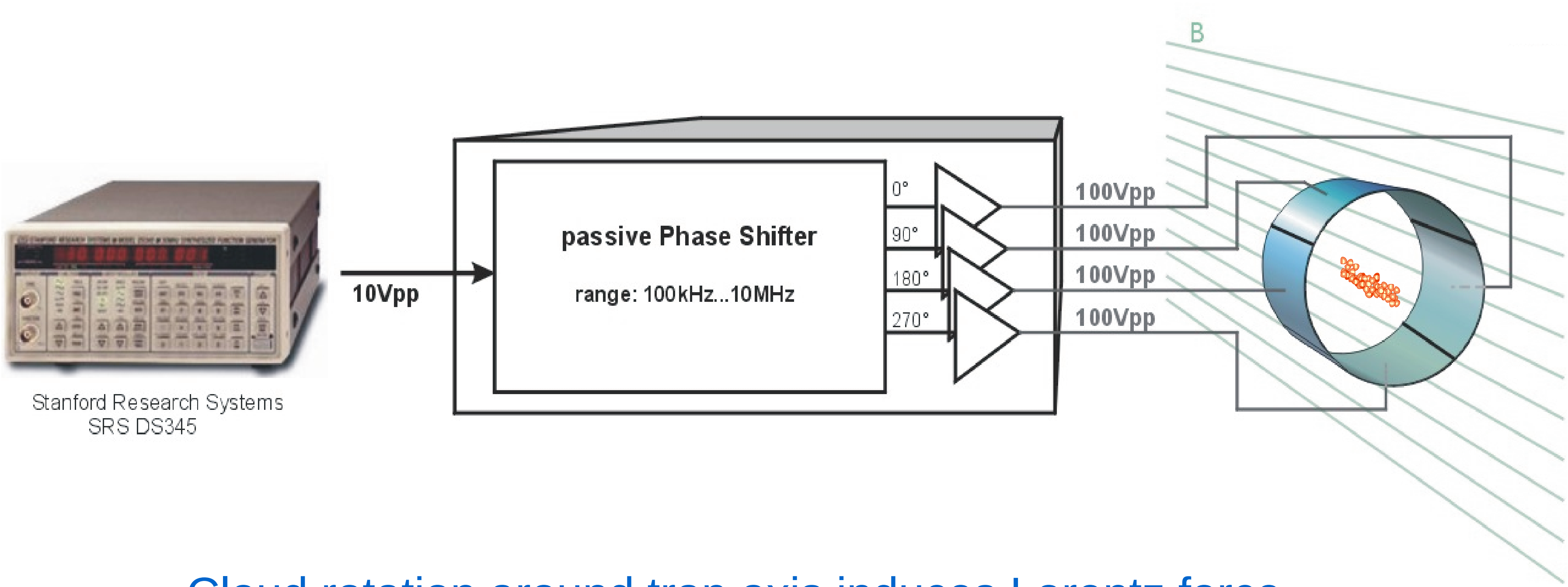
$$\omega_{LC} = \frac{1}{\sqrt{LC}} \sim \text{MHz}$$

$$Q = \frac{\omega_{LC}}{\Delta\omega} \sim 500$$

$$\tau = \frac{m(2z_0)^2}{Q L \omega_z q^2}$$

R

Rotating wall technique

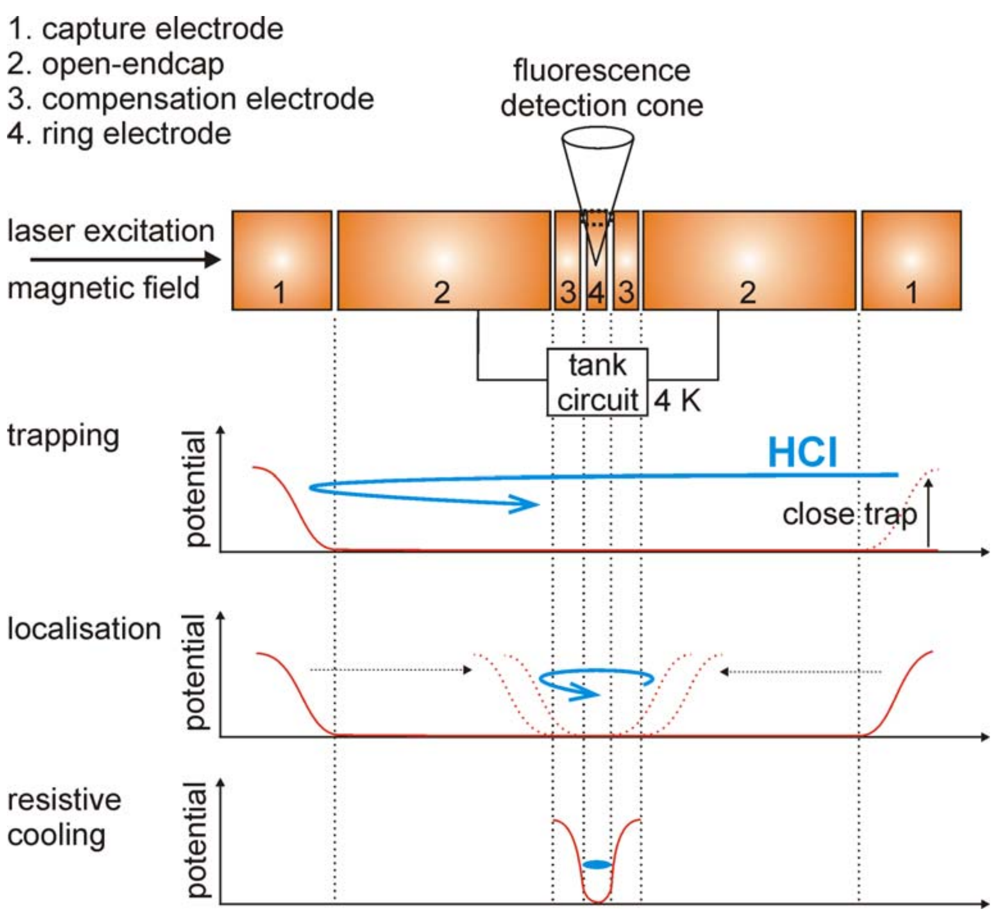


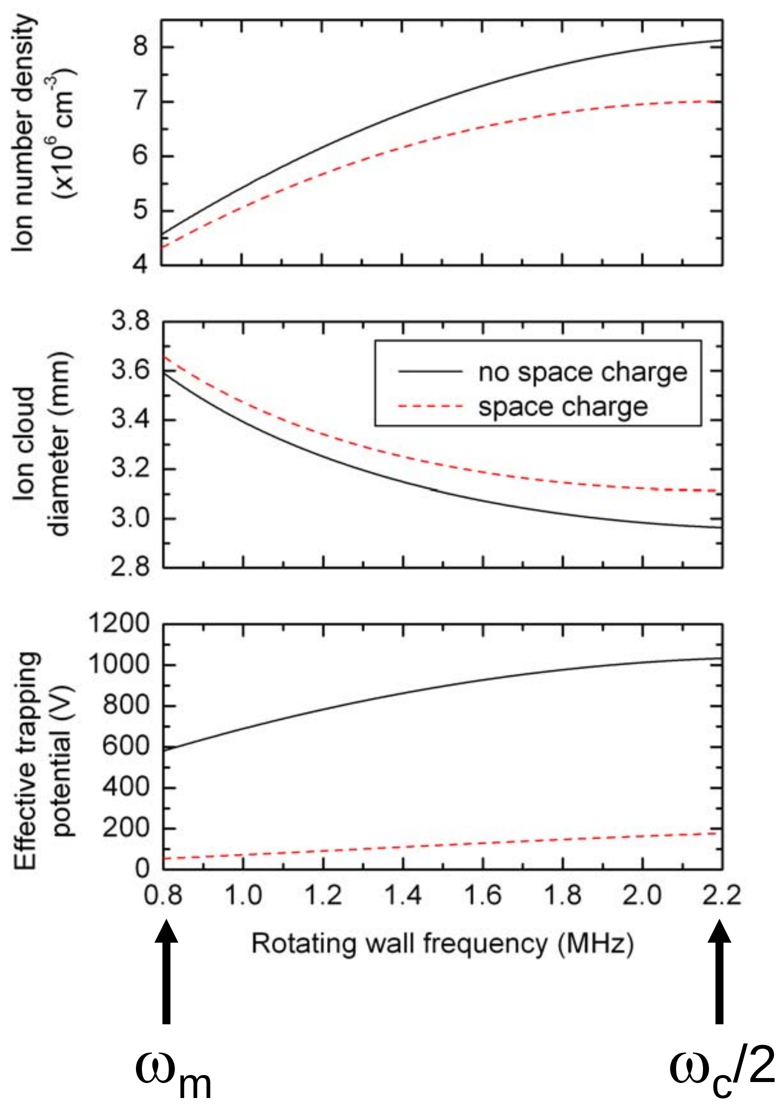
Cloud rotation around trap axis induces Lorentz force which compresses the cloud radially

$$\text{torque} \sim \frac{A}{\Delta\omega \sqrt{T}} \qquad \text{density} \sim \frac{m\,\omega(\omega_c - \omega)}{q^2}$$

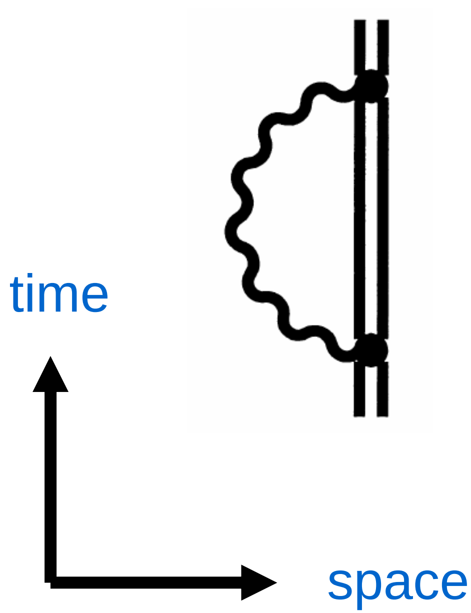
rotating wall frequency ramp: $\omega_m \rightarrow \omega_c/2$

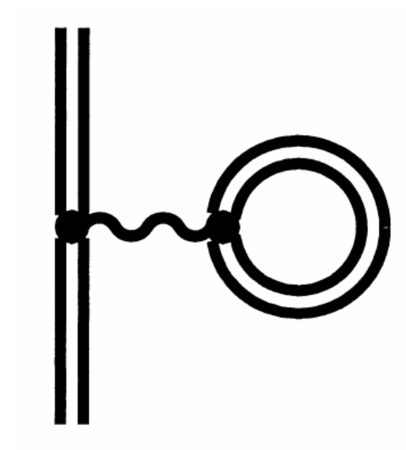
Loading, cooling and compressing the ion cloud





Feynman diagrams of QED effects

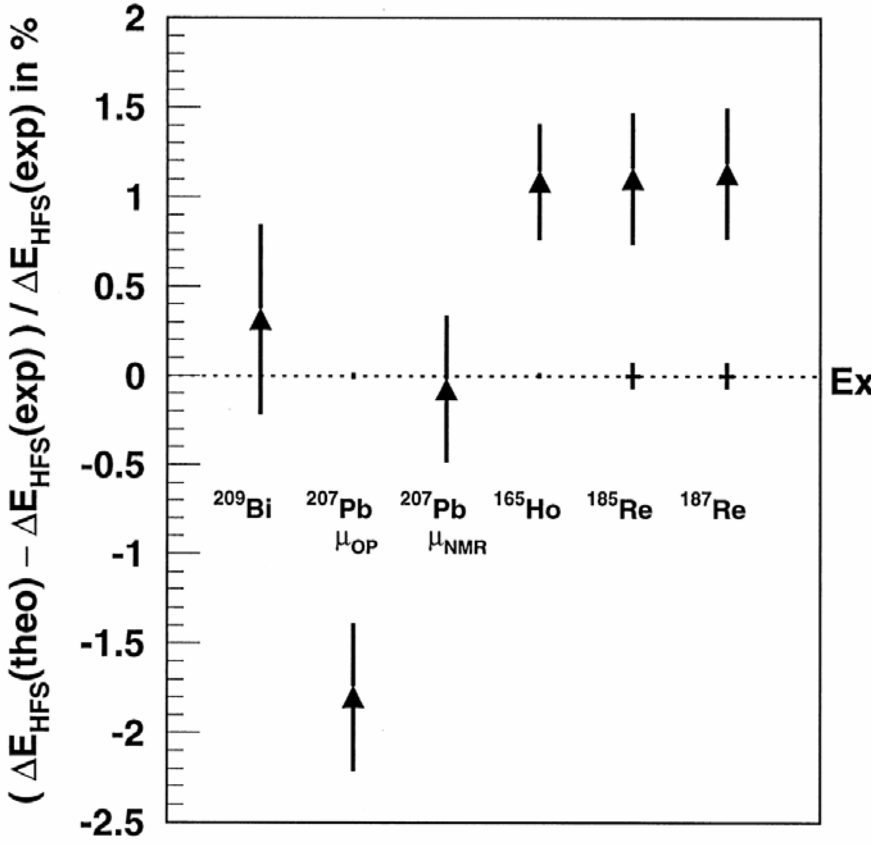


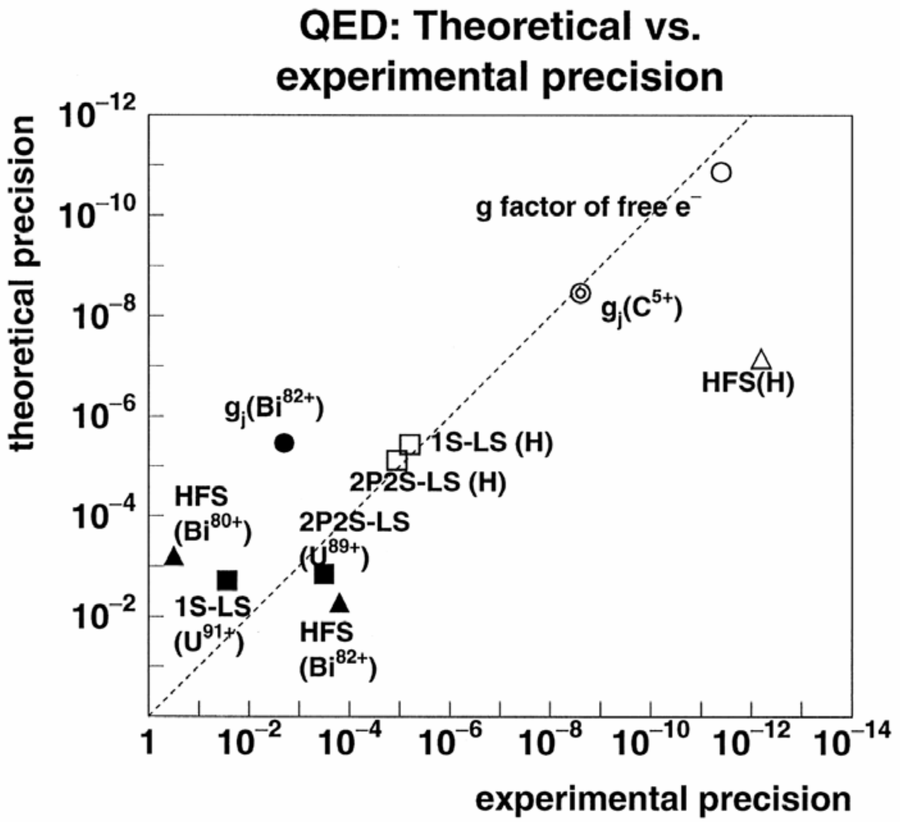


"Self energy" is the emission and reabsorption of a virtual photon by an electron

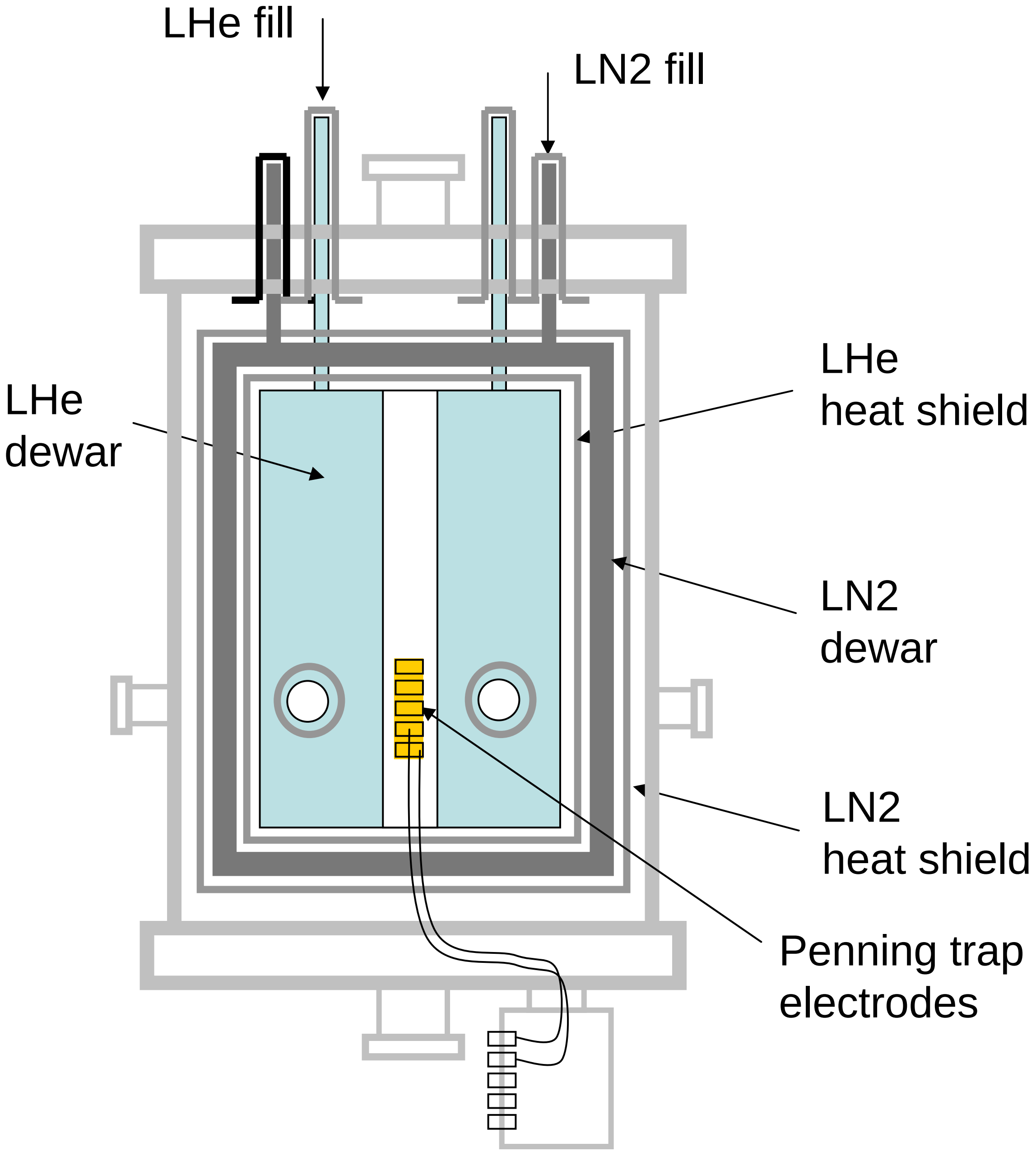
"Vacuum polarisation" is the creation and reannihilation of a virtual electron-positron pair by a photon

Theory versus Experiment

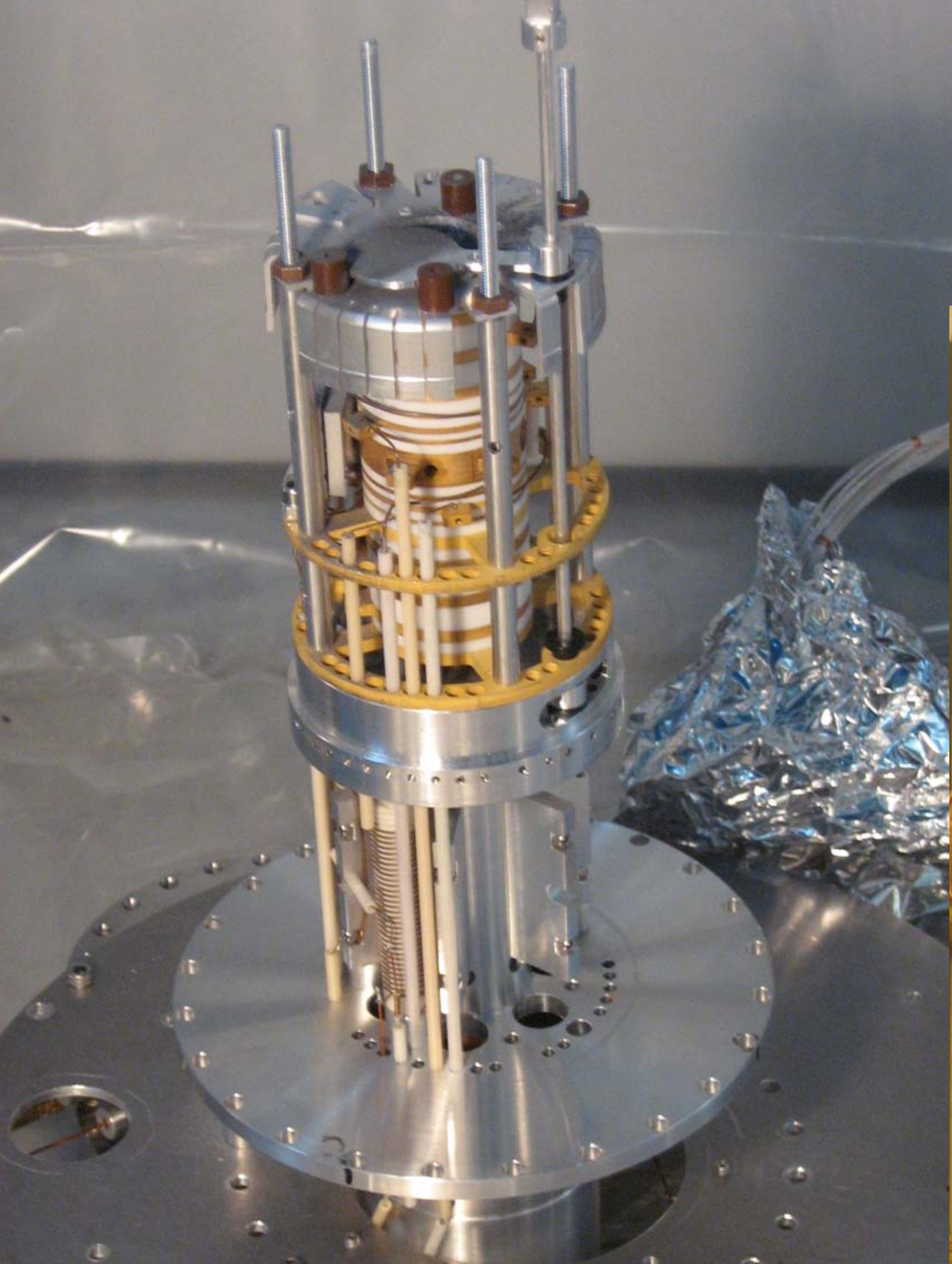


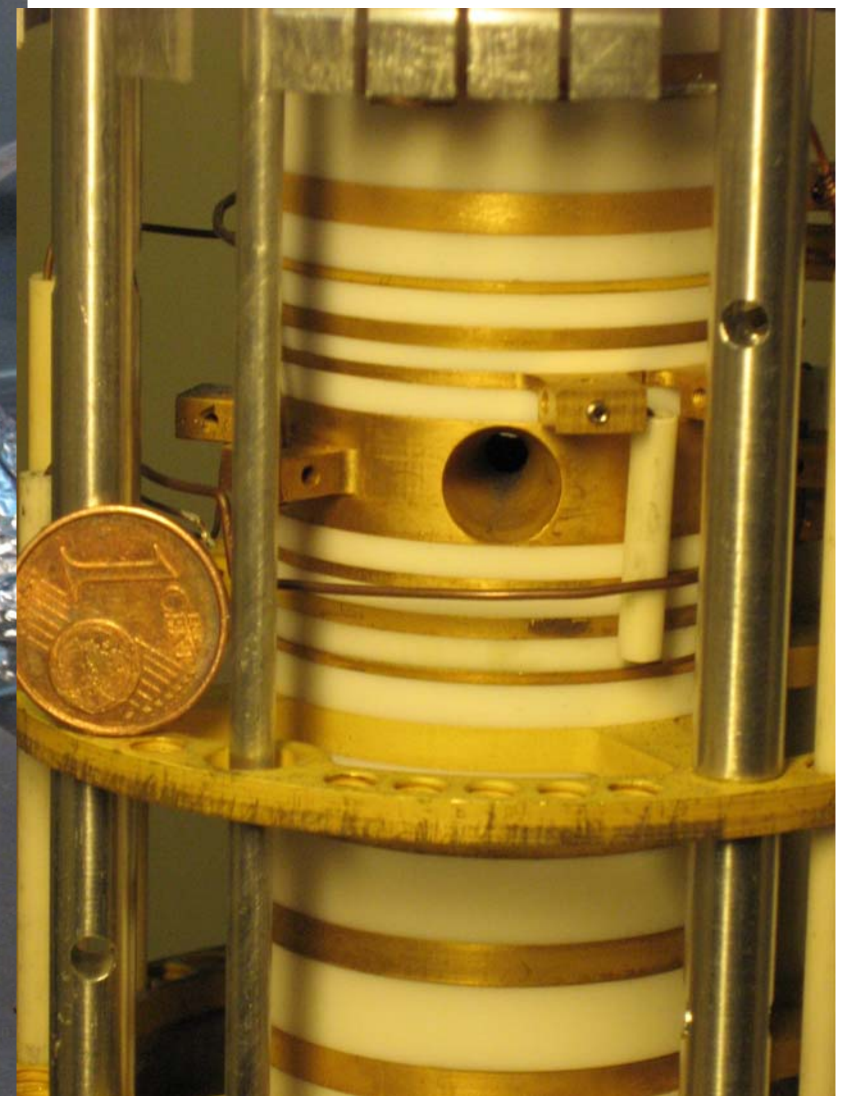


T. Beier, Phys. Rep. **339,** 79 (2000).

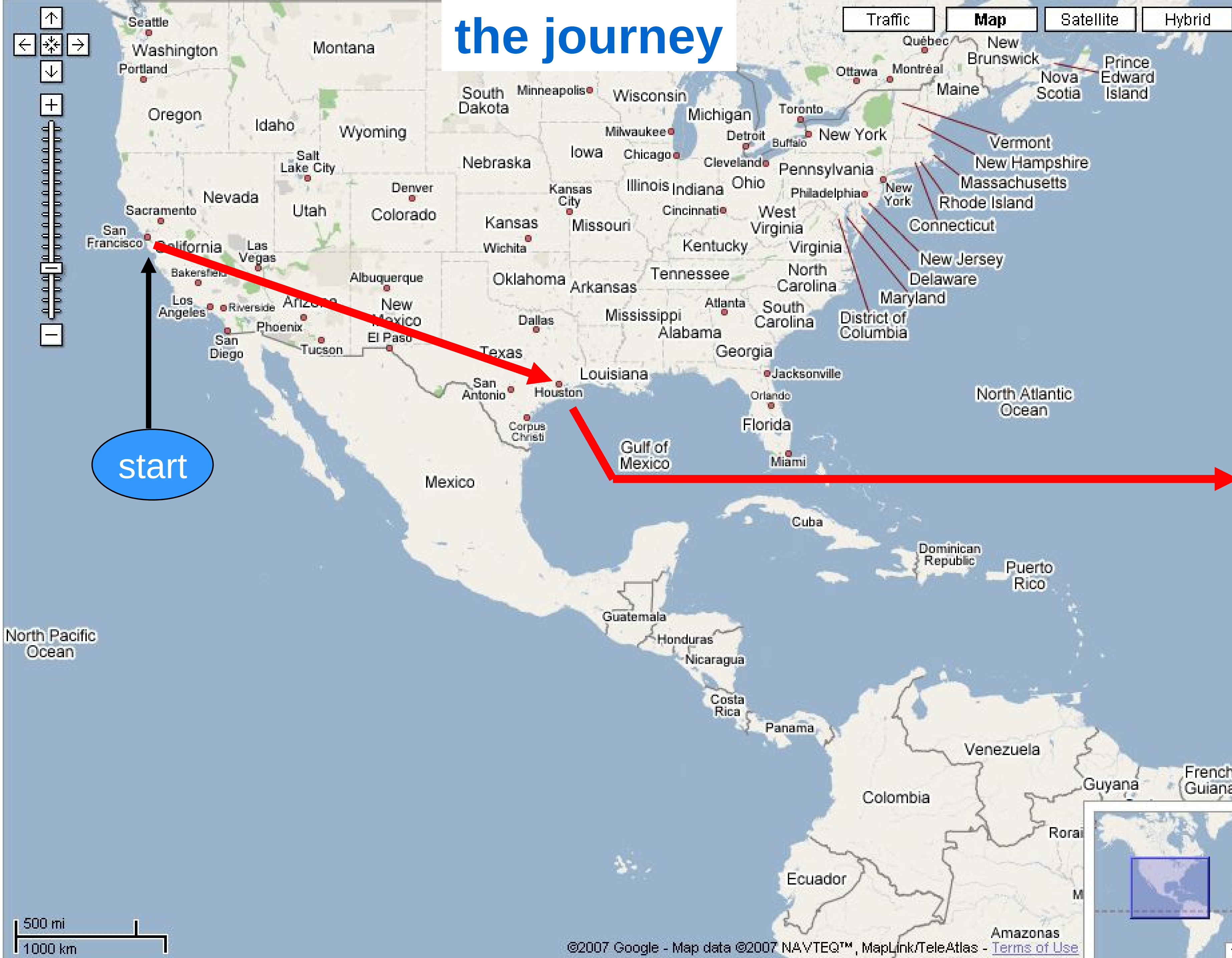

LHe fill
LN2 fill
LHe dewar
LHe heat shield
LN2 dewar
LN2 heat shield
Penning trap electrodes

The famous RETRAP...
(electrode structure)





the journey



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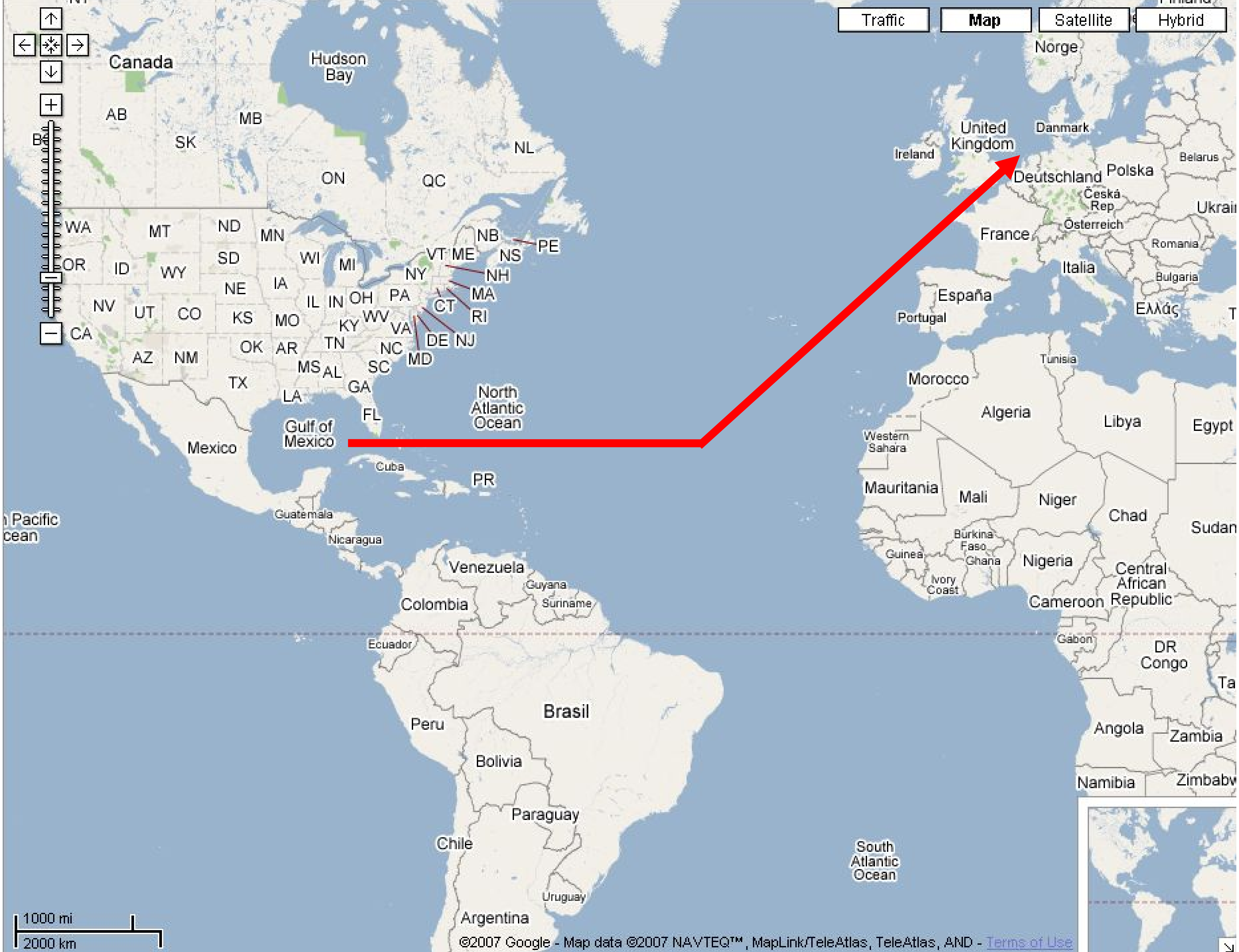
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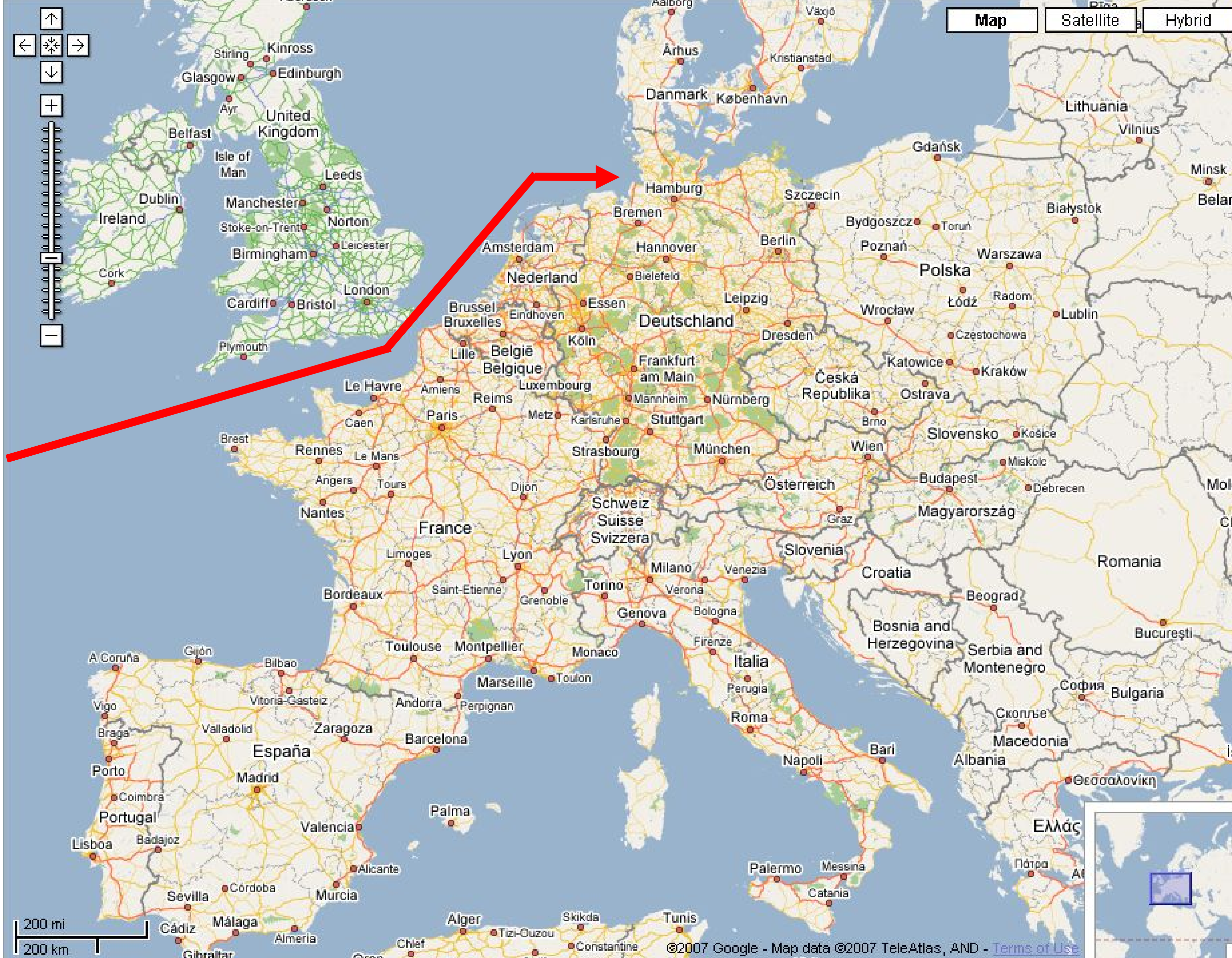
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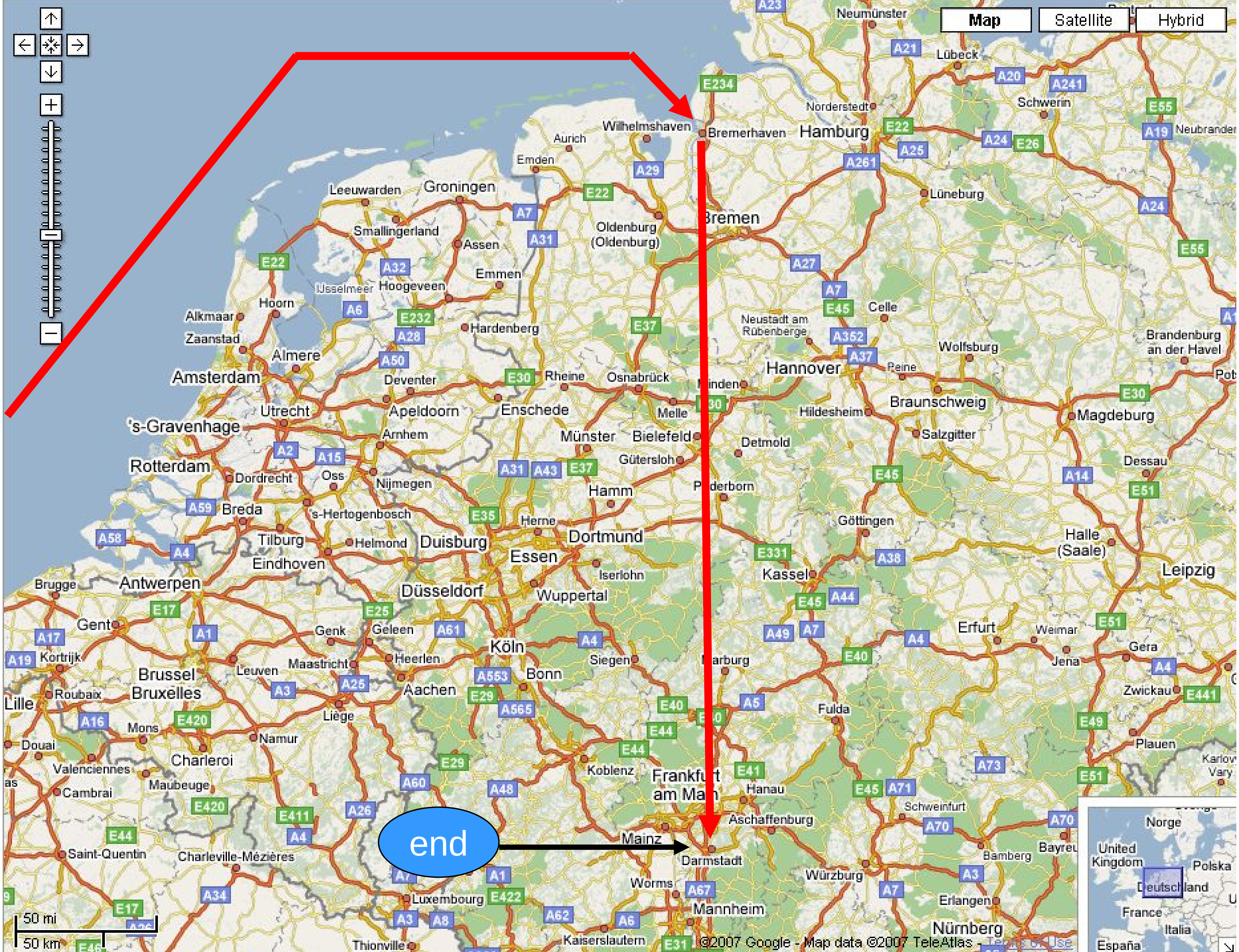
Map
Satellite
Hybrid
Neumünster
Lübeck
Schwerin
Norderstedt
Hamburg
Wilhelmshaven
Bremerhaven
Aurich
Emden
Lüneburg
Leeuwarden
Groningen
Bremen
Smallingerland
Assen
Oldenburg (Oldenburg)
IJsselmeer
Hoogeveen
Emmen
Celle
Hoorn
Alkmaar
Zaanstad
Hardenberg
Neustadt am Rübenberge
Wolfsburg
Brandenburg an der Havel
Almere
Amsterdam
Hannover
Peine
Deventer
Rheine
Osnabrück
Minden
Braunschweig
Utrecht
Apeldoorn
Enschede
Melle
Hildesheim
Magdeburg
's-Gravenhage
Arnhem
Münster
Bielefeld
Detmold
Salzgitter
Rotterdam
Dordrecht
Oss
Nijmegen
Gütersloh
Dessau
Hamm
Paderborn
Breda
's-Hertogenbosch
Herne
Göttingen
Tilburg
Helmond
Duisburg
Dortmund
Halle (Saale)
Eindhoven
Essen
Iserlohn
Kassel
Leipzig
Brugge
Antwerpen
Düsseldorf
Wuppertal
Gent
Genk
Geleen
Köln
Erfurt
Weimar
Gera
Kortrijk
Brussel Bruxelles
Leuven
Maastricht
Heerlen
Siegen
Marburg
Jena
Lille
Roubaix
Aachen
Bonn
Zwickau
Liège
Fulda
Mons
Namur
Douai
Charleroi
Plauen
Valenciennes
Koblenz
Frankfurt am Main
Hanau
Cambrai
Maubeuge
Schweinfurt
Aschaffenburg
Mainz
Darmstadt
Bamberg
end
Saint-Quentin
Charleville-Mézières
Worms
Würzburg
Luxembourg
Mannheim
Erlangen
Nürnberg
Kaiserslautern
Thionville
50 mi
50 km
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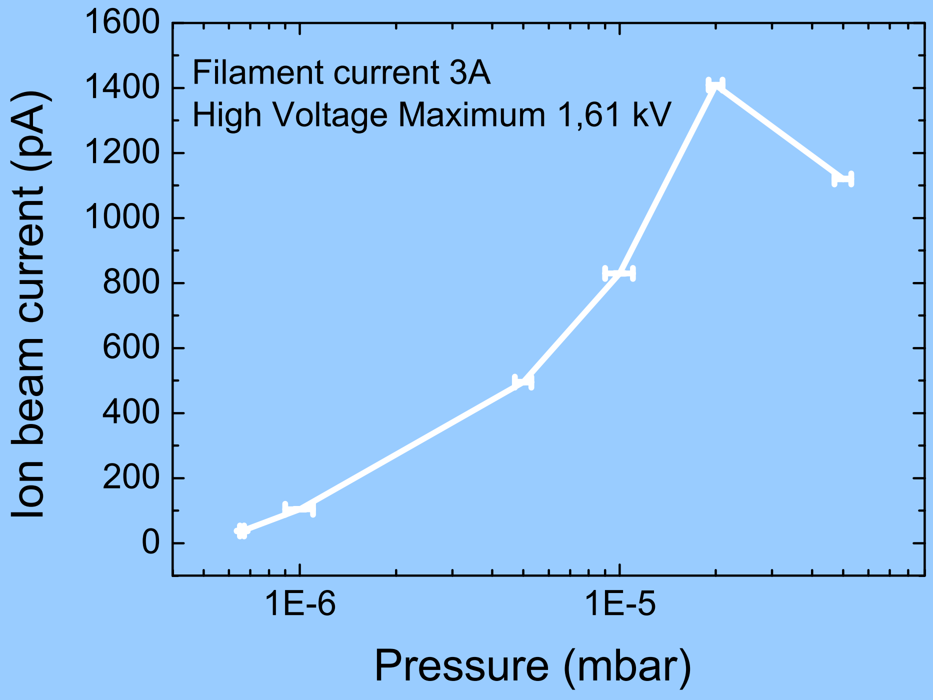
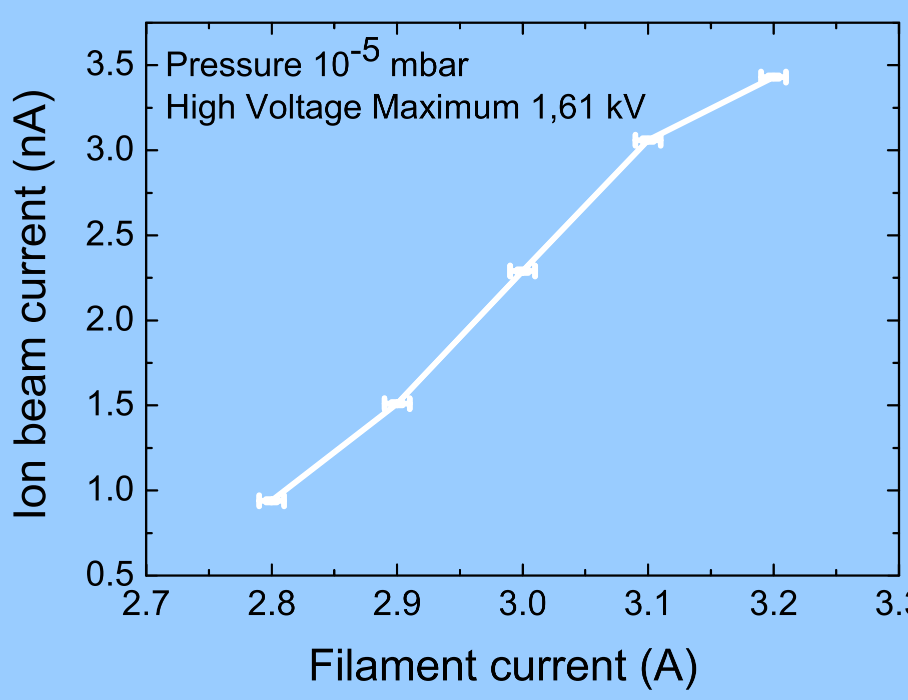
Norge
United Kingdom
Polska
Deutschland
France
Italia
España

Results


Filament current 3A
High Voltage Maximum 1,61 kV
Ion beam current (pA)
Pressure (mbar)
1600
1400
1200
1000
800
600
400
200
0
1E-6
1E-5


Pressure 10^{-5} mbar
High Voltage Maximum 1,61 kV
Ion beam current (nA)
Filament current (A)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2.7
2.8
2.9
3.0
3.1
3.2
3.3