Accelerators: from the source to the target

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FAIR Synchrotrons

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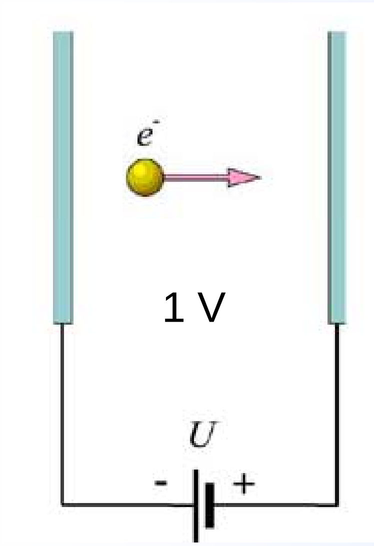
Contents

- Motivation: Why do we build accelerators?
- Some examples from around the world.
- Basic functions
- The GSI Accelerator Complex
- An outlook to the FAIR Project
- Discussion

Part I: Motivation and Overview

Accelerator Energies

Definition electron volt:



1 eV=1.602 10^{-19} J

1 keV= 10^{3} eV
1 MeV= 10^{6} eV
1 GeV= 10^{9} eV
1 TeV= 10^{12} eV

Energies in eV

Lower limit of the mass of the Higgs boson	114 GeV
W, Z exchange bosons of the weak interaction	82/93 GeV
Restmass of antiprotons: $E=mc^2$	0.938 GeV
Excitation energies in nuclei	MeV
Energies of electronic levels in heavy ions	keV
Ionisation energy of The hydrogen atom	13 eV

Accelerated particles

Electrons:

$m_e = 9.1 \times 10^{-31}$ kg
$q = -e$, $e = 1.6 \times 10^{-19}$ C

Pro:
- Elementary particles
- Simple generation

Cons:
- Synchrotron radiation

Protons:

$m_p = 1836 m_e$, $q = e$

Pro:
- Synchrotron radiation
- Generation

Cons:
- Not a elementary particle

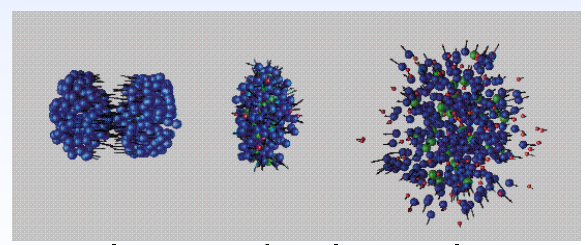
Heavy Ions:

$m = A m_p$, $q = Ze$,
Example: $^{238}U^{92+}$

Pro:
- Synchrotron radiation
- <u>High nucleon density</u>
- Energy deposition

Cons:
- Generation
- Lifetime

Not only the energy counts:



Example "Quark-Gluon Plasma"

Accelerated particles

Electrons:

$m_e = 9.1 \times 10^{-31}$ kg
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Pro:
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- Simple generation

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$m = A m_p, \quad q = Ze,$
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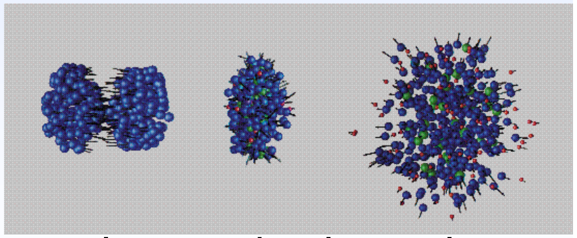
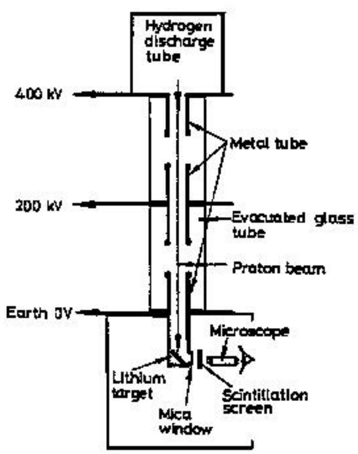
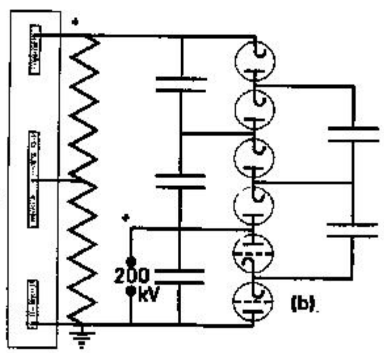


Example “Quark-Gluon Plasma”

Accelerators in History

Cockcroft-Walton:
Electrostatic accelerator
(400 kV)





DC Generator

Energy (p)

2005: CERN/LHC	7 TeV
1987: FermiLab/Tevatron	1 TeV
1981: CERN/SPS	400 GeV
1971: CERN/ISR	60 GeV
1962: BNL/AGS	15 GeV
1932: Cockcroft und Walton (Nobel price 1951)	400 keV

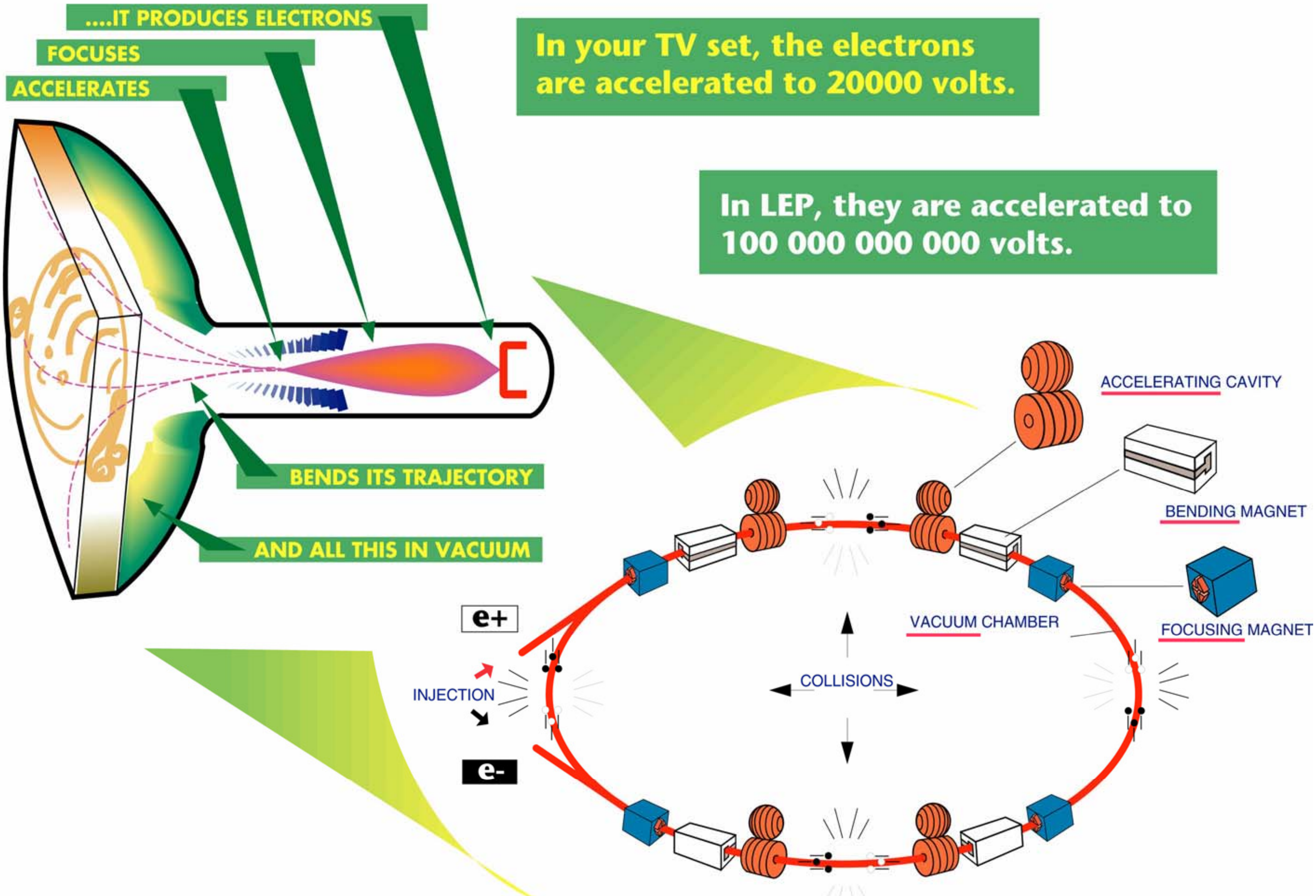
Typical Accelerator Types

- electrostatic
  - van de Graff, Tandem: to about 10 MeV; for nuclear physics and isotope production

  cascade
  - Cockcroft-Walton: to several MeV; X-ray sources and injectors

  Linear
  - RFQ   radio frequency quadrupole
  - drift-tube(Wideroe, Alvarez): preaccelerators
  - Waveguide: electrons only(SLAC, NLC)

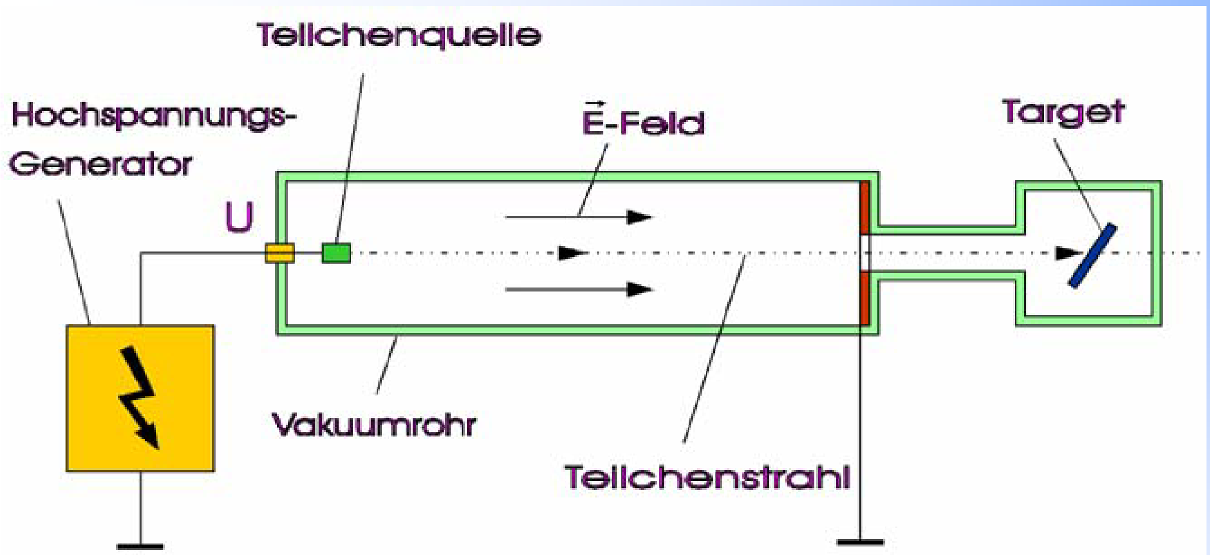
DID YOU KNOW Y0UR TELEVISION SET IS AN ACCELERATOR ?

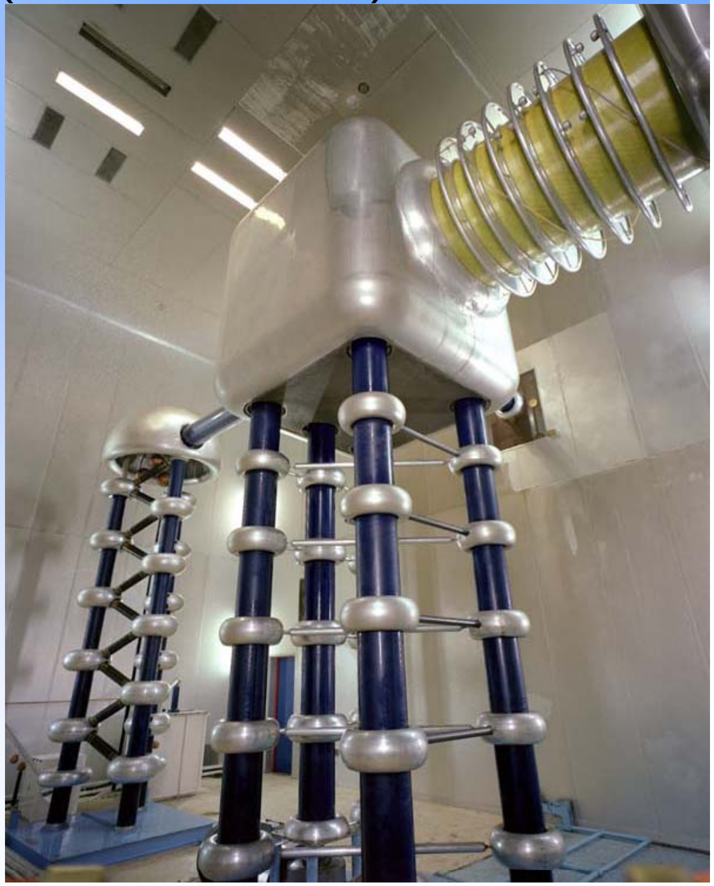


CERN AC - Z34 va - V13/3/98

Electrostatic Accelerators

700 kV Cockcroft-Walton (FNAL)
(0.7 MeV Protons)

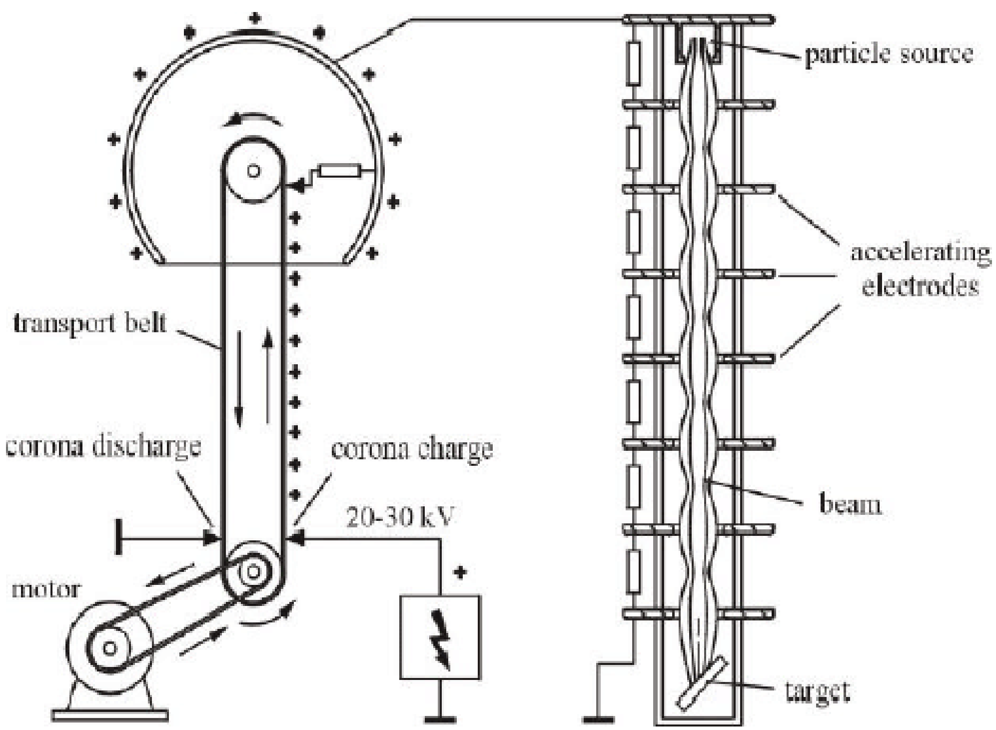




Limited to < 10 MeV !

Electrostatic Van de Graaff Accelerator

5 MV Van de Graaff at Hahn-Meitner, Berlin



Electrostatic Van de Graaff Accelerator

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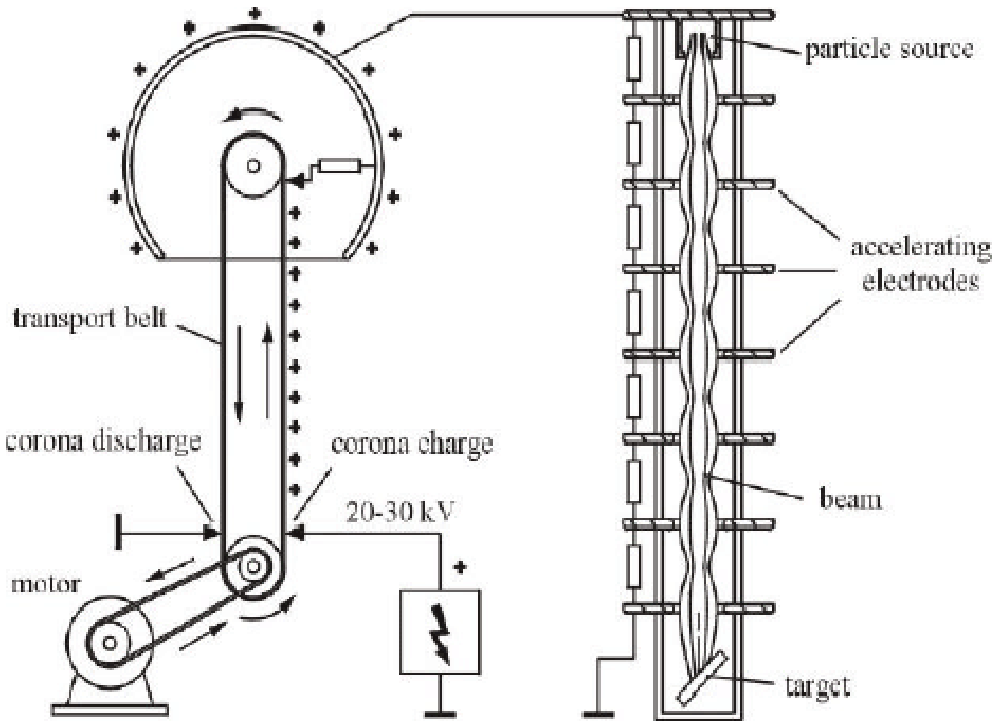
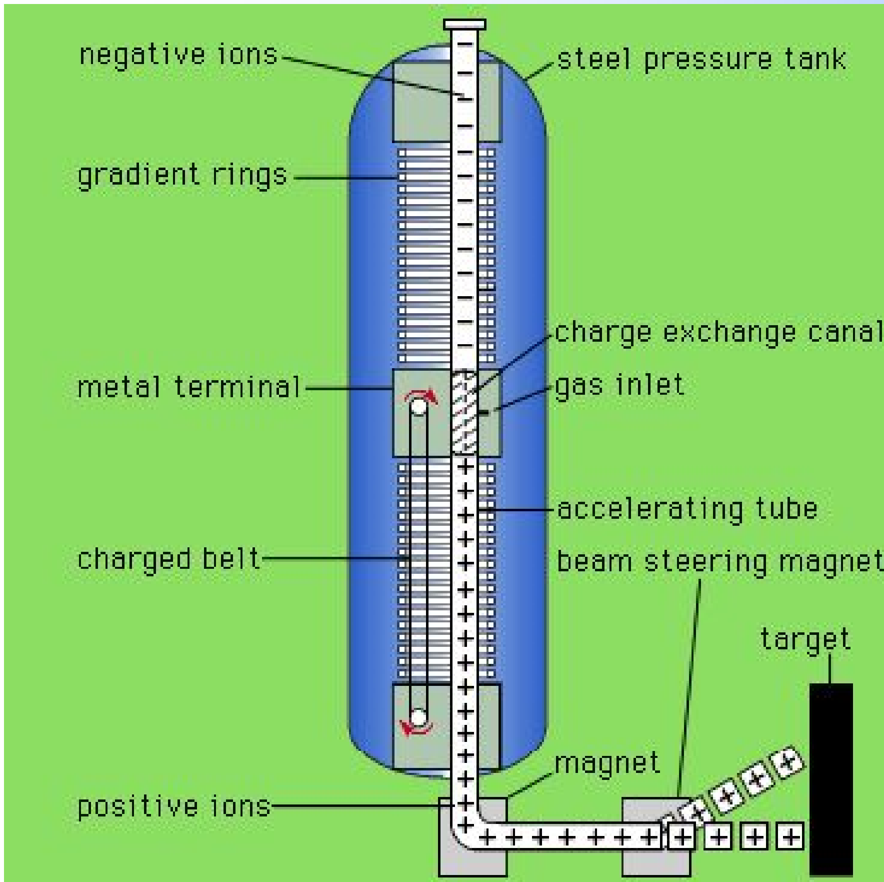


Tandem Accelerator

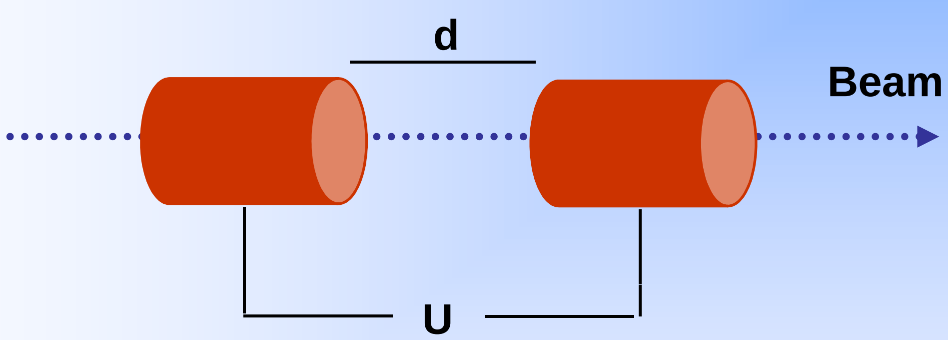


Tandem Accelerator in Munich

Electrostatic potential is used twice due to charge exchange in the foil.

AC / DC electric field strengths

Field = Voltage/Distance = U/d



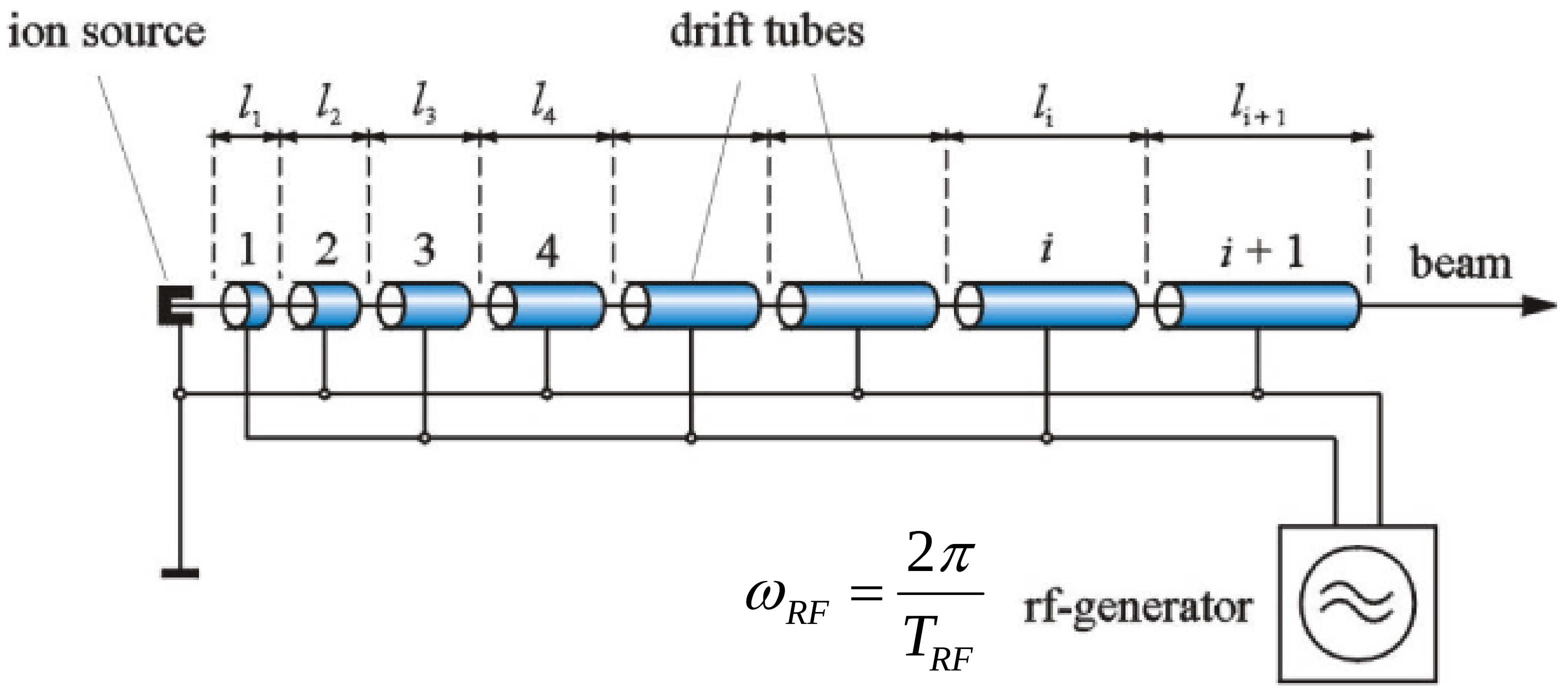
Maximum dc – field strength : 5 MV/m

Maximum 30 GHz- field strength : 150 MV/m

acceleration in ac-field is much more efficient

BUT -> acceleration of dc–beams in ac–fields does not work! Why?!

Linear RF Accelerators: Wideröe (Aachen 1928)

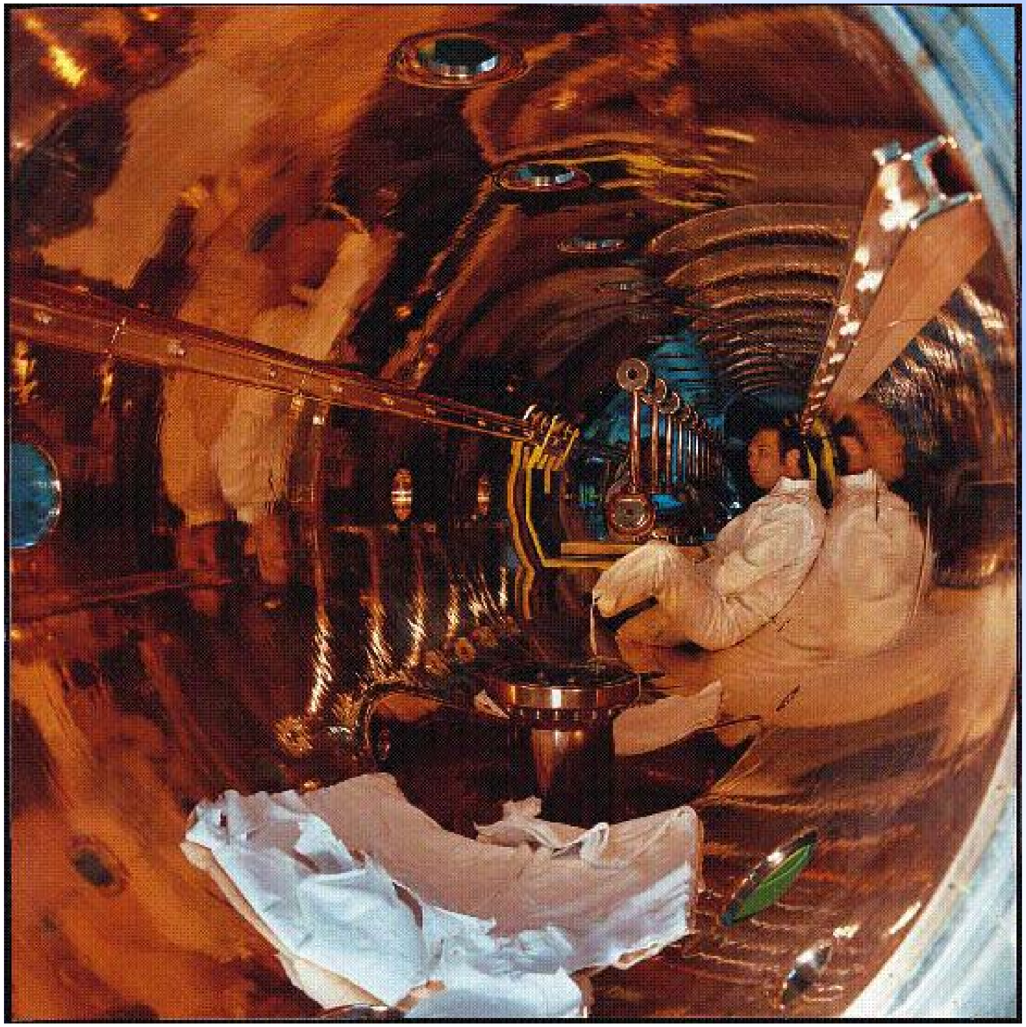


$$\omega_{RF} = \frac{2\pi}{T_{RF}}$$

$$l_i = \frac{1}{2} v_i T_{RF} \qquad E_i = \frac{1}{2} m v_i^2 \qquad E_{i+1} = E_i + qV \qquad \Rightarrow l_i = \frac{T_{RF}}{2}\sqrt{\frac{2}{m}(E_0 + iqV)}$$

For 10 (100) MHz and 2 MeV protons we get a maximum drift tube length of 1 (0.1) m !

GSI Wideröe



Acceleration of p to U^{10+} up to 1.4 MeV/u.

Frequency 27 MHz.

130 drift tubes per tank. 4 tanks total.
Total length 30 m.

Installed 1975.
Deinstalled 1999.

Resonant Radio Frequency (RF) Accelerators

Energy gain per passage:

$$\Delta E = qV\sin(\omega_{RF} t)$$

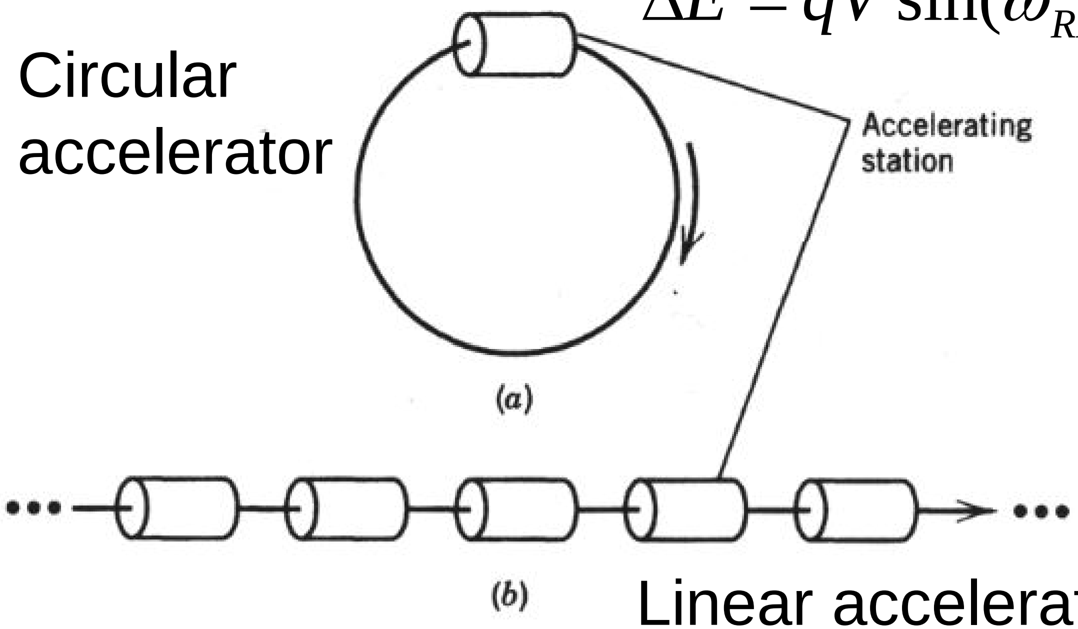
Resonant RF cavity:

$$E(r) = E_0 J_0\left(\frac{\omega}{c} r\right).$$

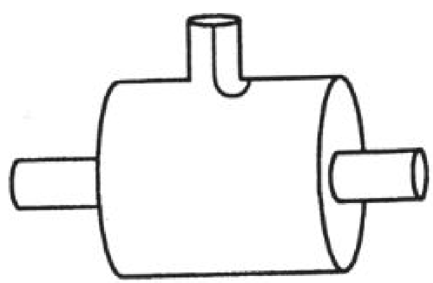
$$\frac{2\pi f}{c} R = 2.405.$$

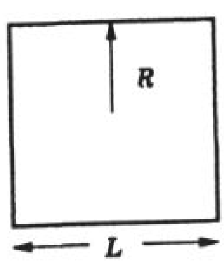
$$f \approx 100\ MHz$$

Circular accelerator



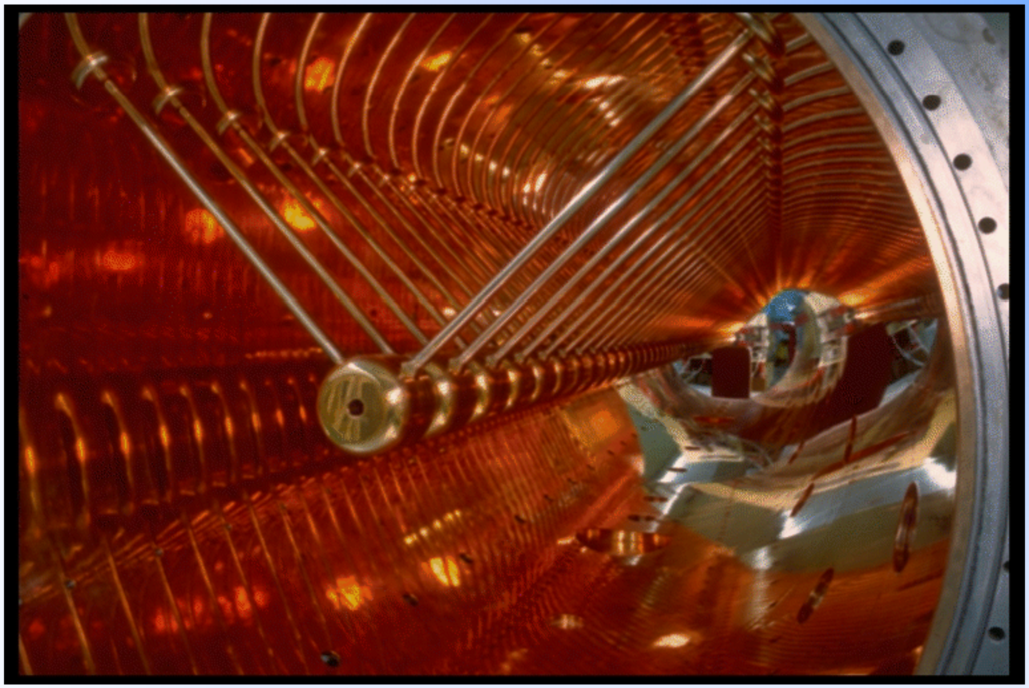
Linear accelerator





GSI Alvarez

L. W. Alvarez, USA 1947



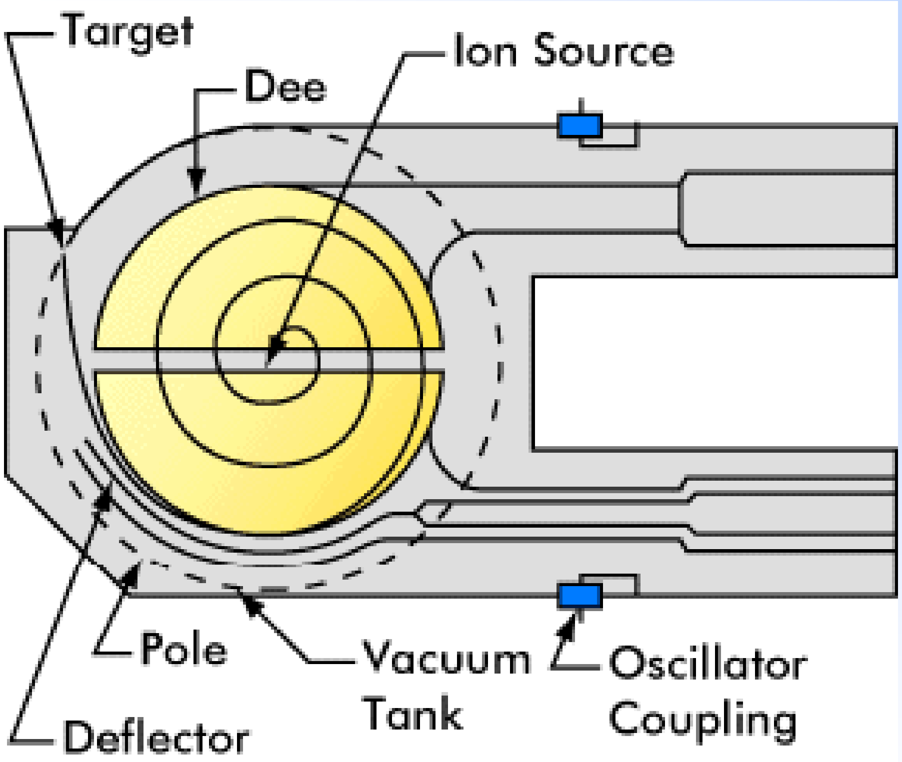
Acceleration of p to U^{28+} from 1.4 to 11.6 MeV/u.

Frequency 108 MHz.

150 drift tubes per tank. 4 tanks total.
Total length 55 m.

Circular Accelerators: Cyclotron

Constant (magnetic) bending field, increasing radius.



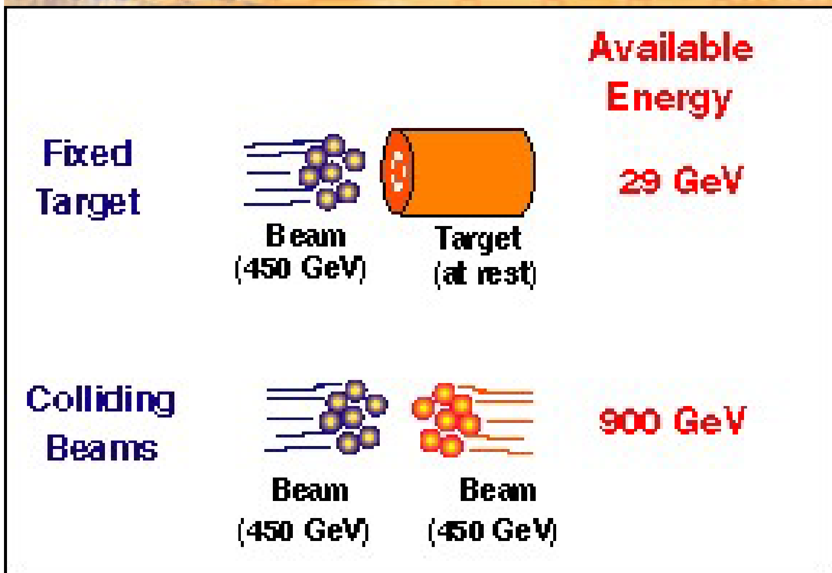
Continuous beam

Old 60-in. cyclotron in Berkeley

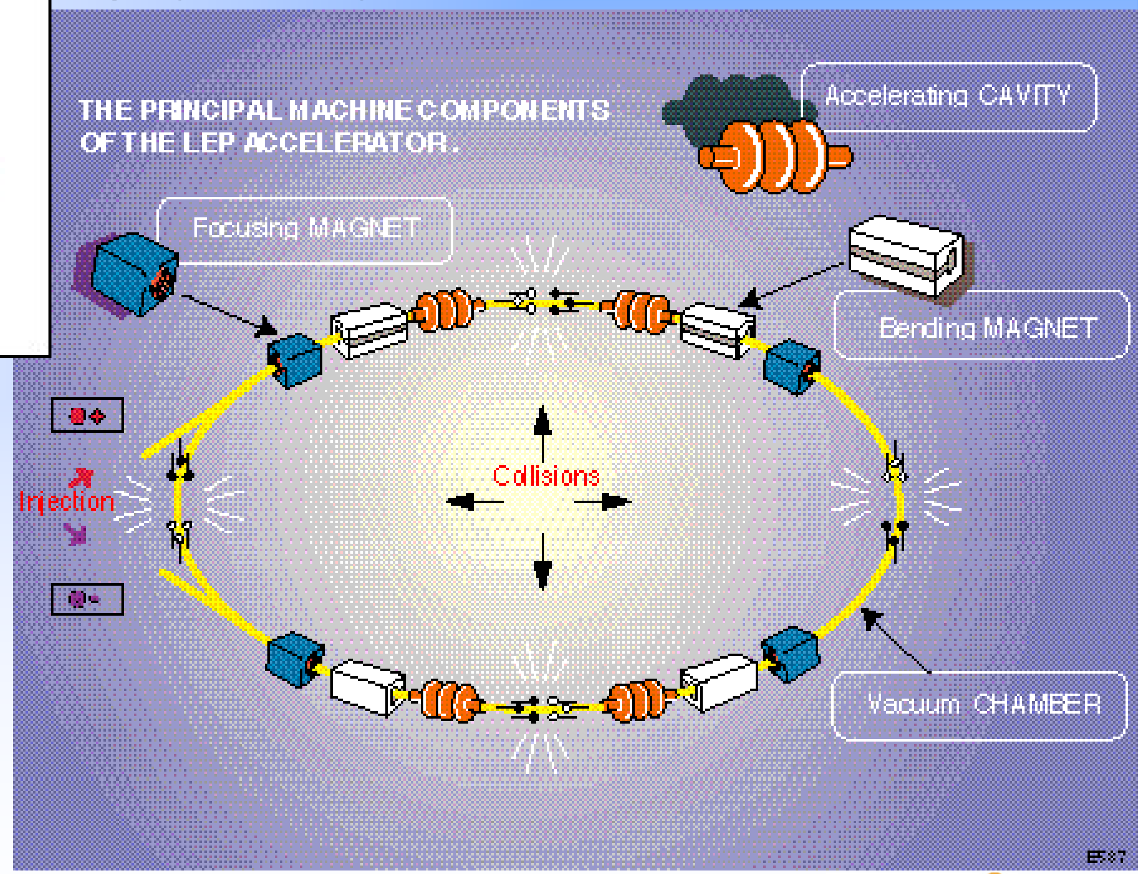
Part II: Modern Accelerators

- Different requirements lead to different accelerator layouts
- Beside the scientific use there are accelerators for industrial and medical applications

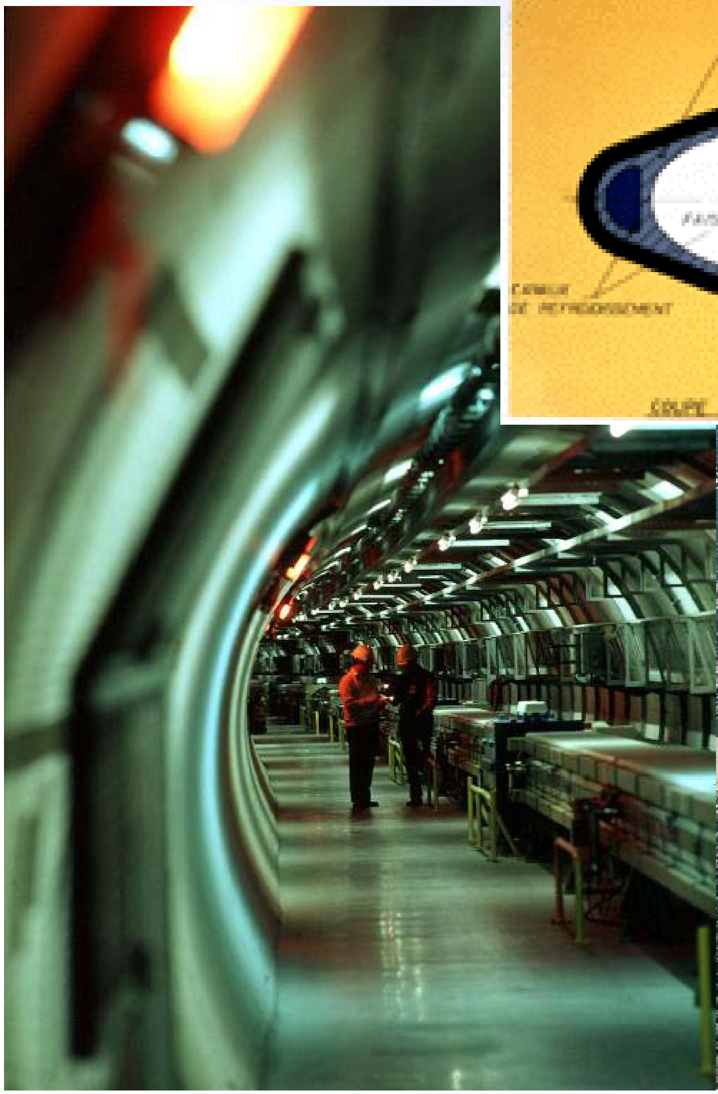
Circular Accelerators: Collider

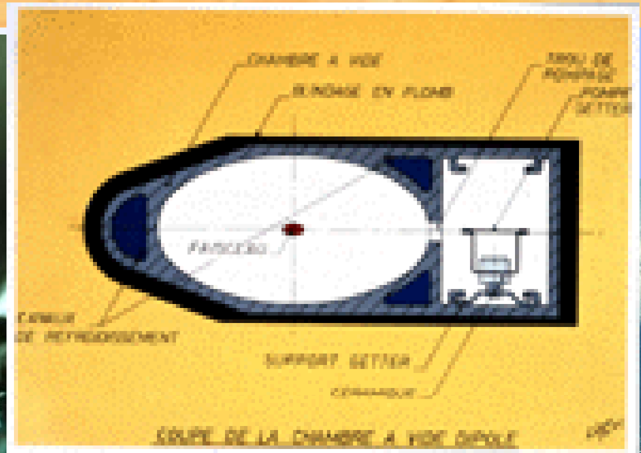


If the incoming beam is simply slammed into a stationary target, much of the energy is taken up by the target's recoil.



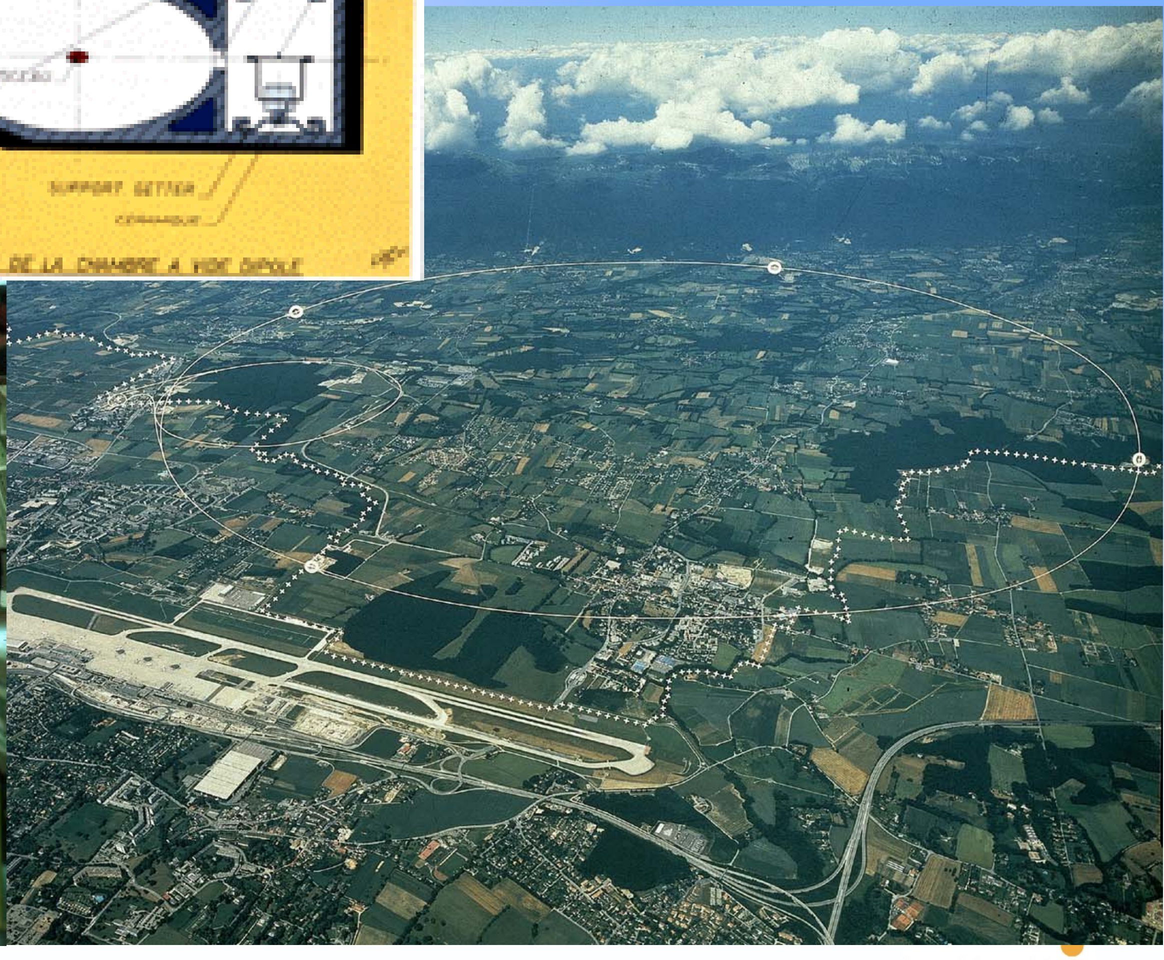
CERN Large Electron-Positron Collider (LEP)





Circumference: 27 km !

1989-November 2000

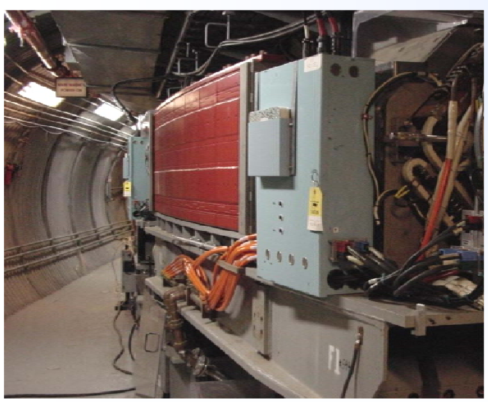


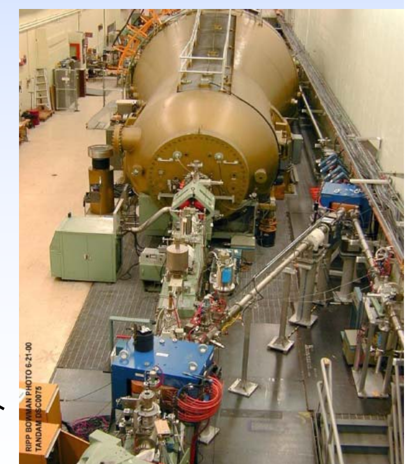
Brookhaven Nat'l Labs, Long Island, USA

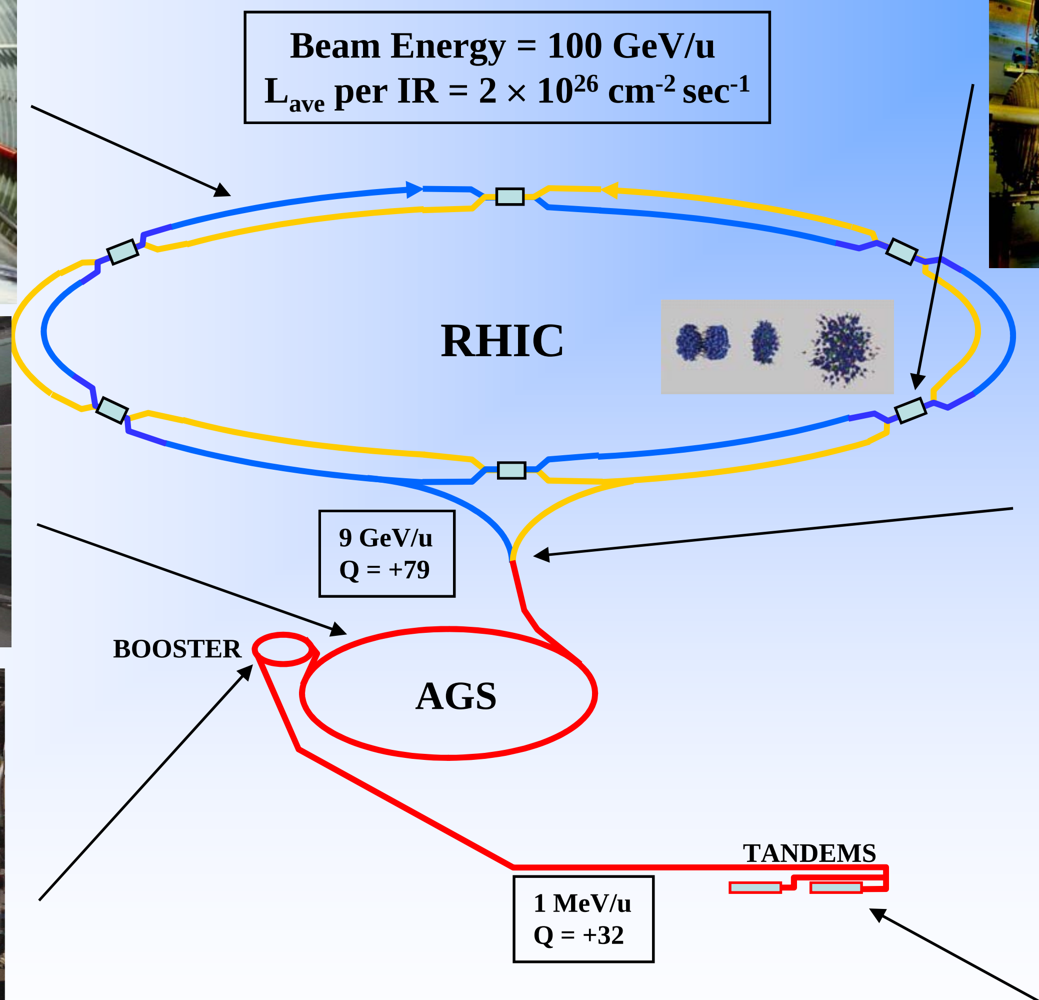
RHIC: Relativistic Heavy Ion Collider

AGS: Alternating Gradient Synchrotron

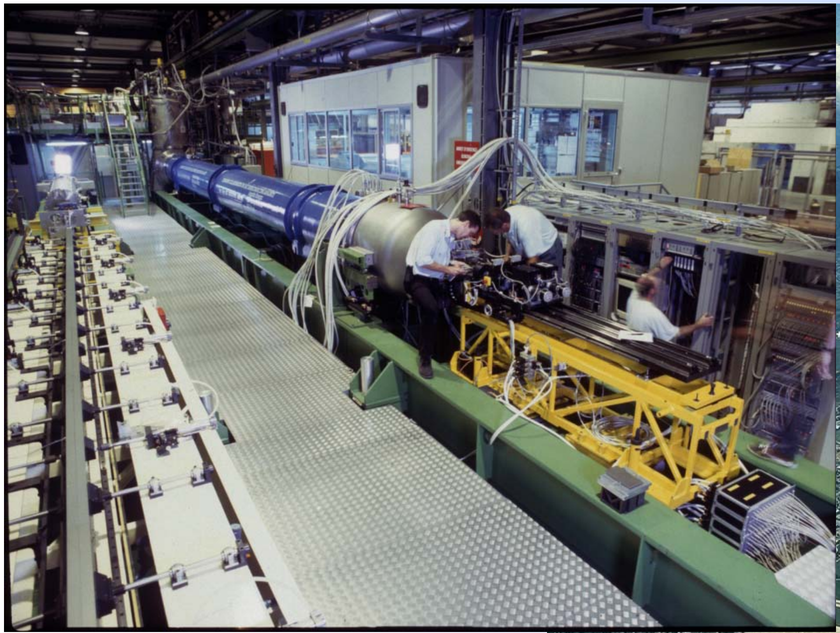
Gold-Gold Collissions in RHIC







CERN Large Hadron Collider (LHC)

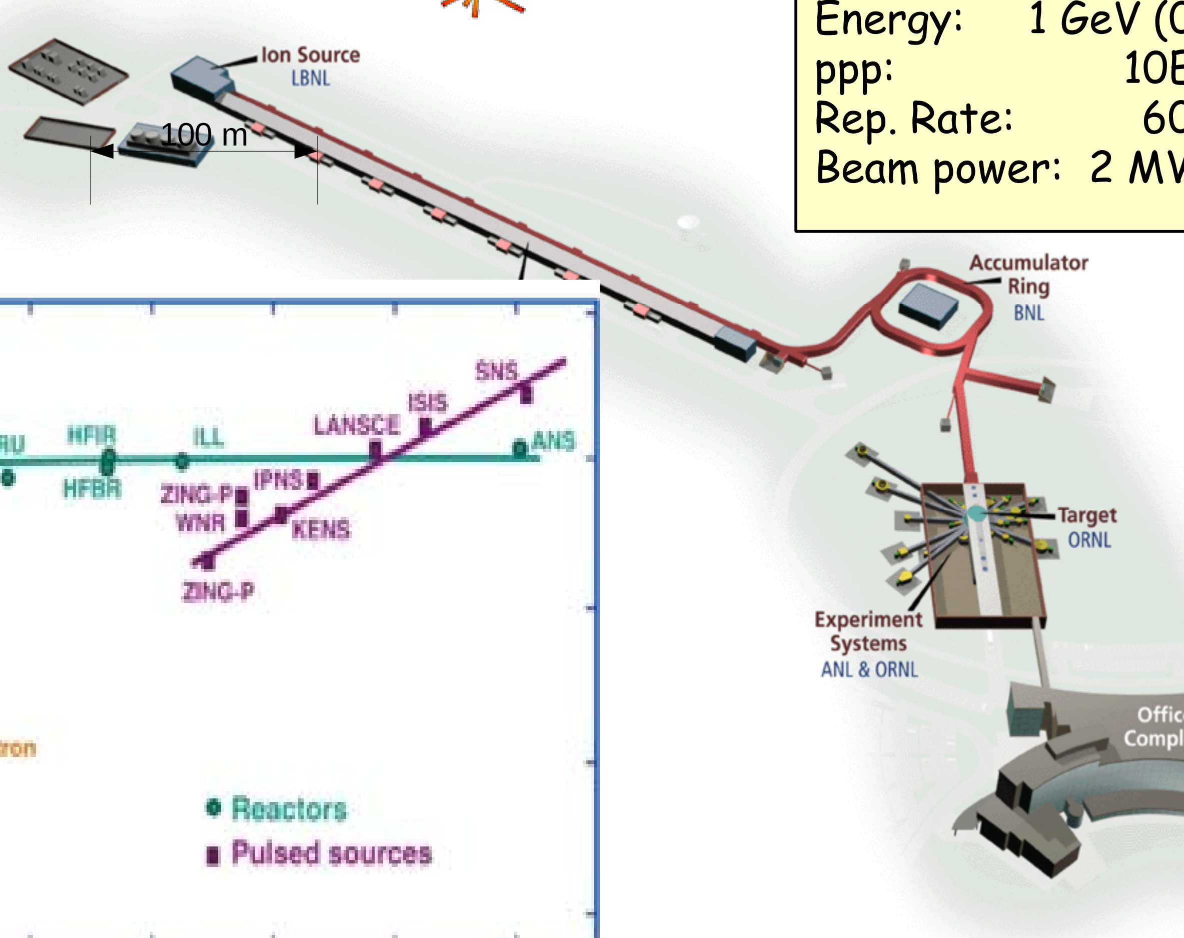


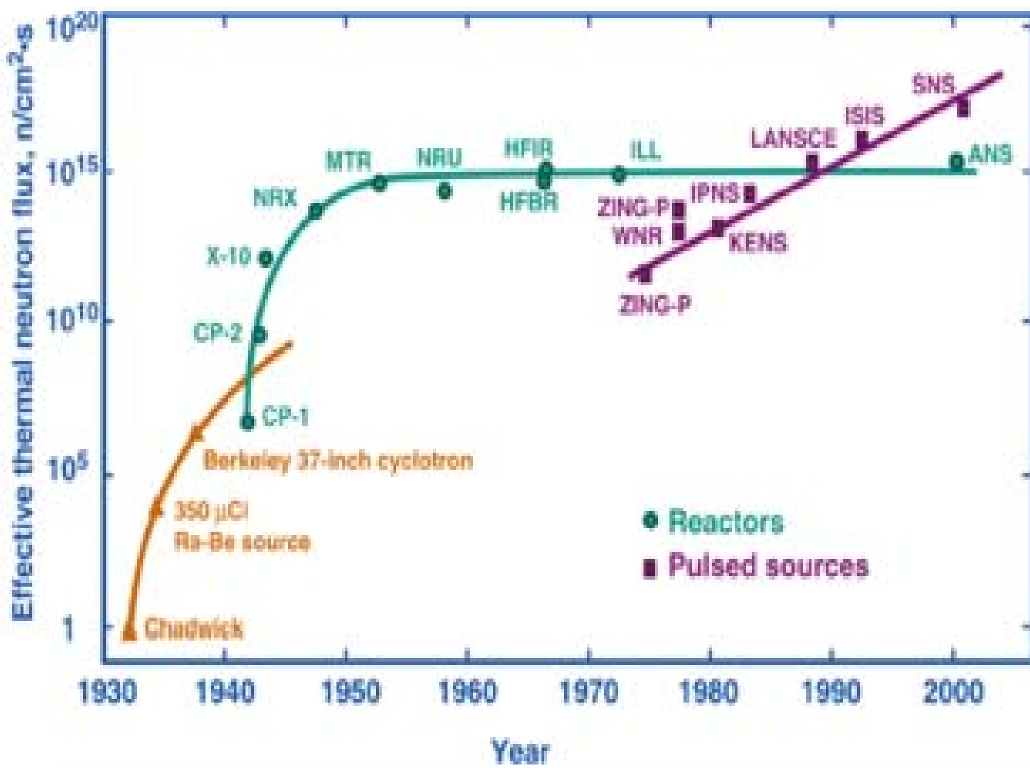
Protons and heavy ions (Pb)
Energy: > 1 TeV
Protons in the ring: 3E14
Current: 0.5 A
Beam energy: 3 MJ
Magnetic dipole field: 8 T

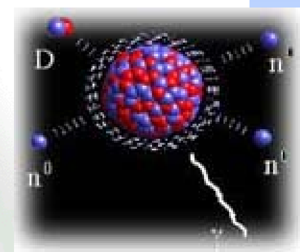
Circumference: 27 km

Neutron Spallation Source: SNS in Oakridge, USA (commissioning finished)

Ion:	Protons
Energy:	1 GeV (0.88c)
ppp:	10E14
Rep. Rate:	60 Hz
Beam power:	2 MW





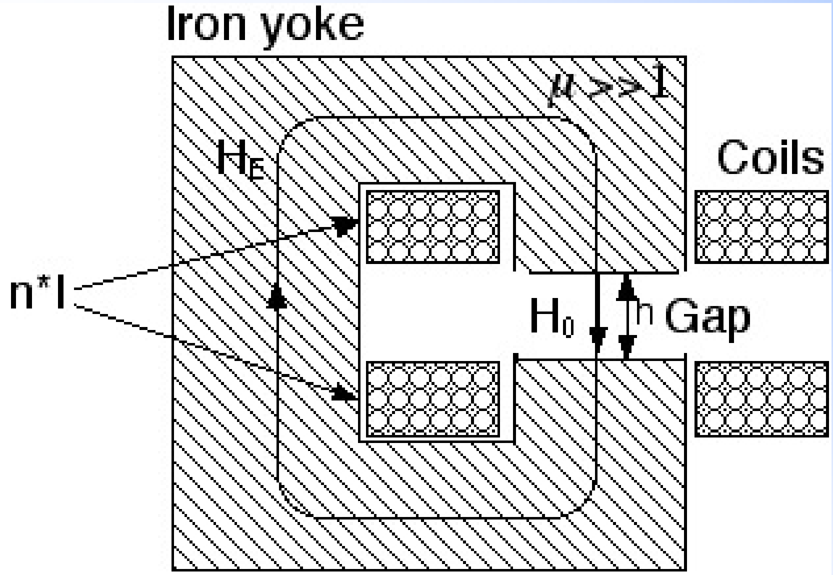


Part III: Basic principles

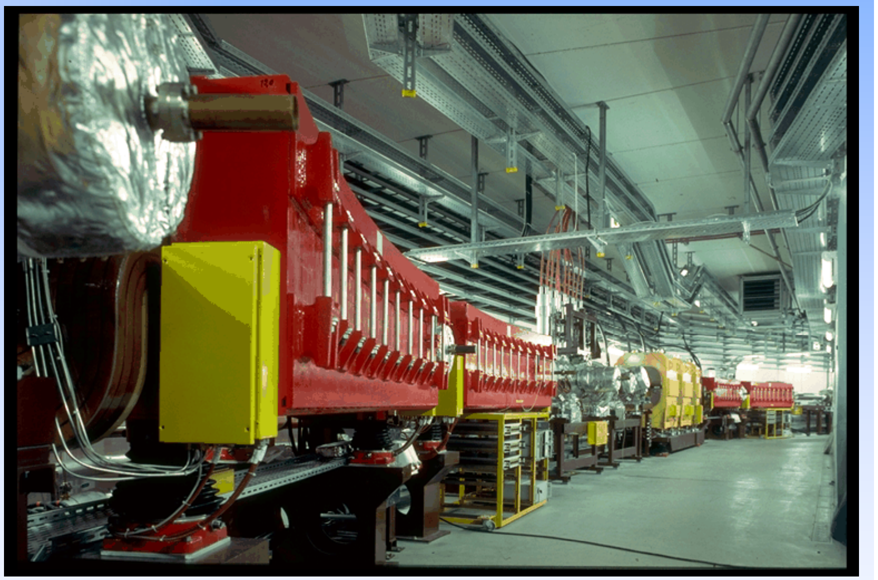
- The ions in the accelerator a guided by electric and magnetic devices. This ion-optical layout is called "lattice".
- The function of an accelerator facility is assured by the lattice. The requirements of the experiments "form" the machine.

Dipole Magnets

As linacs are dominated by cavities, circular machines are dominated by magnets



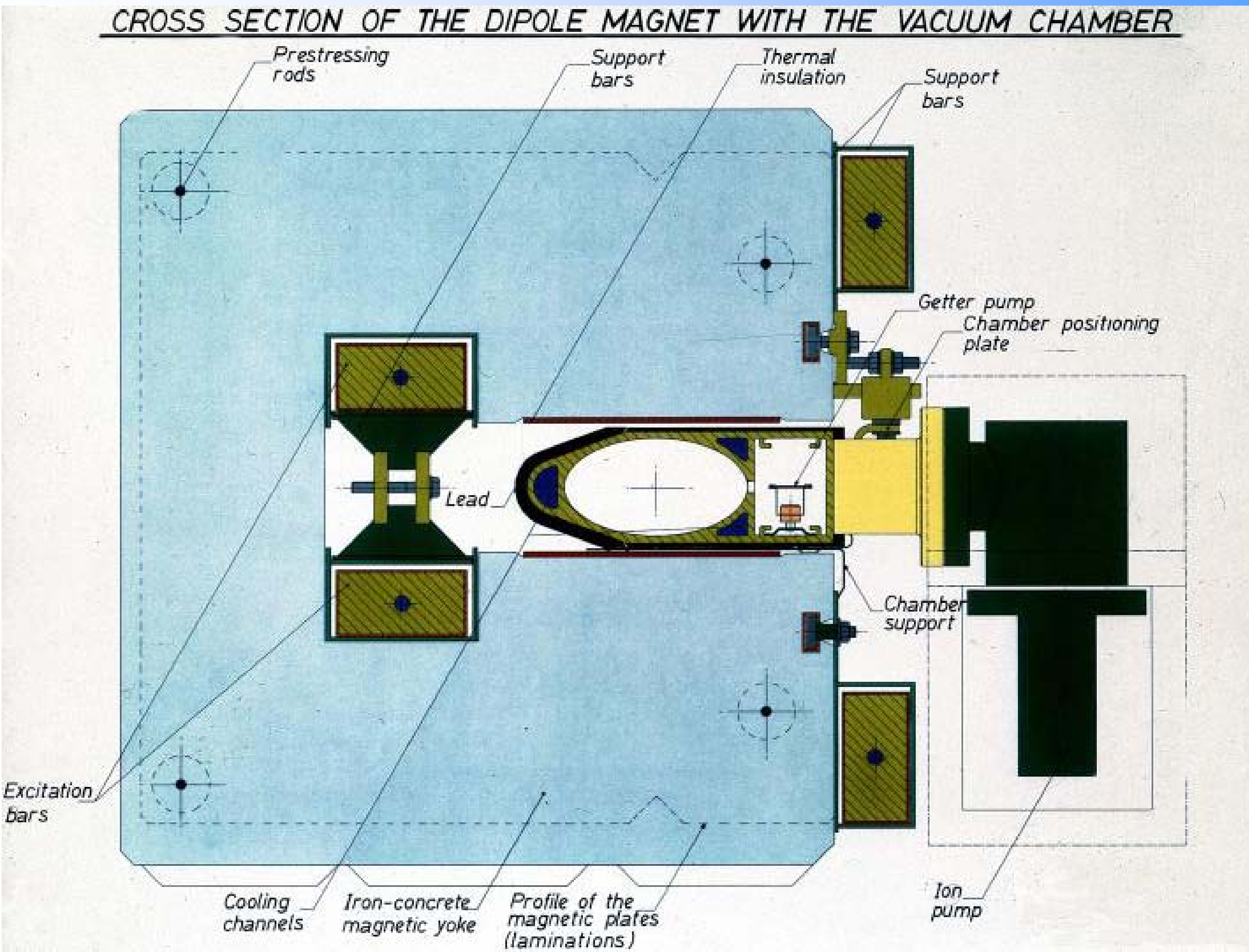
$$nI = \oint \vec{H} d\vec{s} = H_E l_E + H_0 h \approx H_0 h \quad \Rightarrow \quad B = \mu_0 \frac{nI}{h}$$



Iron dipole magnet: B<2 T

superconducting dipole magnets: B=3-8 T

LEP (Large Electron Positron Collider) Dipolmagnet, CERN



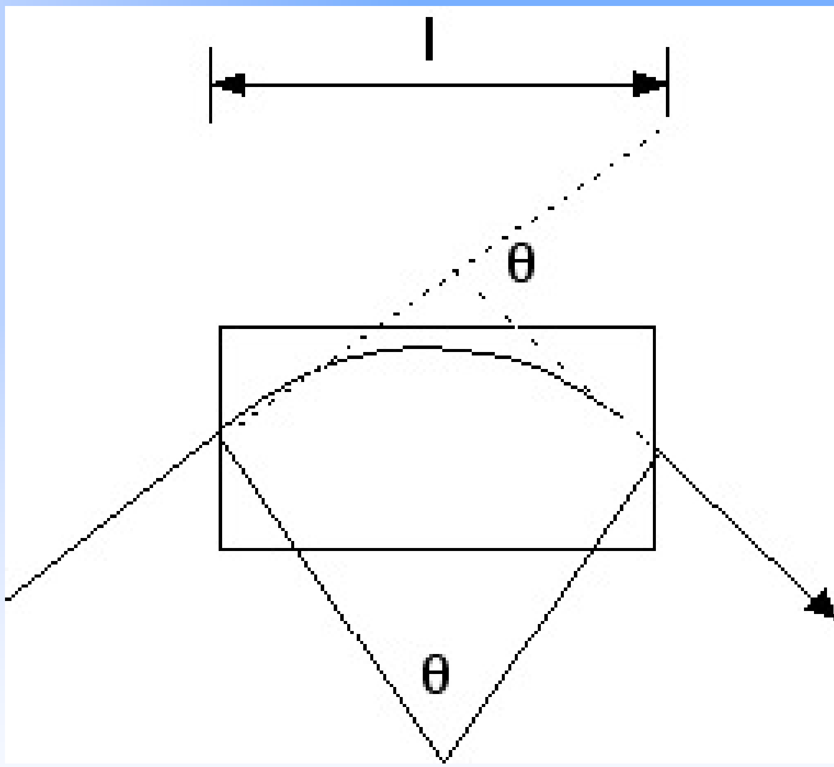
Bending in a dipole magnet

$$\dot{\theta} = \frac{qB_y}{\gamma m}$$

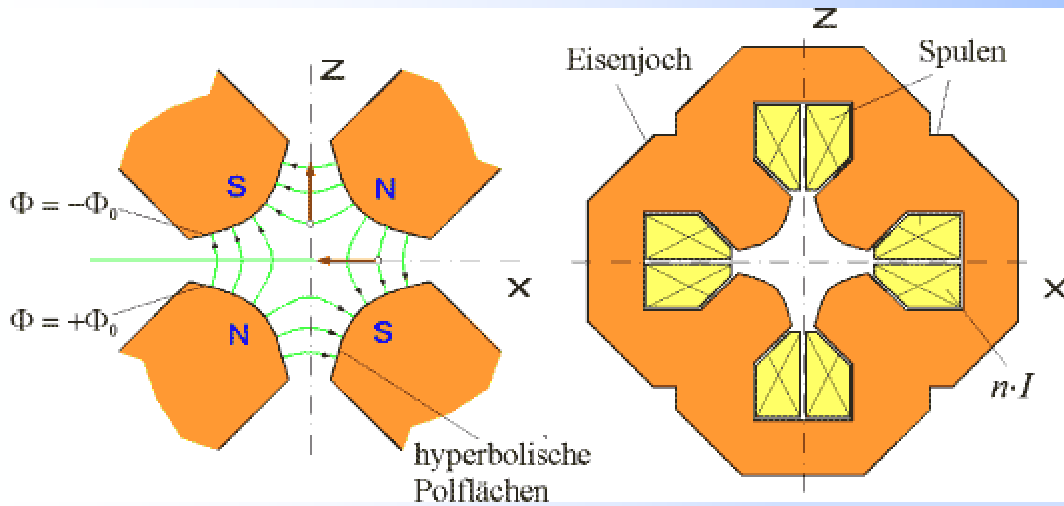
$$\theta = \frac{q}{p_s}\int_{s_1}^{s_2} B_y ds \approx \frac{l}{R}$$

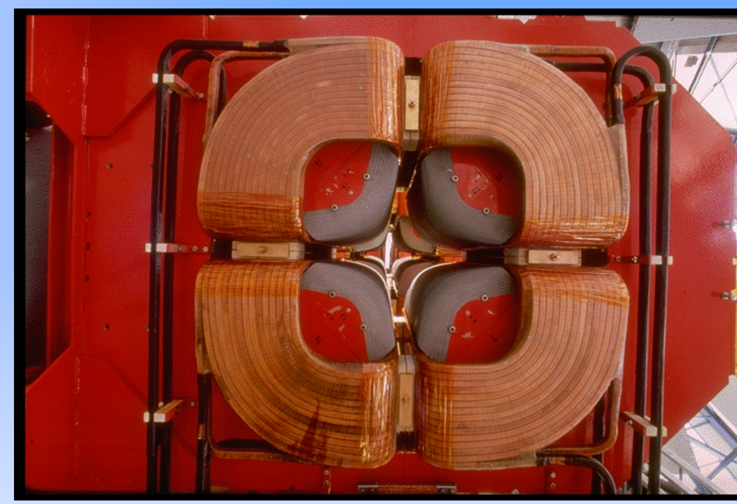
$$\oint B_y ds = 2\pi p_s/q = 2\pi B_0 R_0$$

Rigidity: B_0R_0 [Tm]



Focusing (Quadrupole) Magnets





$$B_y = B_0 \frac{x}{a}, \quad B_x = B_0 \frac{y}{a}$$

- orbit correction proportional to orbit offset
- good correction in x means bad correction in y

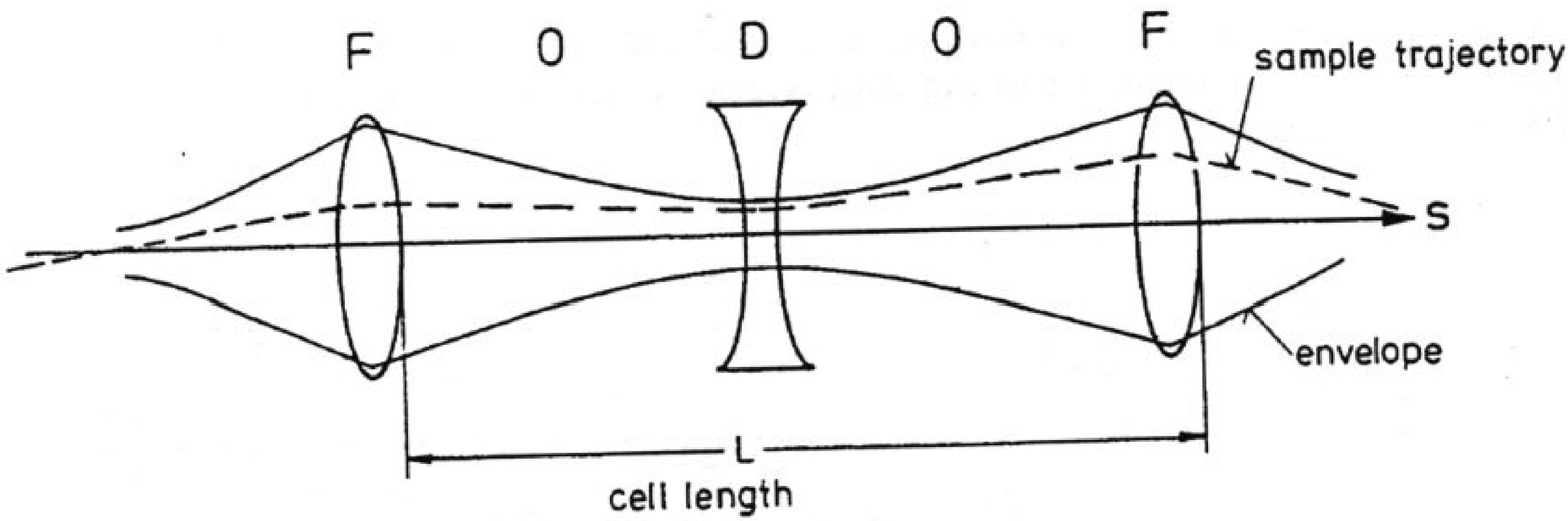
Magnetic vs. electric fields:

$$\kappa = \frac{qE_0}{\gamma m a v_s^2}.$$

For v=c B=1 T corresponds to 300 MV/m !

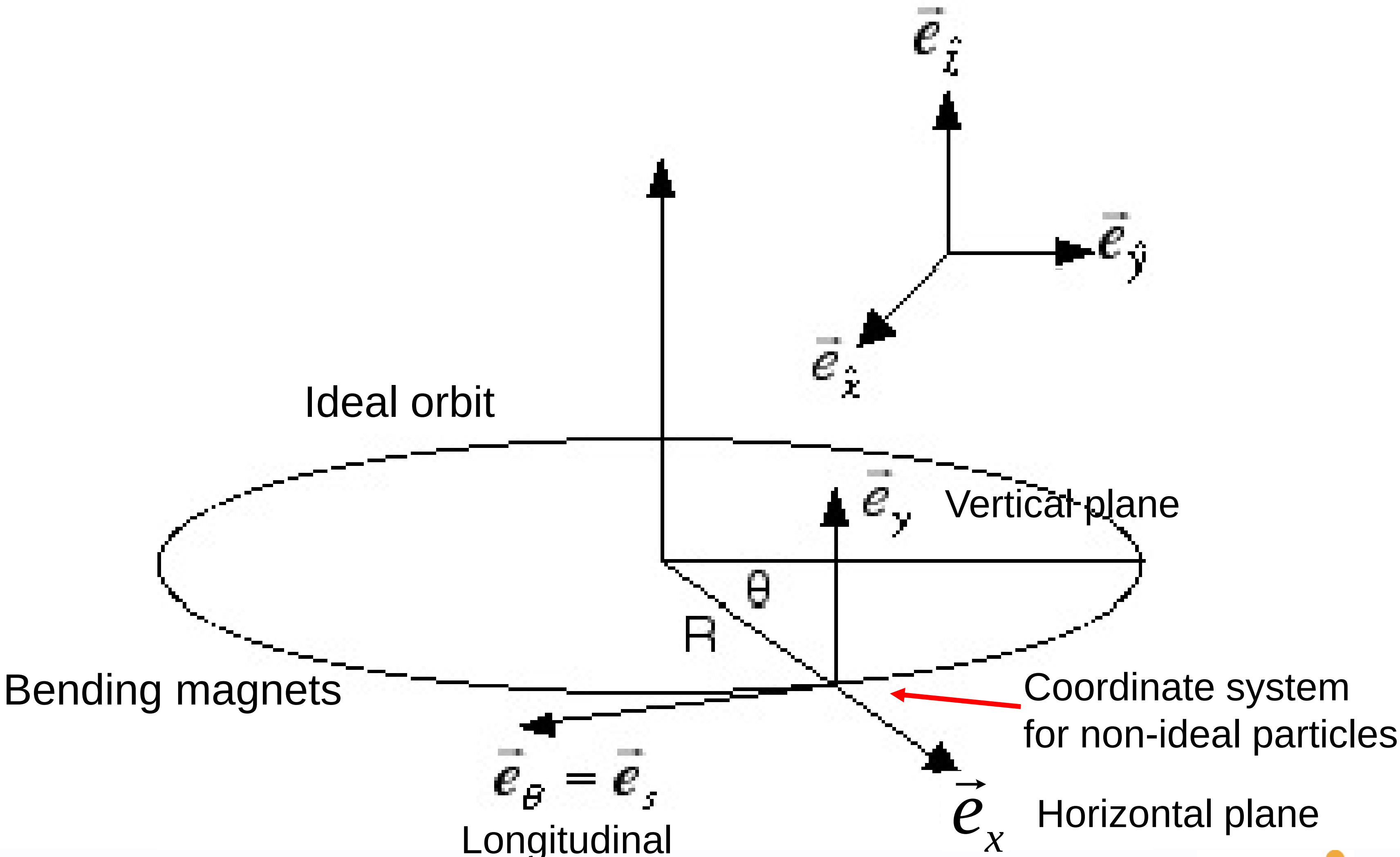
Alternating Gradient Focusing

Focusing quadrupole **Drift** **De-focusing quadrupole** **Drift** **Focusing quadrupole**



Sequence of focusing and de-focusing lenses acts as effective focusing lens

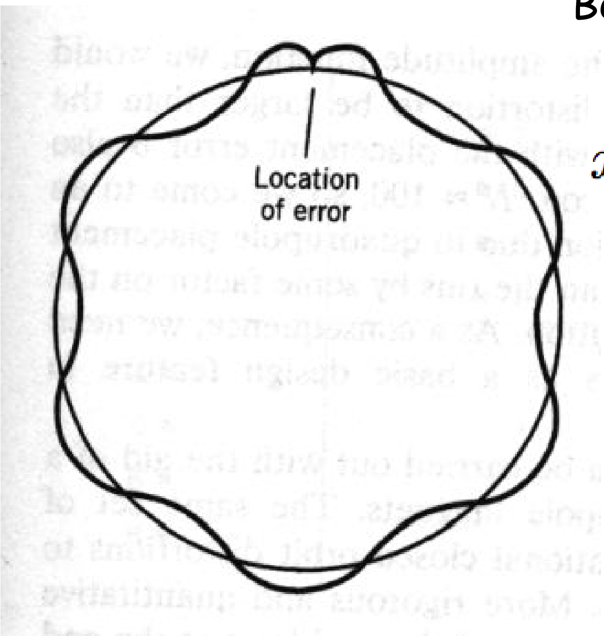
Particle Coordinates in Circular Accelerators



Errors: The ions try from the ideal path

$$\begin{pmatrix} x_0 \\ x_0' \end{pmatrix} = (I - M)^{-1} \begin{pmatrix} 0 \\ \theta \end{pmatrix} = \frac{\theta}{2\sin\pi Q} \begin{pmatrix} \hat{\beta}_0 \cos\pi Q \\ \sin\pi Q - \hat{\alpha}_0 \cos\pi Q \end{pmatrix}$$

Betatron oscillation



$$x(s) = \frac{\theta \beta_0^{1/2} \beta(s)^{1/2}}{2\sin\pi Q} \cos(\psi(s) - \pi Q)$$

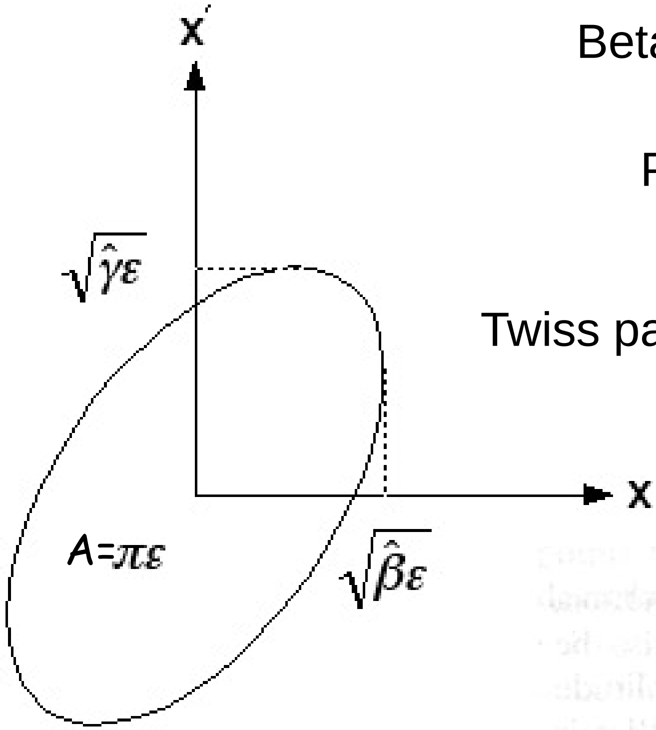
The errors of the dipoles are additive

$$\theta = \sum_j \theta_j = \sum_j \frac{l_j}{R} \frac{\Delta B_j}{B} \approx \frac{\Delta B}{B} \approx 10^{-4} \text{ rad}$$

resulting amplitude (GSI's SIS18):

$$|\hat{x}| \approx \frac{(10^{-4} \text{ rad})(30 \text{ m})}{2\sin\pi 4.2} \approx 1 \text{ cm}$$

What is this emittance everybody keeps talking about?!

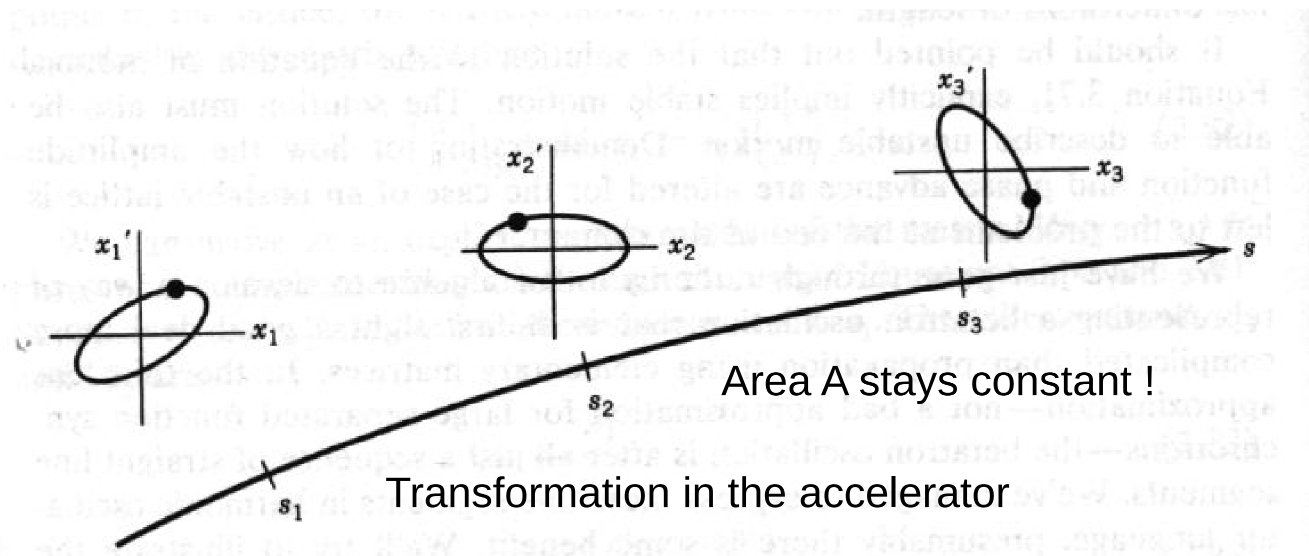


Betatron movement: $x(s) = \sqrt{\epsilon}w(s)\cos(\psi(s)+\psi_0)$

Phase advance: $\sigma = \psi(s) - \psi(s+L)$

Twiss parameter: $\hat{\beta} = w^2(s), \quad \hat{\alpha} = -\frac{1}{2}\hat{\beta}', \quad \hat{\gamma} = \frac{1+\hat{\alpha}^2}{\hat{\beta}}$

Ellipse: $\hat{\gamma}(s)x^2 + 2\hat{\alpha}(s)xx' + \hat{\beta}(s)x'^2 = \epsilon$



Transformation in the accelerator

Single particles and envelopes

Twiss matrix;

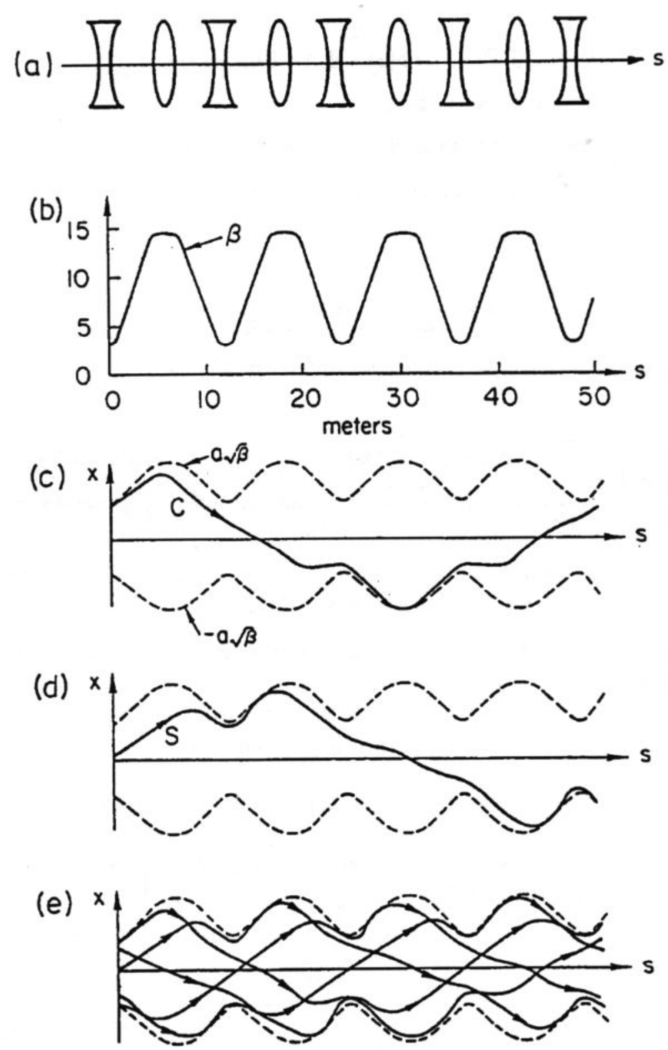
$$B = \begin{pmatrix} \hat{\beta} & -\hat{\alpha} \\ -\hat{\alpha} & \hat{\gamma} \end{pmatrix}$$

Transformation of the Twiss matrix:

$$B(s) = M(s) \cdot B_0 \cdot M^T(s)$$

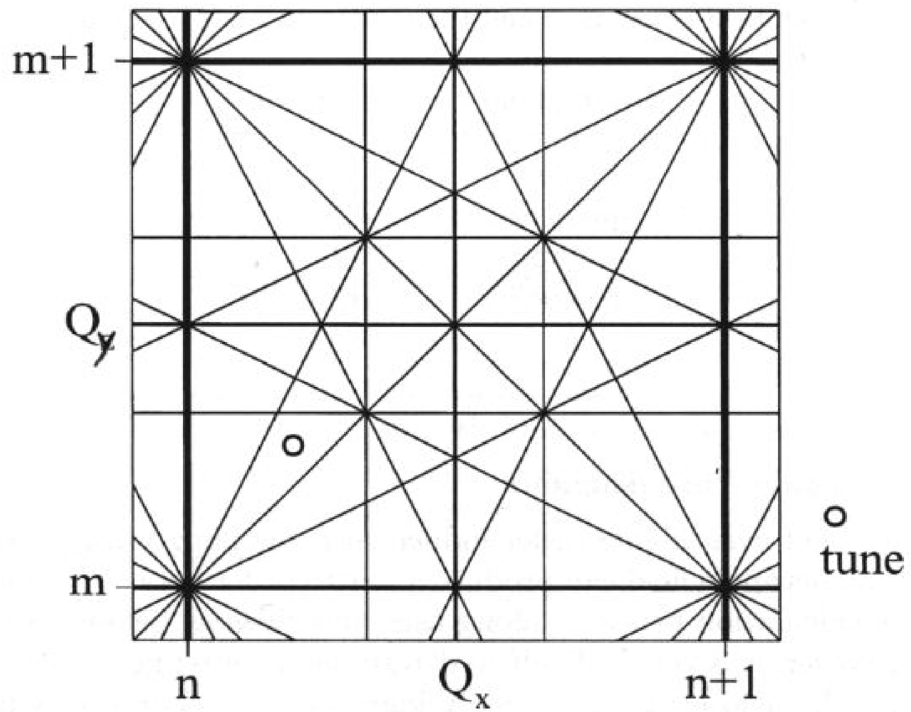
Envelope:

$$x_m = \sqrt{\hat{\beta}(s)\varepsilon_x}$$

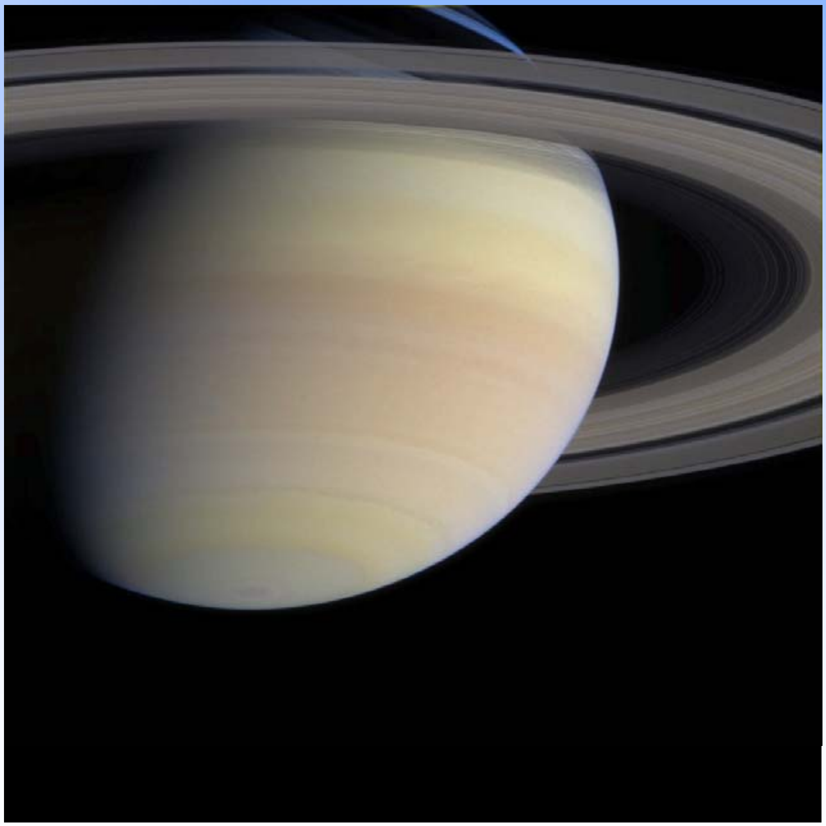


Tune and resonances

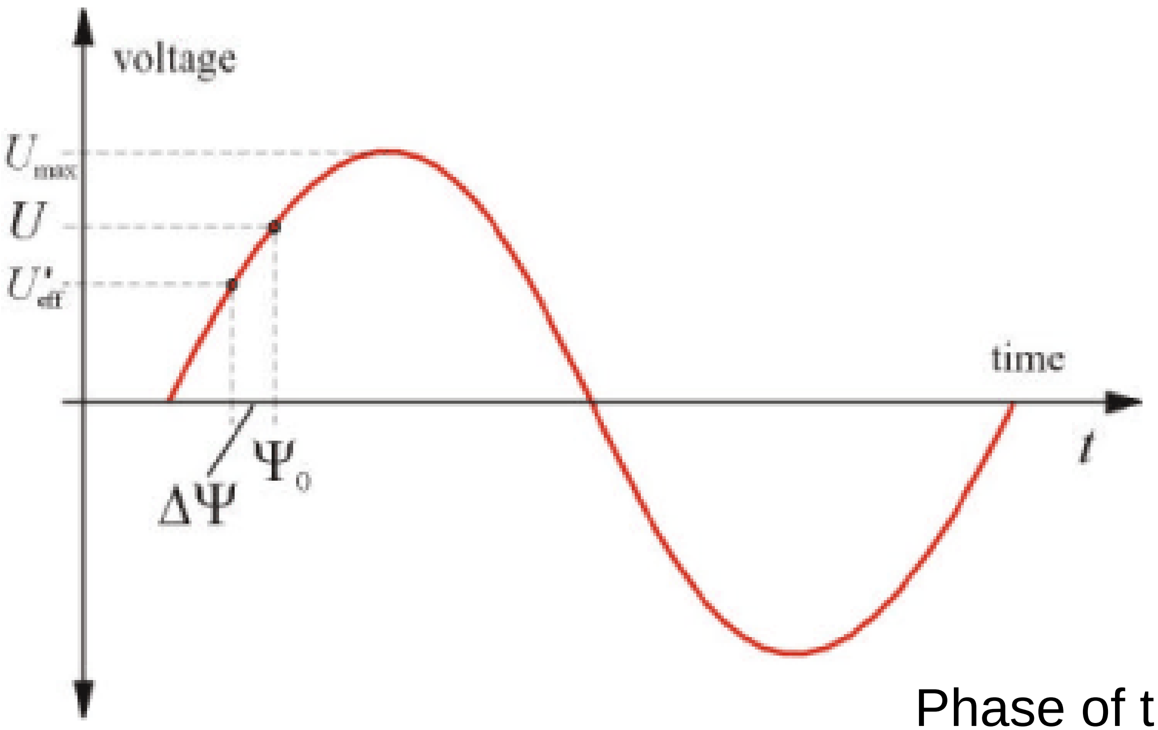
$$nQ_x + mQ_y = p$$



Order of resonance:
|n+m|



Phase Stability and Longitudinal Focusing



Synchrotron oscillations:

$$\frac{d^2\Delta\phi}{dn^2} = -(2\pi\nu_s)^2\Delta\phi$$

$$\nu_s = \sqrt{-\frac{\eta h c^2 q V \cos\phi_s}{2\pi v^2 E_s}}$$

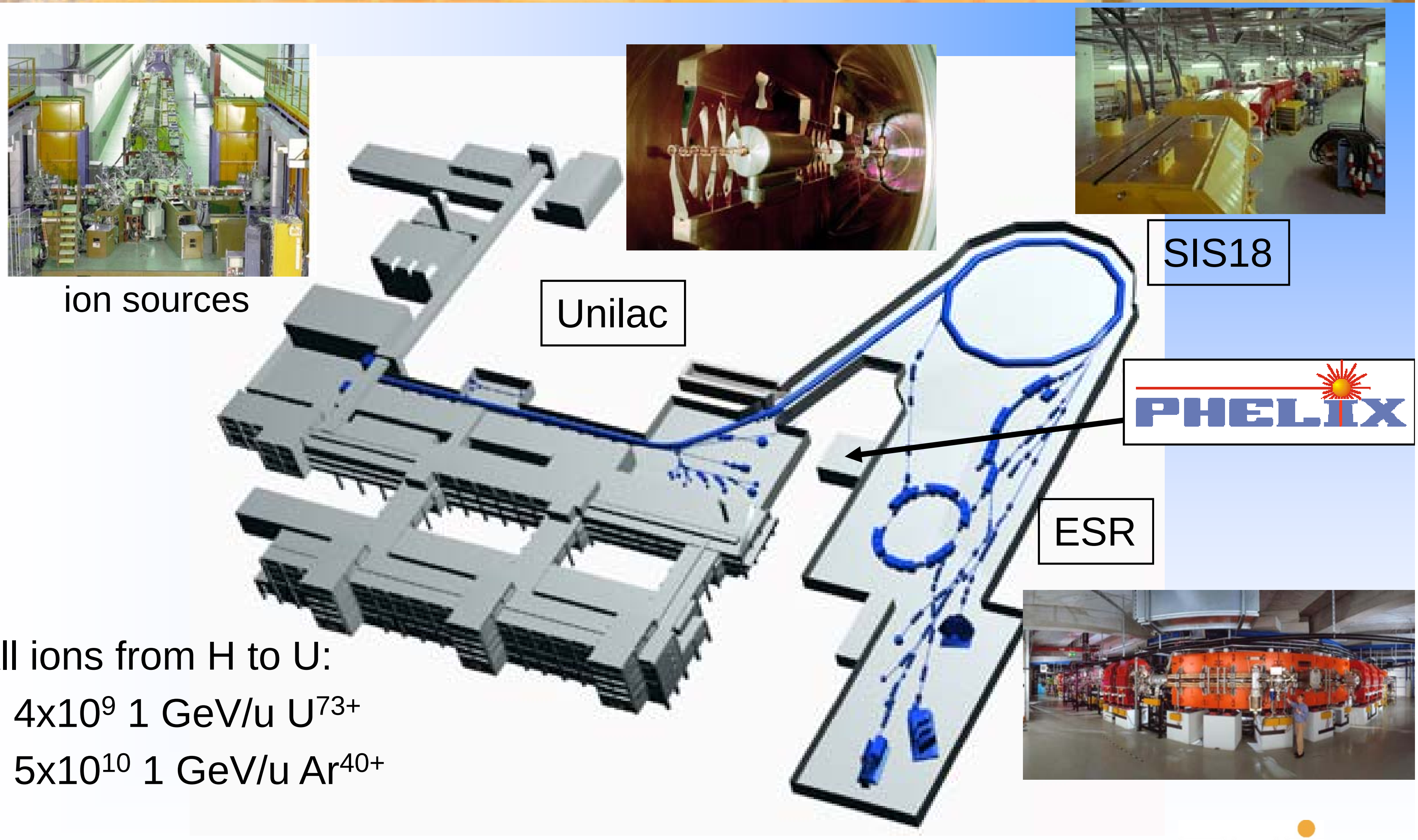
Phase of the synchronous particle: φ_s

Part IV: Welcome to GSI !

GSI accelerators today:

- Linear injector
- Synchrotron
- Another synchrotron called storage ring

The GSI accelerator complex today



All ions from H to U:

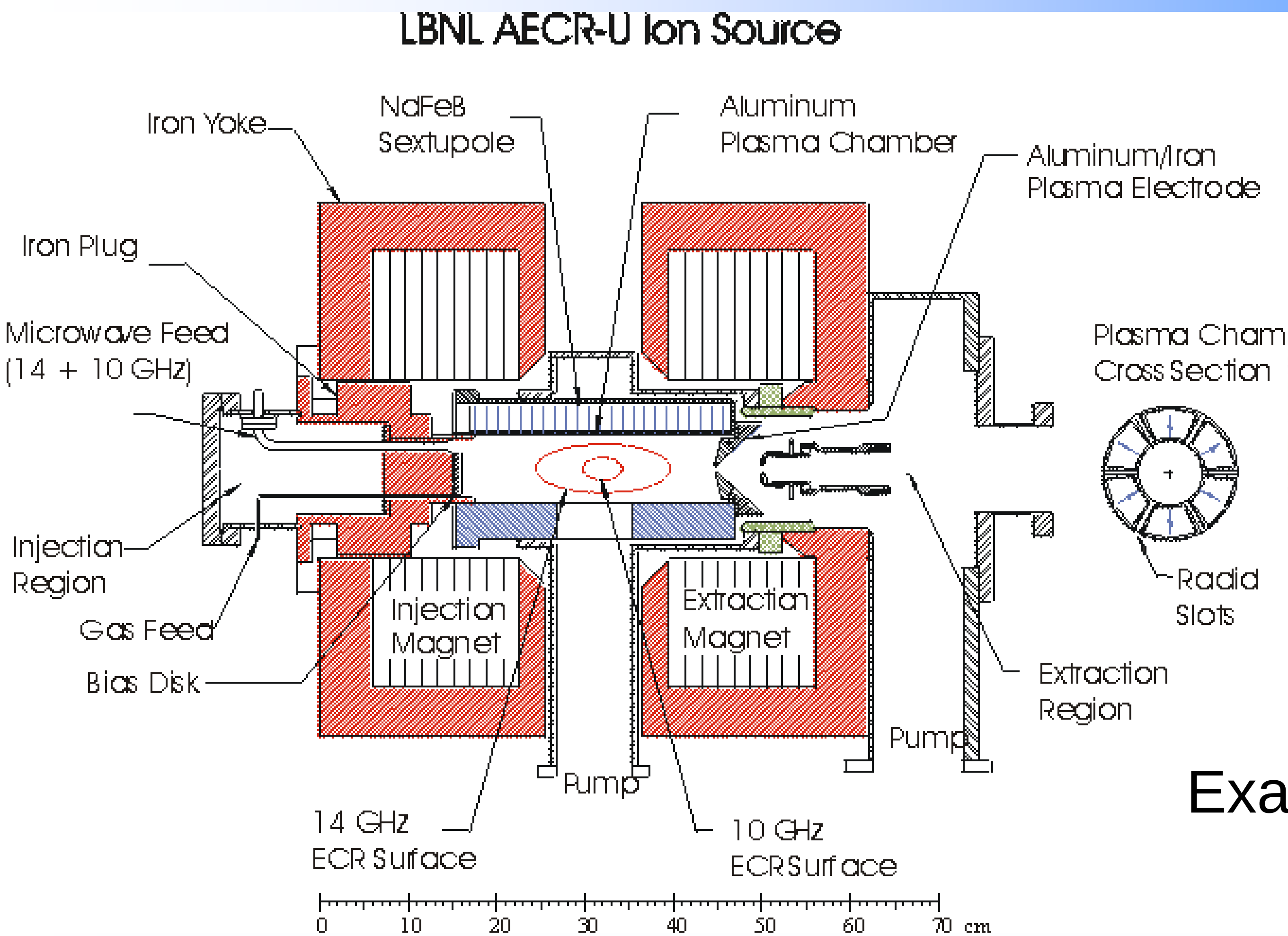
4×10^9 1 GeV/u U^{73+}

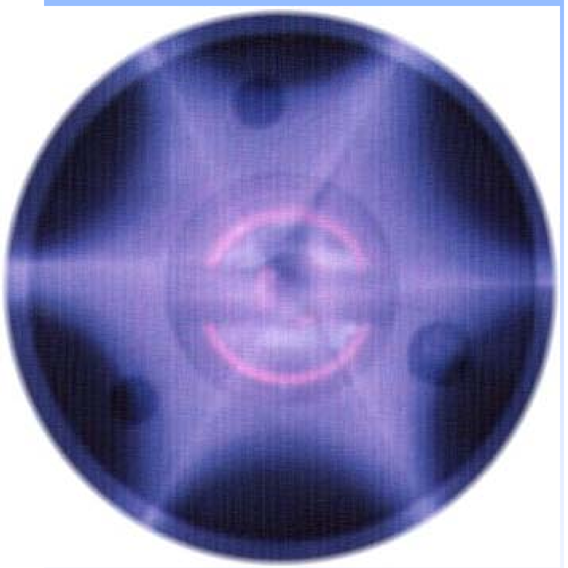
5×10^{10} 1 GeV/u Ar^{40+}

Electron Cyclotron Resonance (ECR) Sources

B_{max}=1.7 T

Electron cyclotron frequency: $\omega_{ce} = \dfrac{eB}{\gamma m_e}$





Example: 11 μA U^{38+}

0.1 μA U^{52+}

Ionization Processes in Ion Sources

;hly-charged ions.

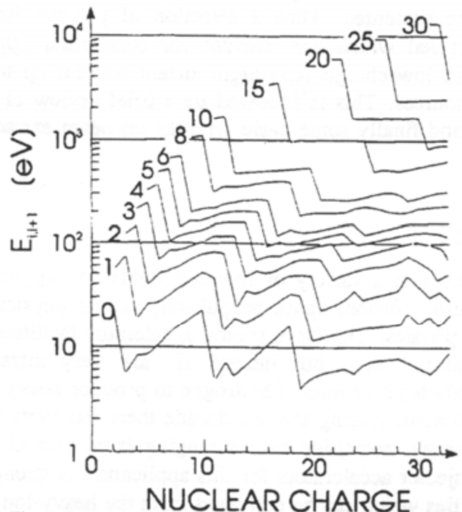


Fig. 1 Ionization energies for step-by-step ionization of elements up to nuclear charge 30

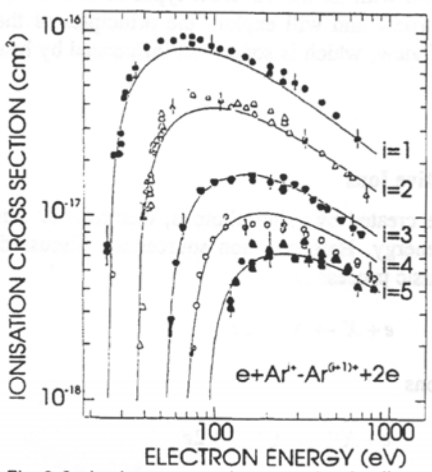


Fig. 2 Ionization cross-section versus bombarding electron energy for different charge states

The basic ionization process:

$$e + X \rightarrow X^{+} + 2e$$

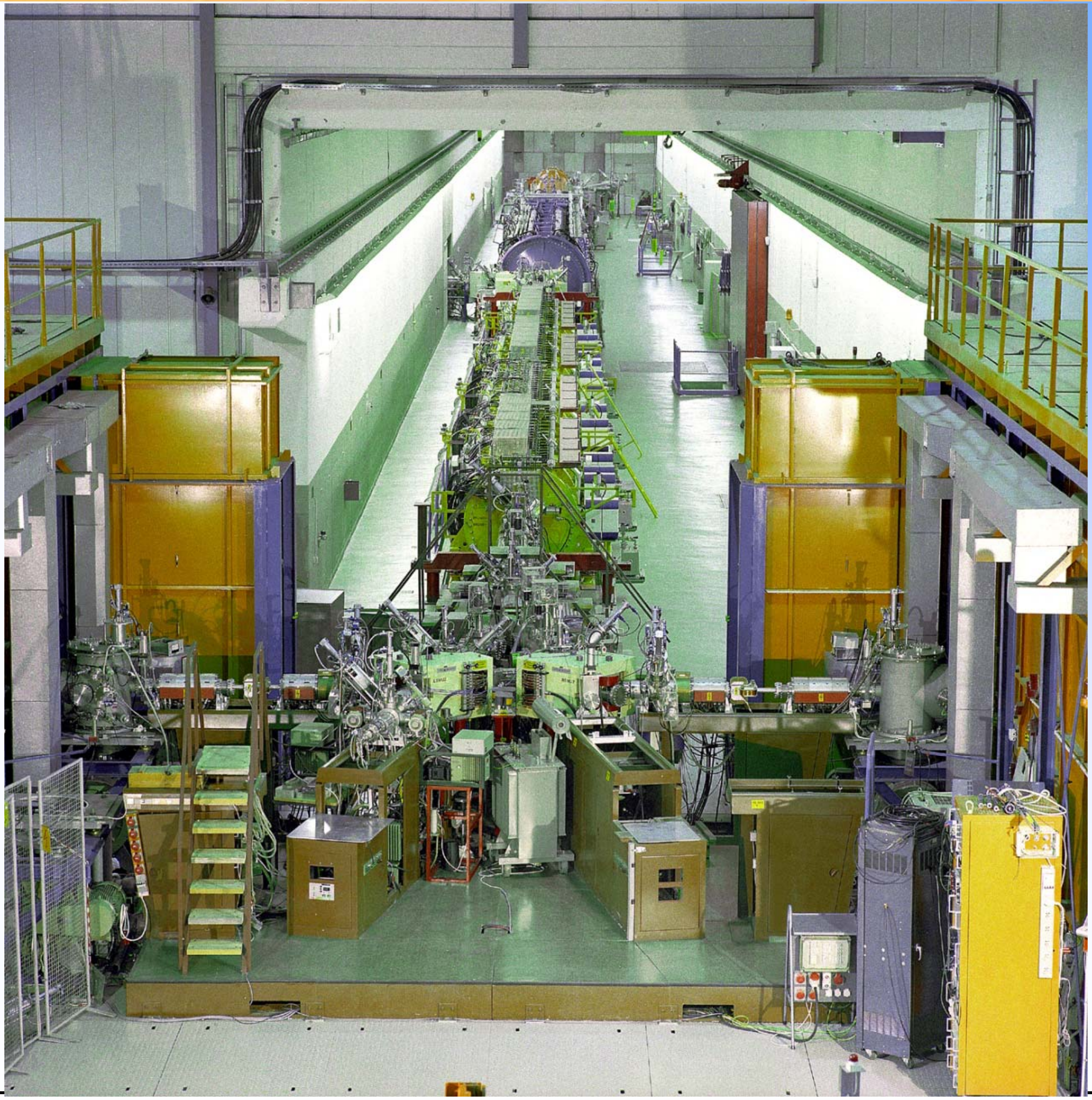
Multiple-charged ions:

$$e + X^{Z+} \rightarrow X^{(Z+1)+} + 2e$$

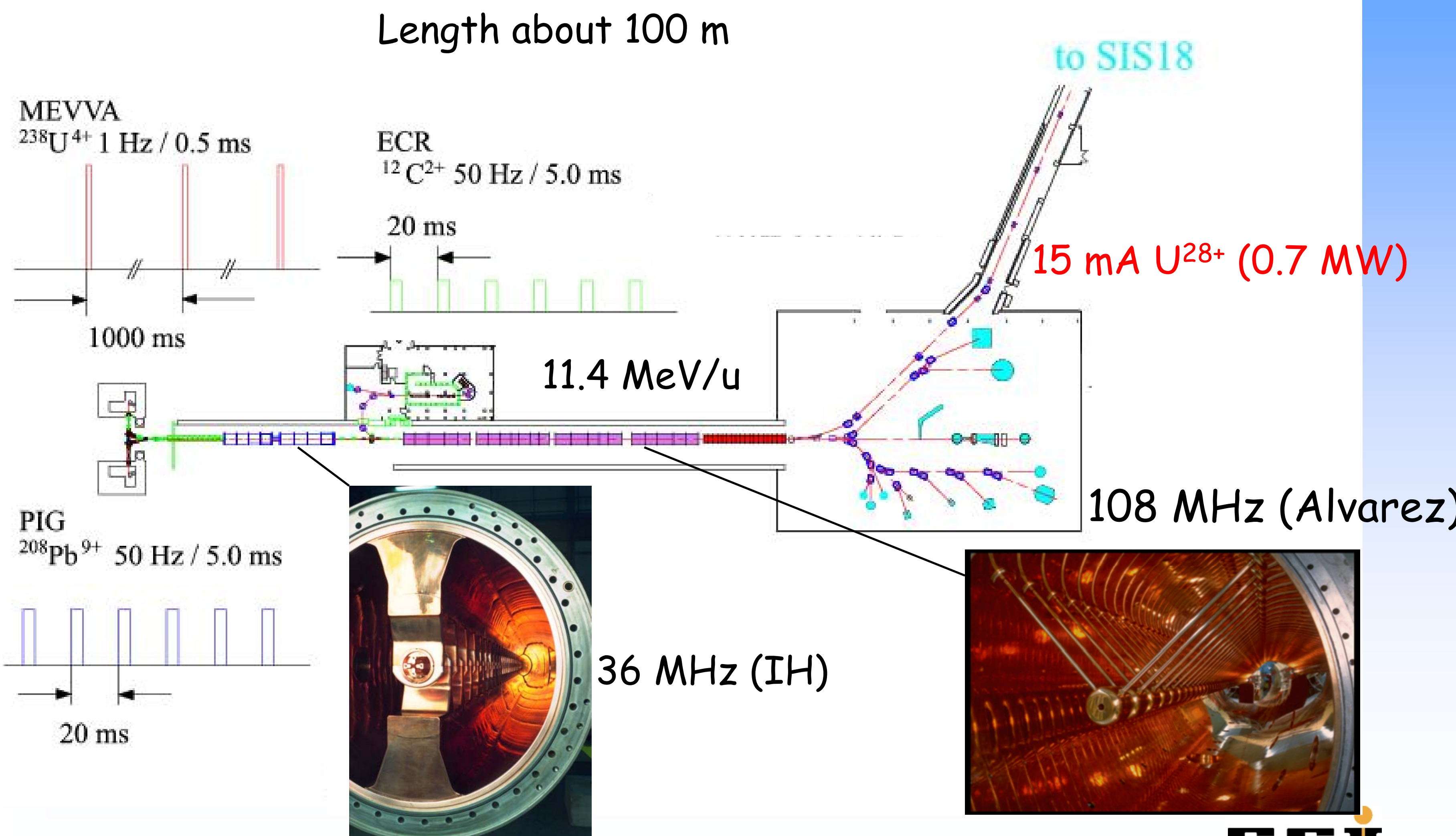
Ionisation cross sections:

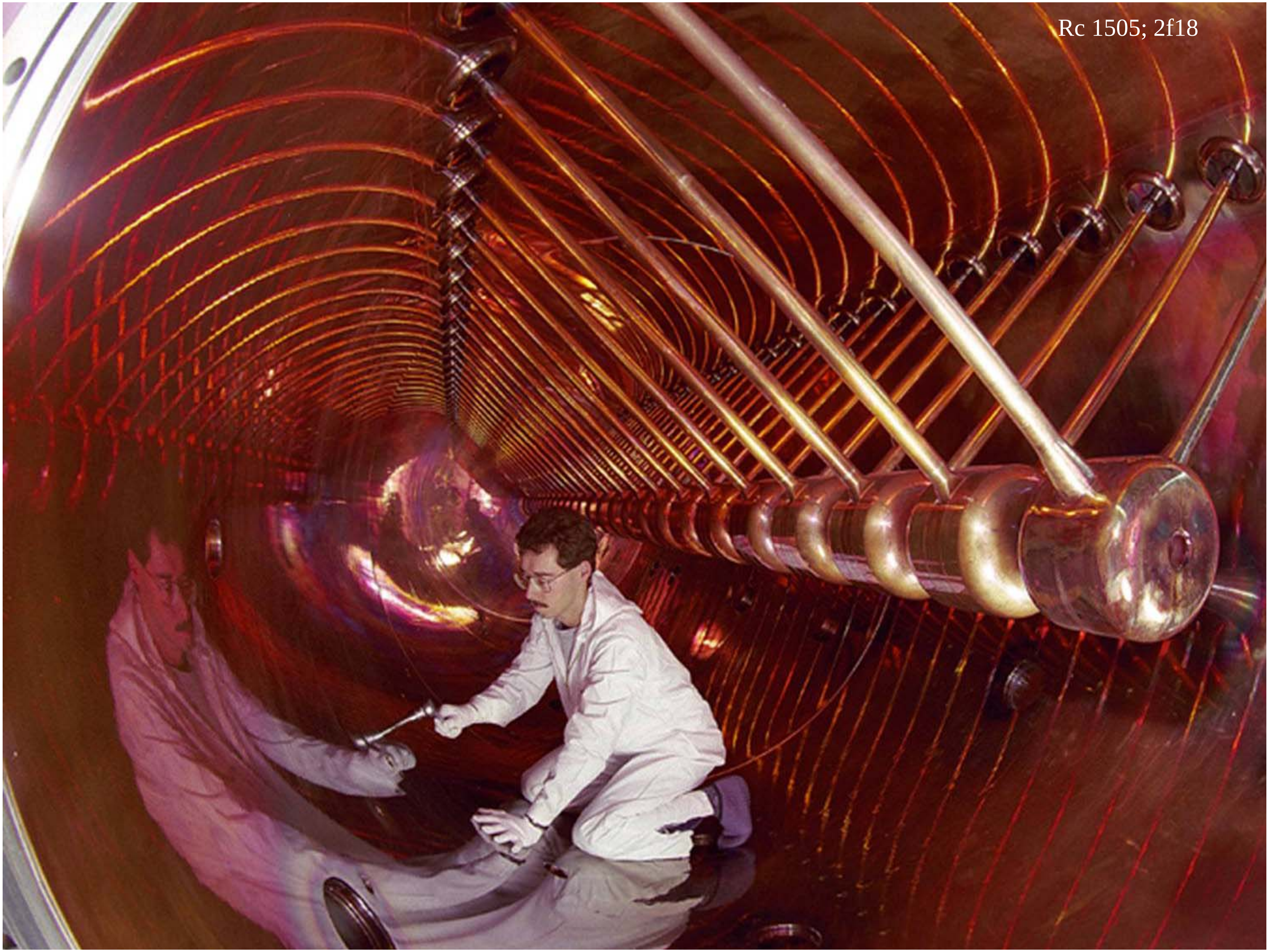
$$\sigma(W_e > W_{Z,Z+1})$$

UNIversal Linear ACcelerator (UNILAC) view from the sources

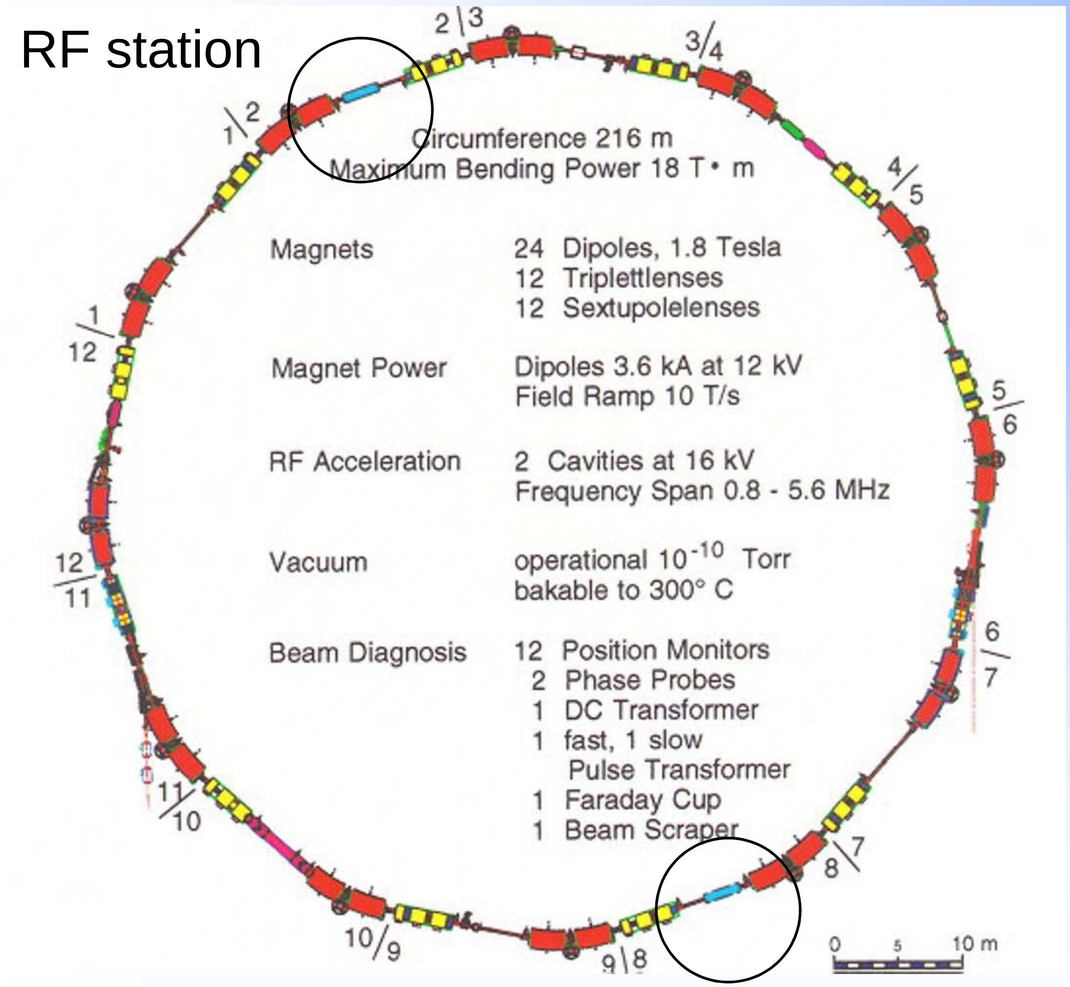


UNIversal Linear ACcelerator (UNILAC)




Rc 1505; 2f18

Schwer Ionen Synchrotron: SIS



SIS: BR=18 Tm

RF station ω_{RF}

Revolution frequency:

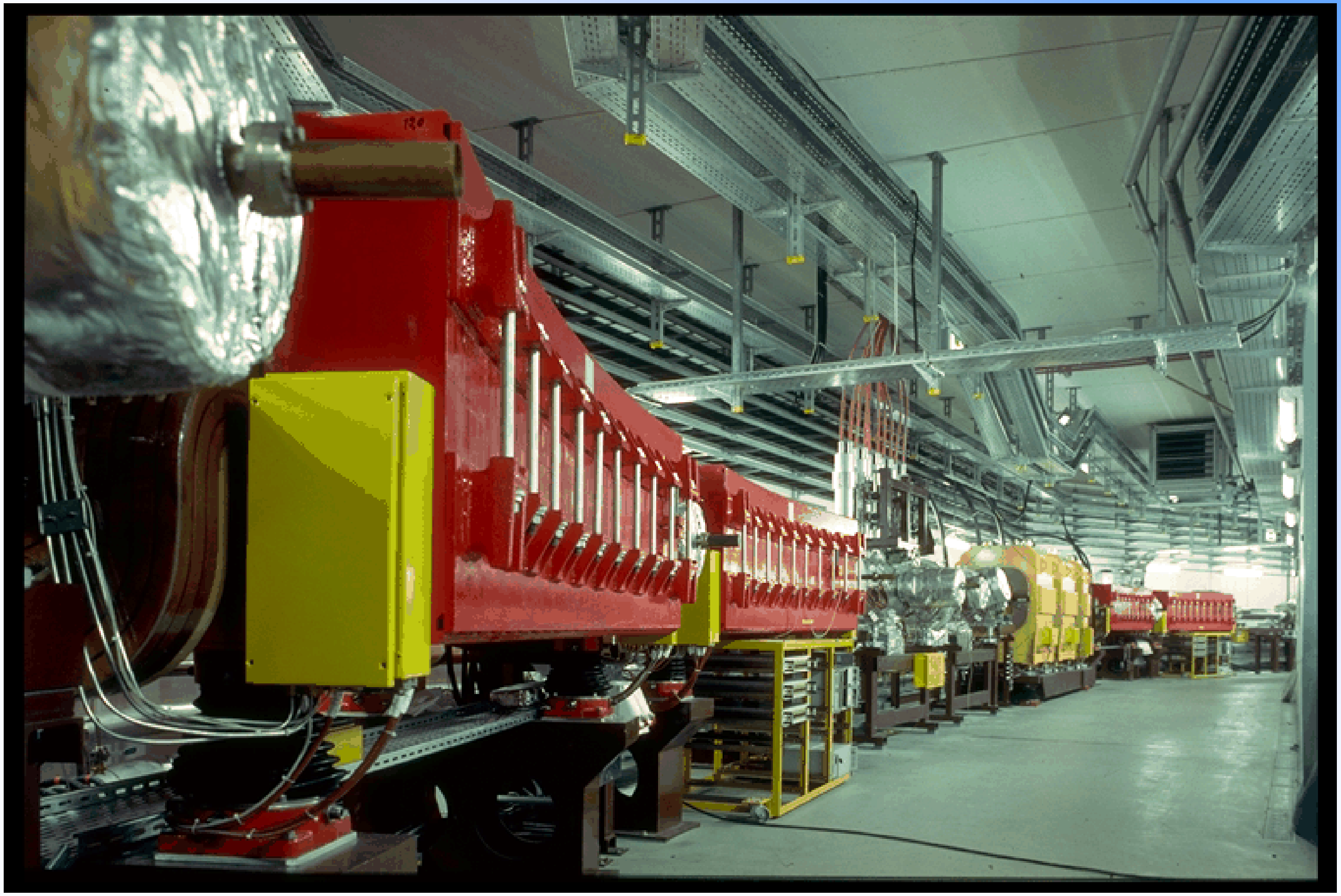
$$\omega_0 = \frac{qB_0}{\gamma m} = \frac{v_s}{R}$$

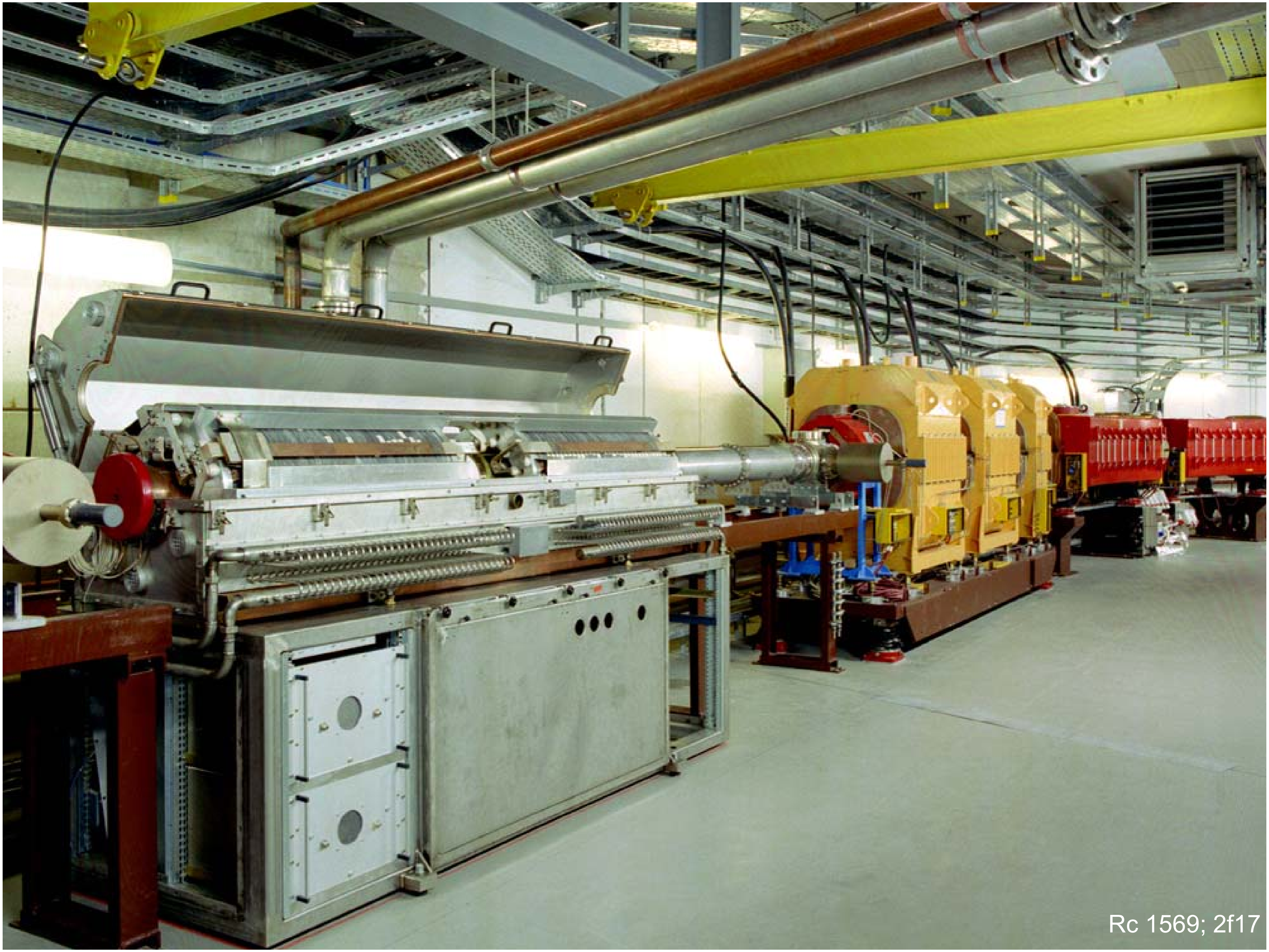
Design momentum:

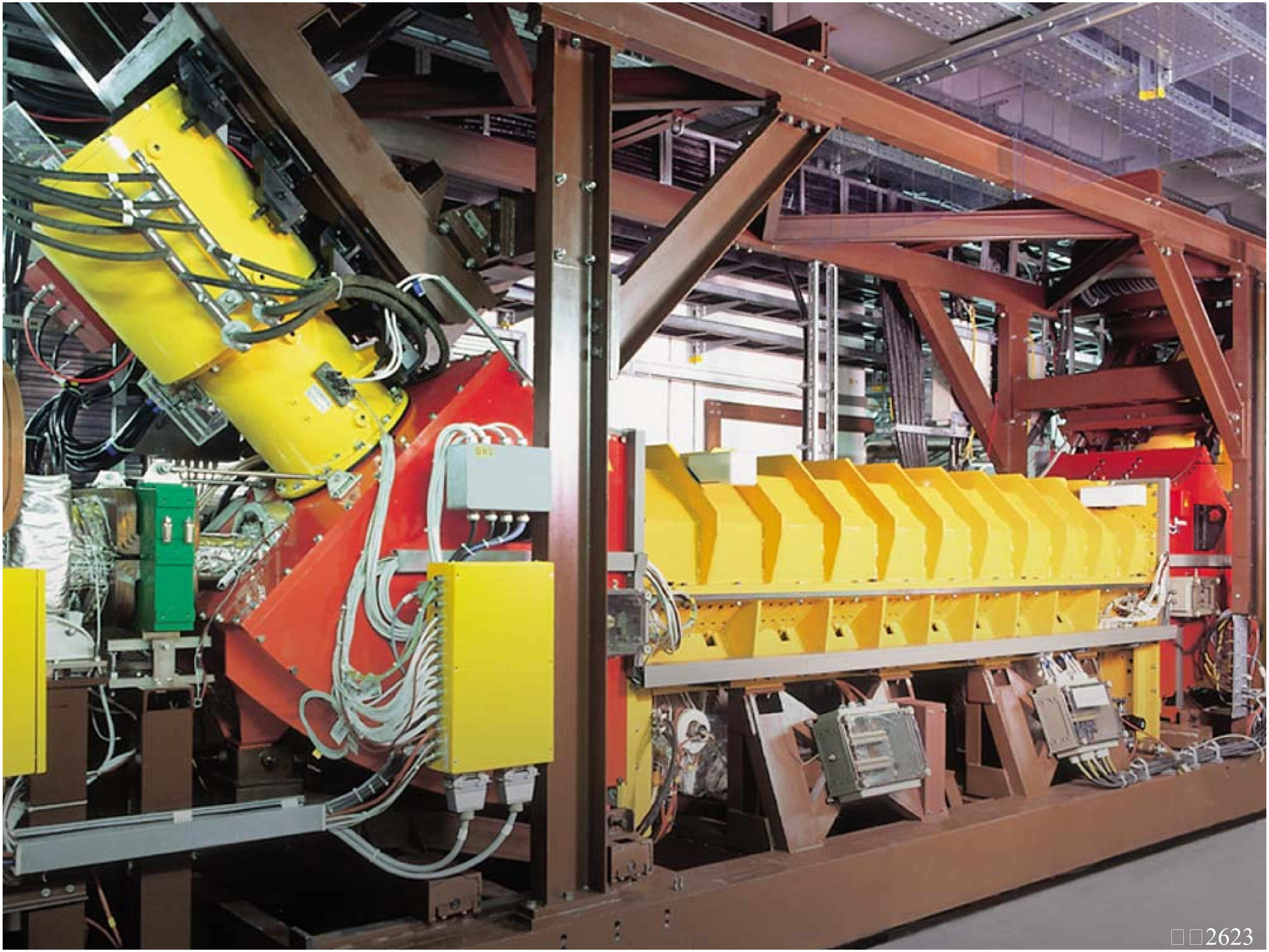
$$p_s = \gamma m v_s = qB_0 R_0$$

- Constant orbit radius
- Variable magnetic fields
- ‚Synchronous': $h\omega_0 = \omega_{RF}$
- Pulsed beams

View into the SIS tunnel




Rc 1569; 2f17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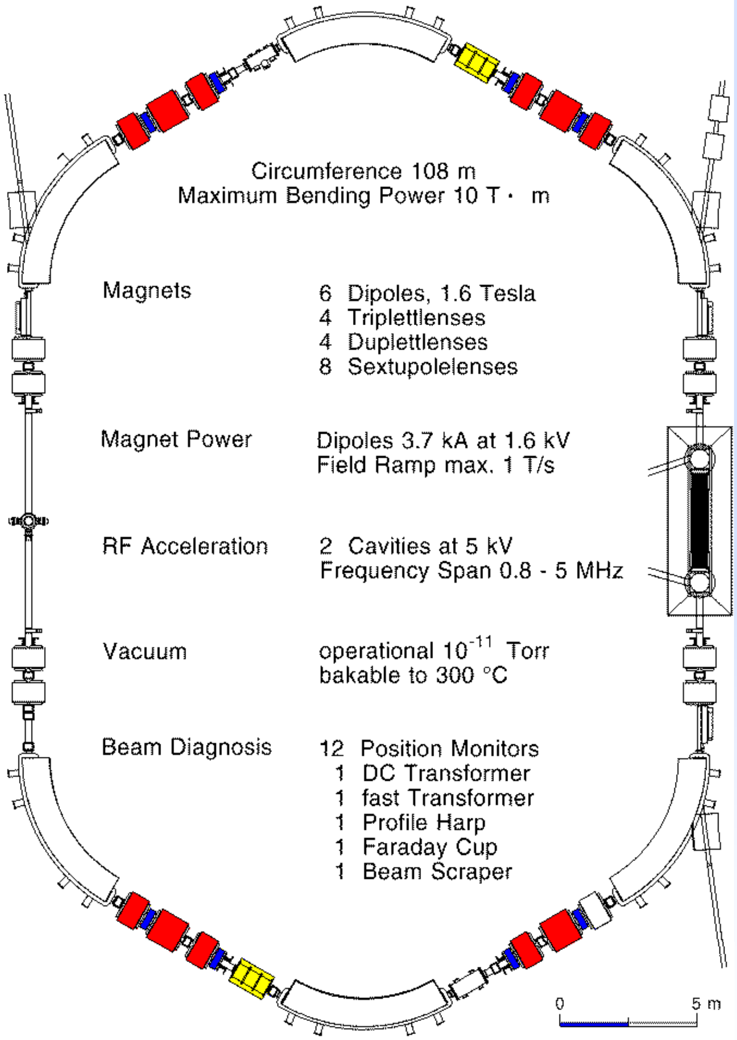
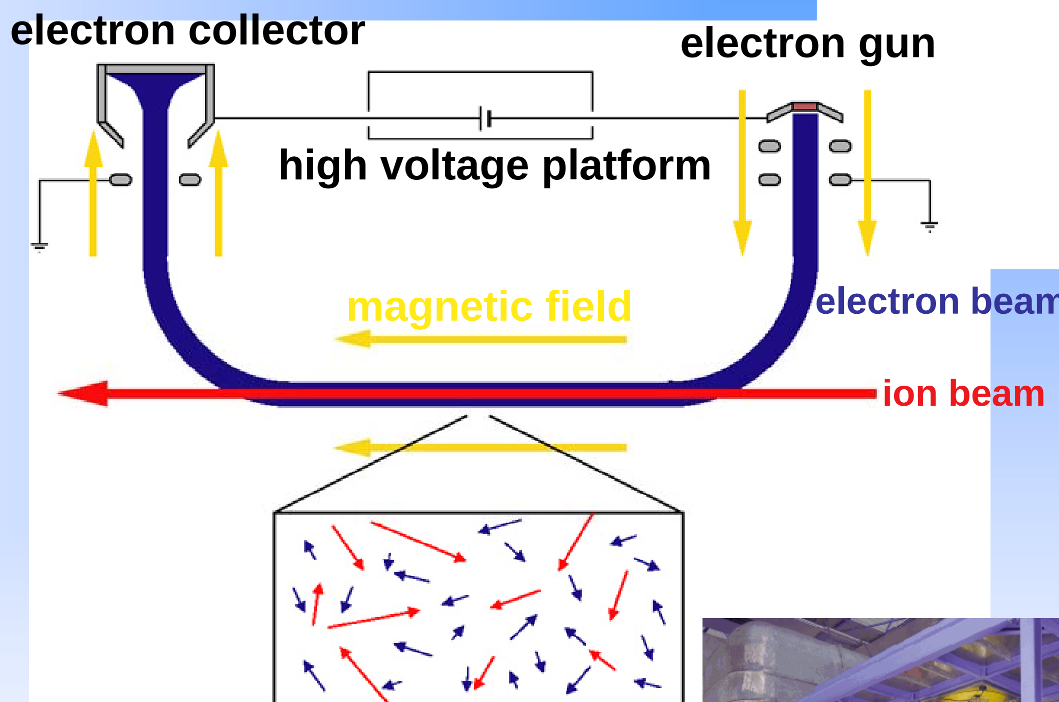
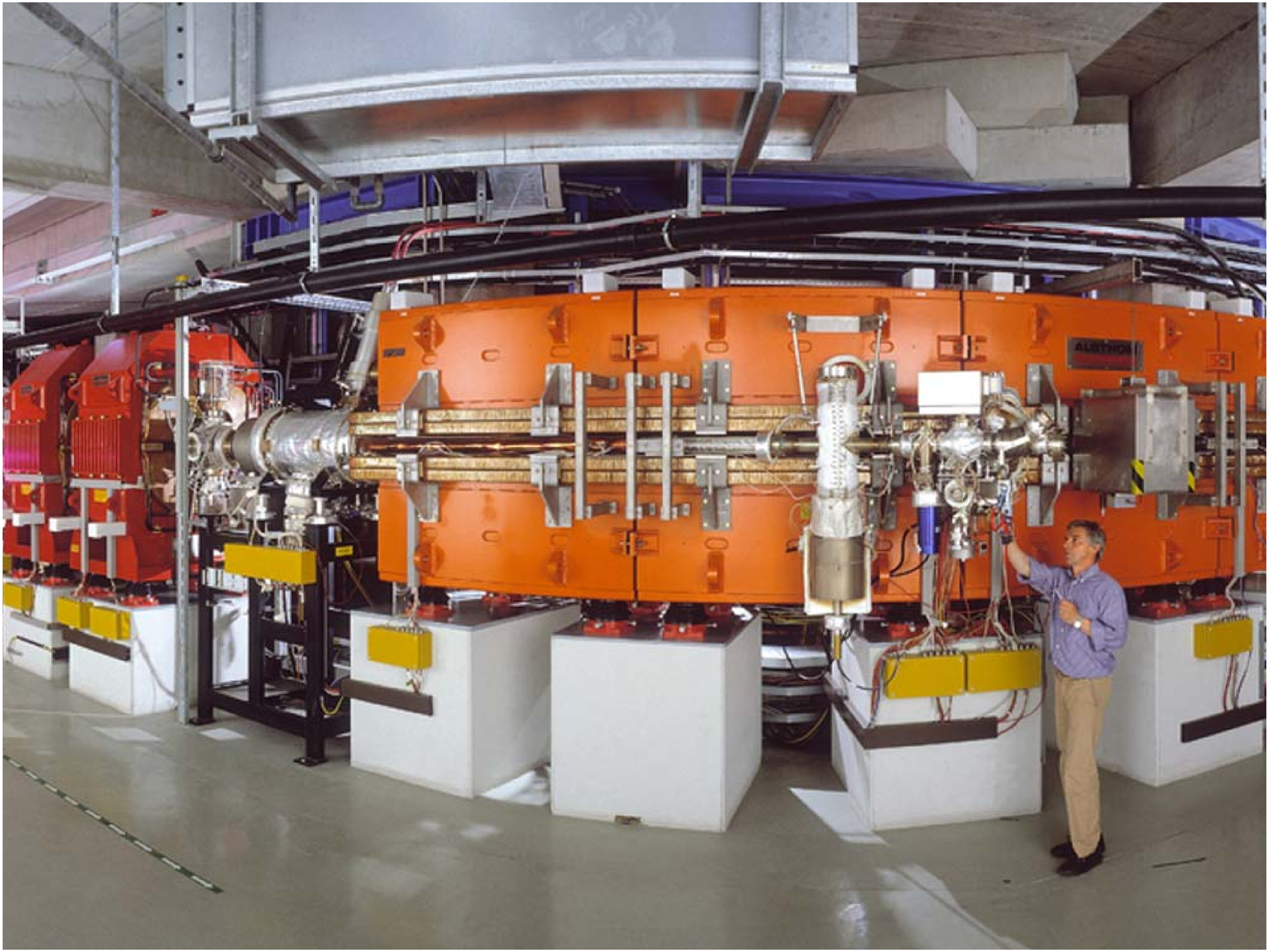
ELIN

Experimentier Speicher Ring: ESR



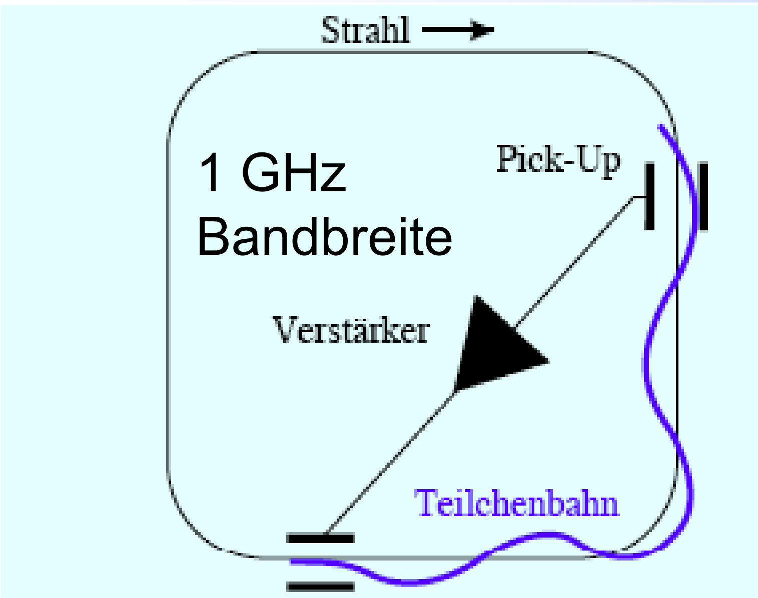


Electron cooler:

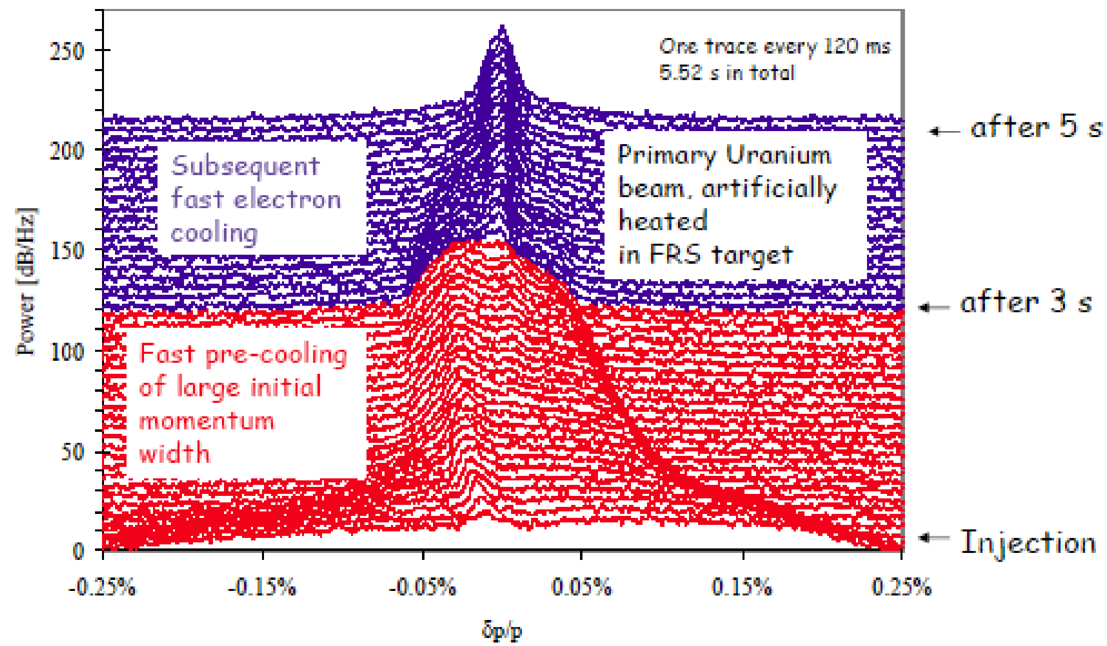


Stochastic cooling in the ESR

Principle of stochastic colling
(S. van der Meer, CERN, 1968,
Nobelprize 1984):



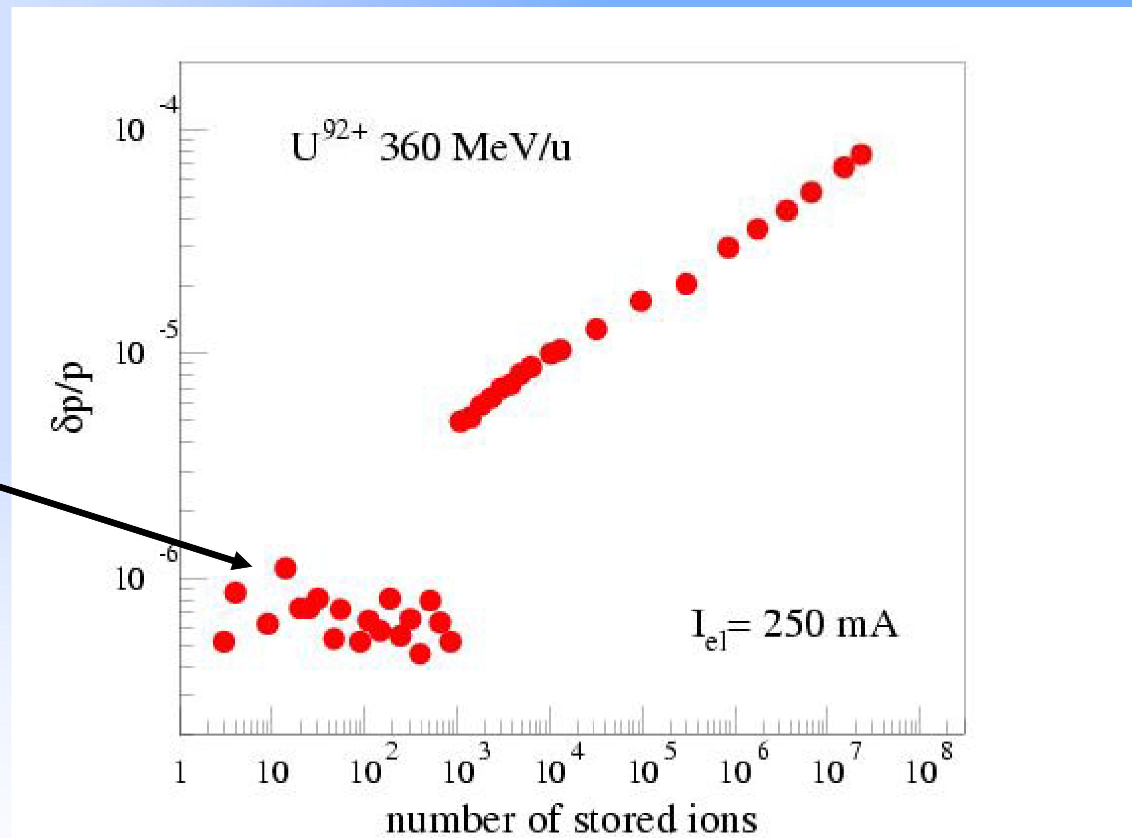
Time evolution of Schottky signals in the ESR:



Pro: Works at high energy and hot beams
Con.: Long cooling time and signal suppression if high phase space density

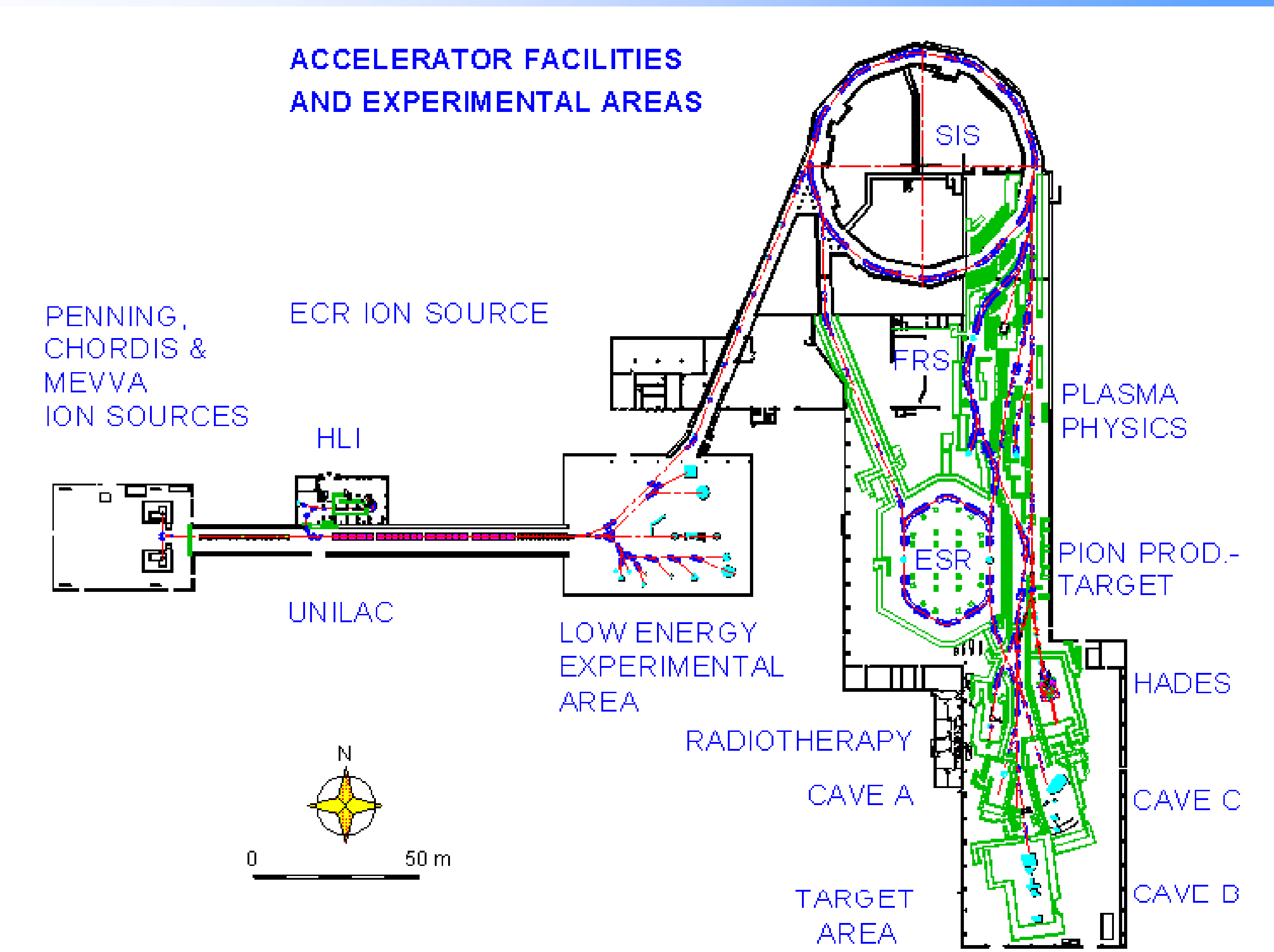
Ultra-Cold Beams

Experiments with electron cooling in the SIS:



M. Steck (1996)
R.Hasse (1999)

How do we operate the machines?



Typical Beam Time Schedule GSI

Block 3 / 2007	August 2007	Schedule as of 31-Jul-2007

Week 31					Week 32							Week 33							Week 34							Week 35				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
		a) U217, Ar Y7				UBIO, Scholz, 20 Ne, 11.4 MeV, X6		U217, Block, 48Ca / ECR, 3.4 4.0 MeV/u, 1 puA, Y7 - SHIPTRAP					c) U219, Ca, X8			U207, Backe/Herfurth, 48Ca, 5 MeV/u, 320 pnA, Y7					U200, Hessberger, 48Ca (ECR), 4.6 MeV/u, 1000 pnA , Y7					U000, 238 U (MEVVA), machine experiments				
	UBIO, Scholz, 7Li, 5-6 MeV, X6							b) S244, Ca, X7			c) U219, Ca, X8				U226, Roth/Blazevic, 48Ca17+, 4,0 MeV/u, 500 pnA, Z6						U200 -X4, Heßberger/Mann, 48Ca, copy of Y7 but only 1 Hz, X4							B-Exp., Bender/ Kollmus, Xe, 1.4MeV/u, max, 5ms, 50Hz, UU		
d)	e) STHE, Li, HTA/HTM			S318, Jonson/Aumann, 20Ne (MUCIS), 500 MeV/u, >1e10/spill, 10s extraction, spill flat, Vacuum at S2, FRS-HTC									S317, Hofmann/Franchetti, 40Ar (MUCIS), 11.4			S322, Kanungo/Nociforo, 48Ca 19+ (ECR), 700-1000MeV/u, 1e9 /spill, FRS										S000, 238U (MEVVA), machine experiments				
E067, Karpuk, Sergej/Nörtershäuser, Wilfried, 7Li+ (EZR), 58.86 MeV/u, >10 muA in ESR, ESR						E075, Kester, 20Ne (MUCIS), 4 MeV/u, 1E6/cycle (ESR), Cooling and deceleration in ESR, HITRAP													f) U221, U, HTA			S334, Wilfinger/Kelic, 238U (MEVVA), 400 MeV/u, 4E9/spill, fast extraction, HHT								
																			E061, Silver/Stoehlker, U92+, U91+ (MEVVA), 350 MeV/u, 1e8 in ESR, SIS cooler, jet target N2, Ar, deceleration in ESR to 20-50 MeV/u, ESR											

Allocated blocks include the accelerator tuning time

a) U217, Block, 40Ar (PIG), 3.4 4.0 MeV/u, 1 puA, Y7 – SHIPTRAP
b) S244, Gerl/Gorska, 48Ca, 10-15MeV/u, 10^6/pulse, X7
c) U219, Schaedel, 48Ca(ECR), 4.5-5.5 MeV/u, 1 pmicroA (Pulse), 5 ms, X8
d) S316, Fujita/Gerl, 58Ni (MEVVA), 680 MeV/u, max. intensity, 4-10s extraction, FRS-S4
e) STHE, Schardt, 7Li, 50-300 MeV/u, 1e3-1e8/spill, 2s extraction, HTA and HTM
f) U221, Braeuning-Demian, 238U (MEVVA), 100 MeV/u , block sharing mode with FRS, HTA

Andreas Tauschwitz, Phone +49-6159-712723, E-mail beamtime@gsi.de

Tuesday, 31 July, 2007 18:16

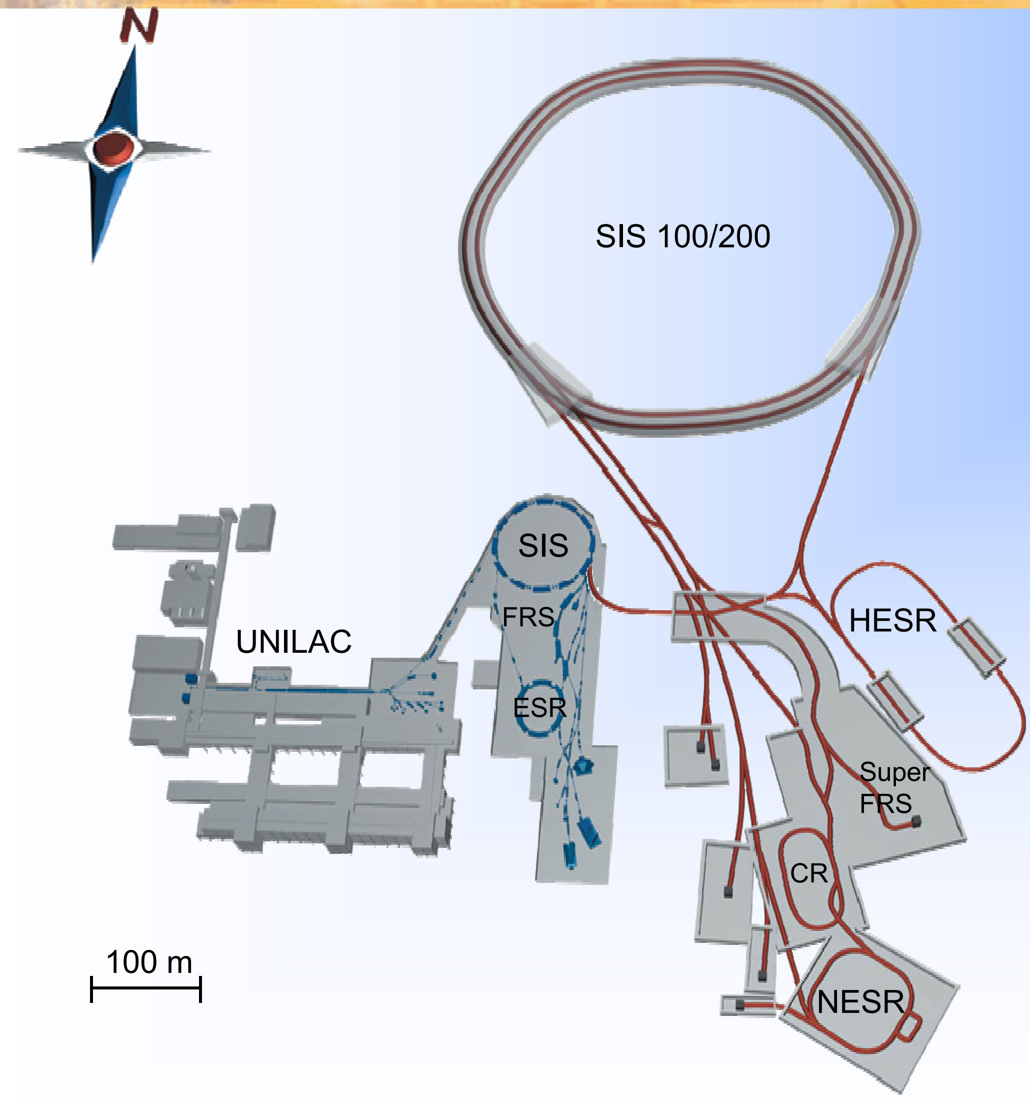
Part V: The future of GSI

FAIR:

The Facility for Antiproton and Ion Reserach

This will be YOUR new accelerator!

FAIR – Facility for Antiproton and Ion Research



Gain Factors

- Primary beam intensity:
  Factor **100 – 1000**
- Secondary beam intensities for radioactive nuclei: up to factor **10,000**
- Beam energy: Factor **15**

Special Properties

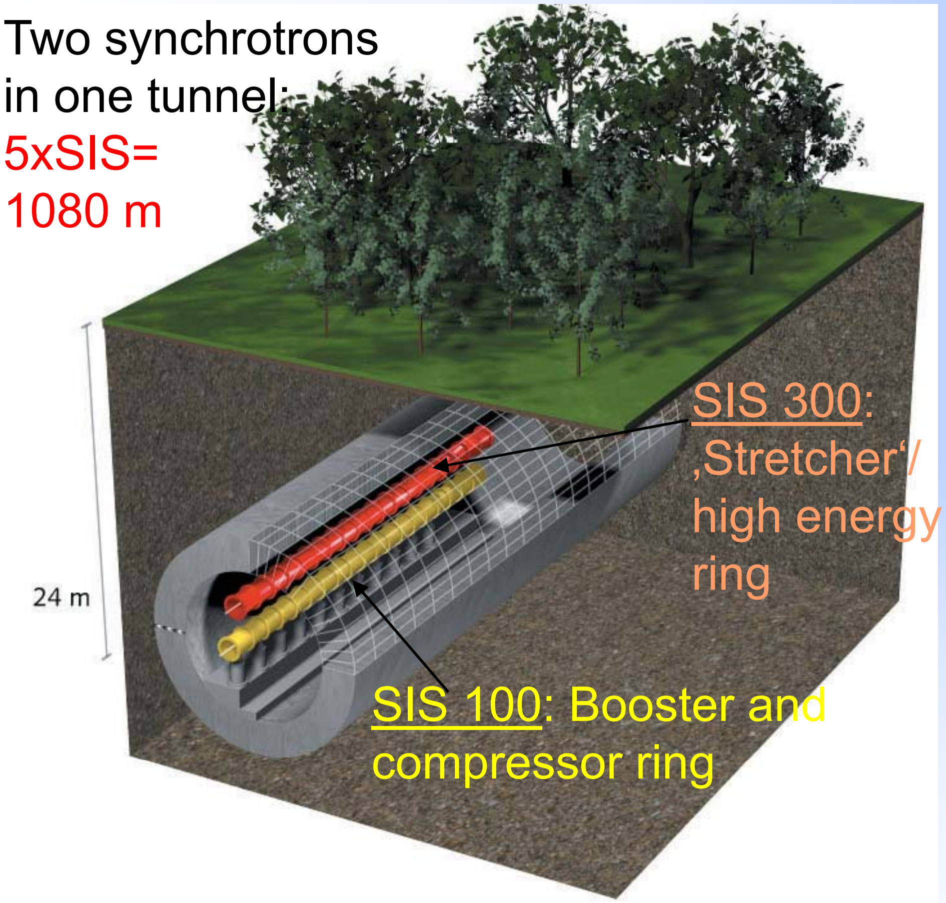
- Intense, fast cooled energetic beams of exotic nuclei
- Cooled antiproton beams up to15 GeV
- Internal targets for high-luminosity in-ring experiments

New Technologies

- Fast cycling superconducting magnets
- Electron cooling at high ion intensities and energies
- Fast stochastic cooling

The SIS 100/300 Double-Synchrotron

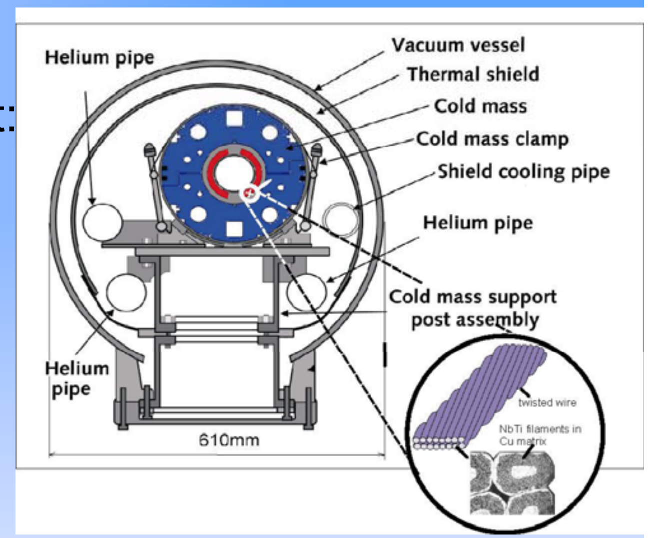
Two synchrotrons in one tunnel:
5xSIS= 1080 m



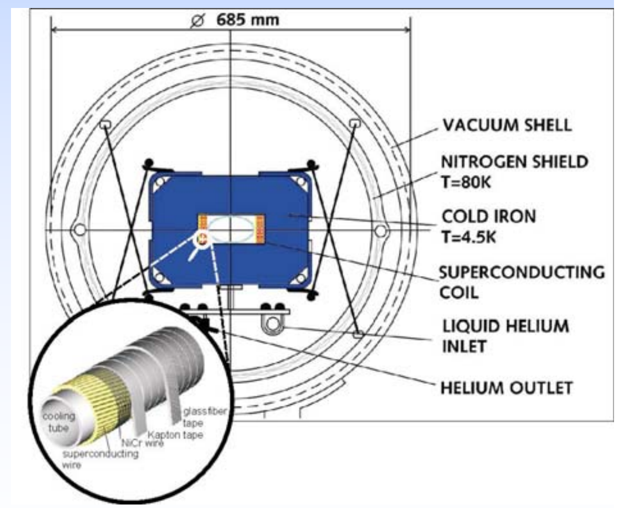
SIS 300: ‚Stretcher'/ high energy ring

SIS 100: Booster and compressor ring

RHIC-typ dipole magnet:
B=4T (6T), dB/dt=1T/s

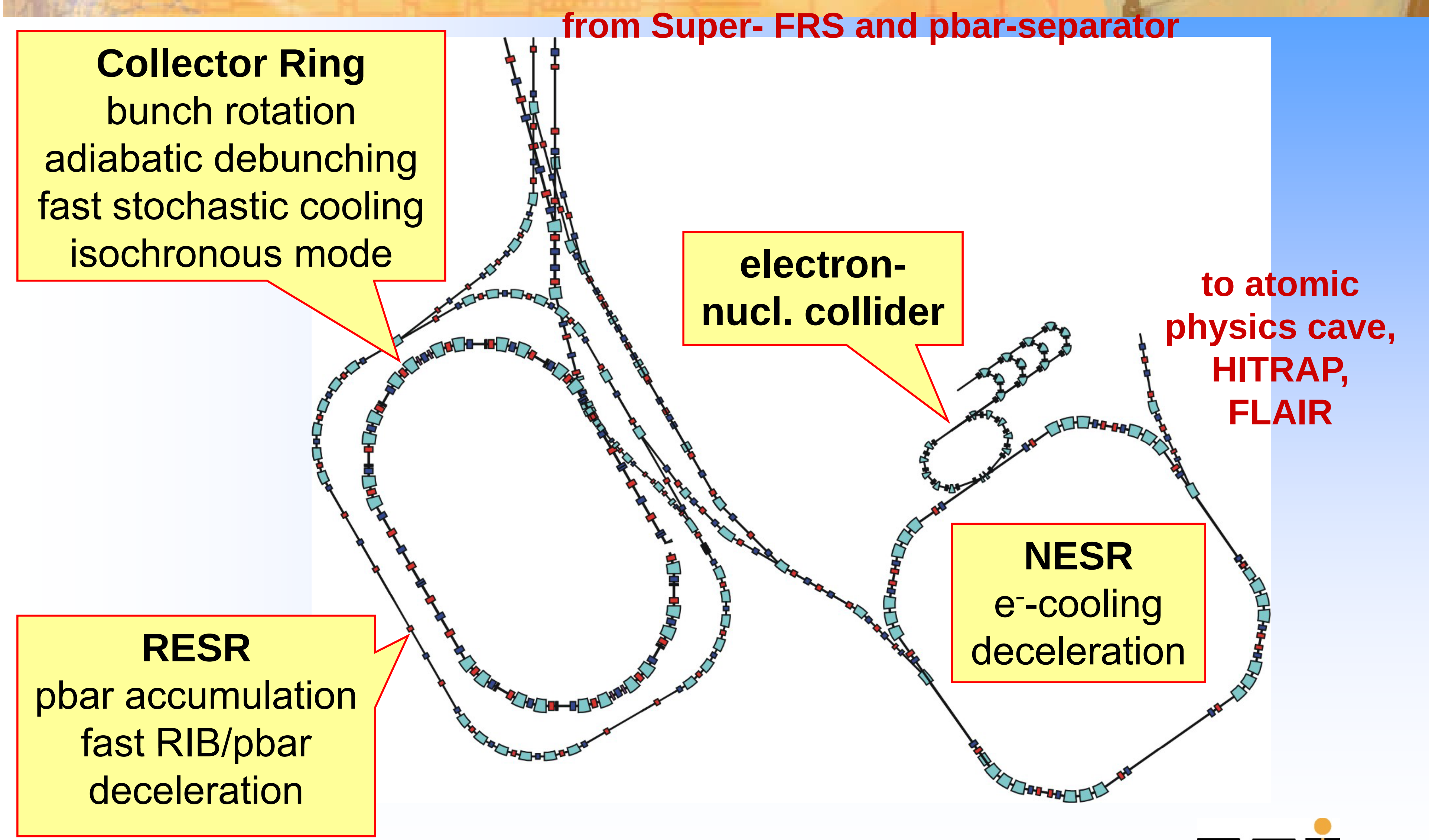


Nuclotron-type dipole magnet:
B=2T, dB/dt=4T/s



2x108 superconducting (SC) dipole magnets
168+156SC quadrupole magnets

Storage Ring Complex for Secondary Beams



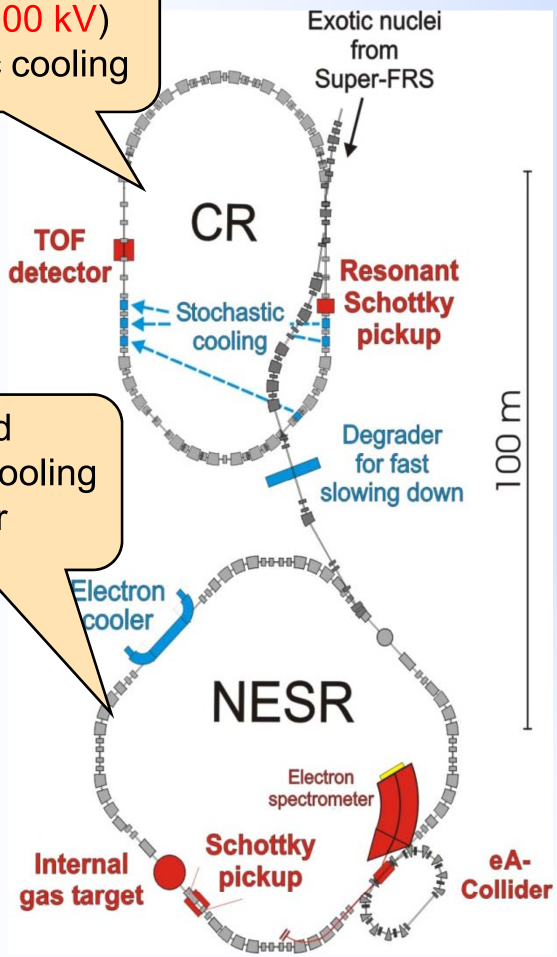
Collector and Accumulator Rings for Exotic Ions

from Target/SFRS

5 'decompressor' cavities (200 kV) + stochastic cooling

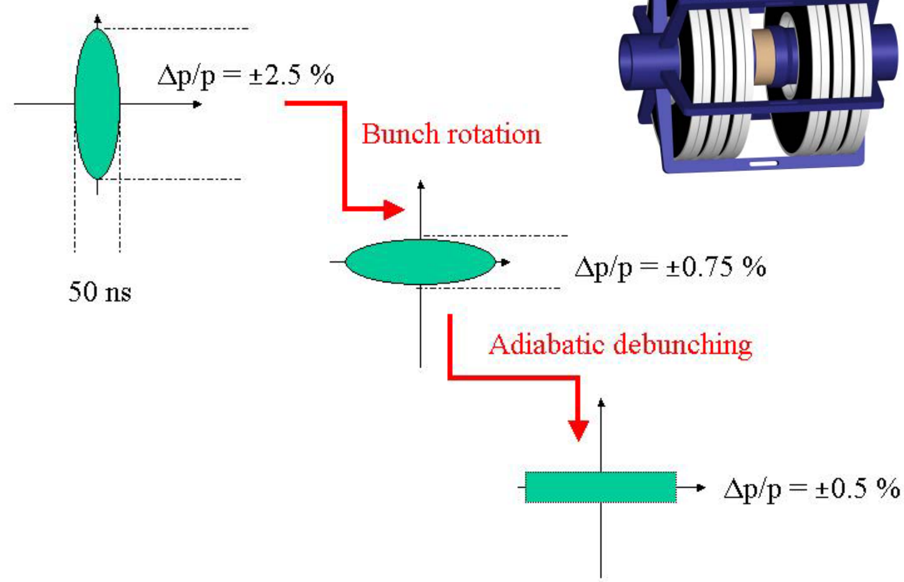
180 m circum- ference

Electron and stochastic cooling + eA collider



210 m circumference (approx. 2xESR)

Fast debunching of exotic nuclei

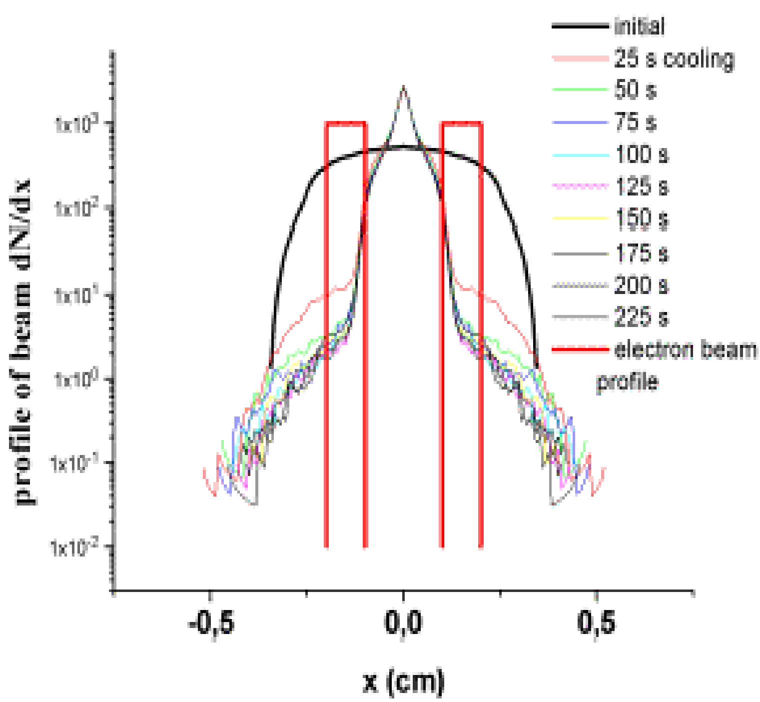


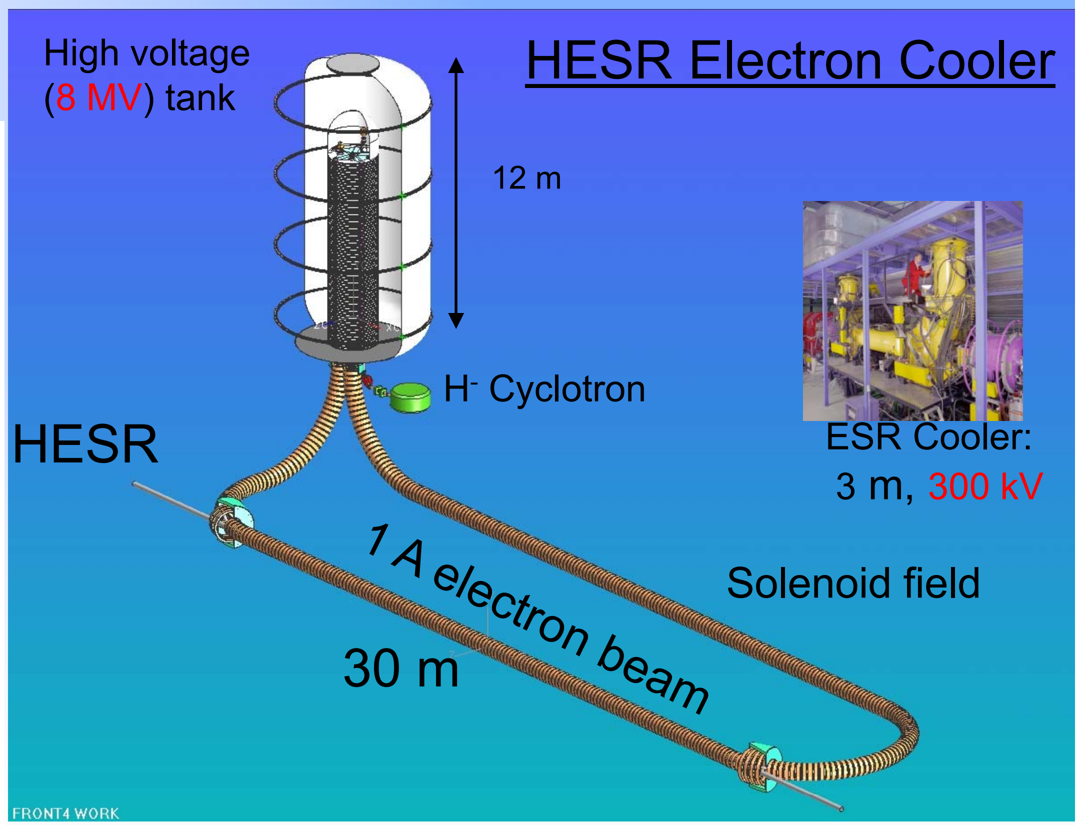
CR+NESR: 2x24 large aperture (±180 mm) superferric (1.6 T) dipole magnets

Antiproton Electron Cooling at High Energies

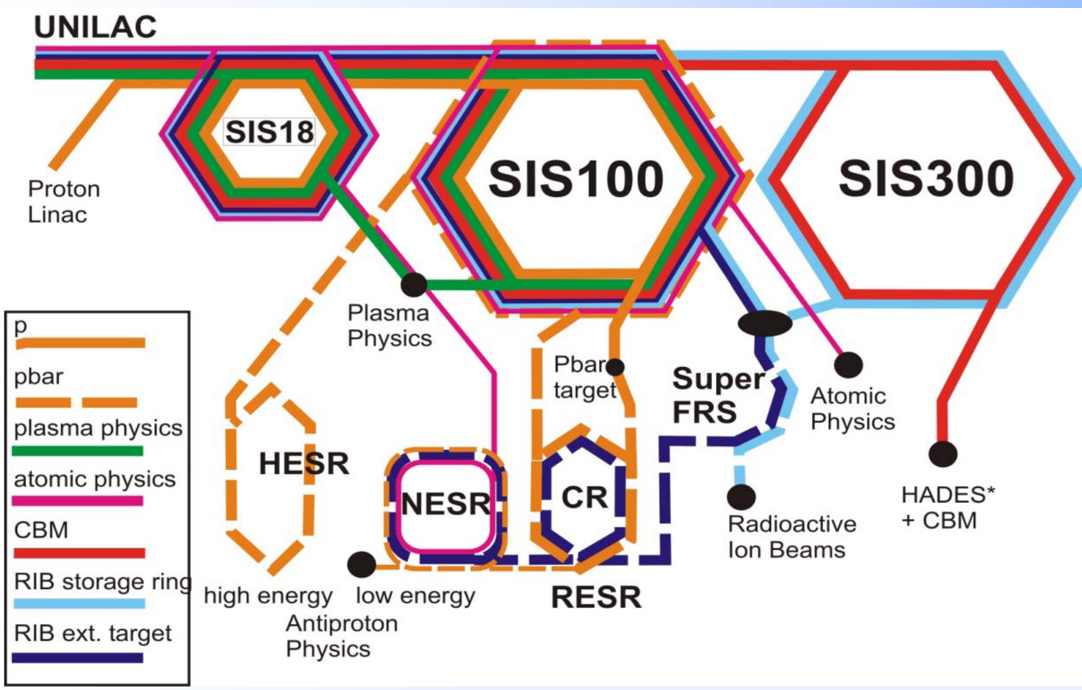
Feasibility study of fast ('seconds') electron cooling for the HESR, Budker Institute, Novosibirsk, RUS

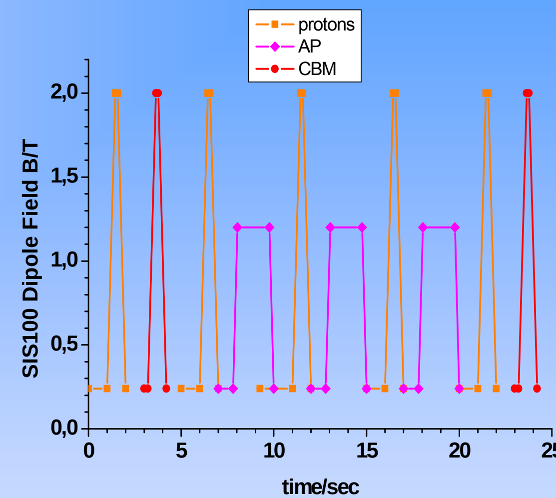
Monte-Carlo-Simulation of pbar cooling:

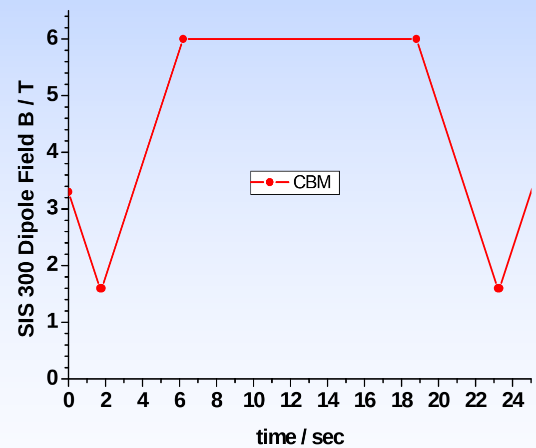




FAIR Operation







- 2 linacs, 3 synchrotrons, >4 storage rings
- Complex parallel operation
- Minimize commissioning times

A big project with major challenges

One problem singled out:

The lifetime of U^{28+} beams in our FAIR accelerators.

U^{28+} :
Reference Ion of the FAIR Project

Present Intensity in SIS12/18

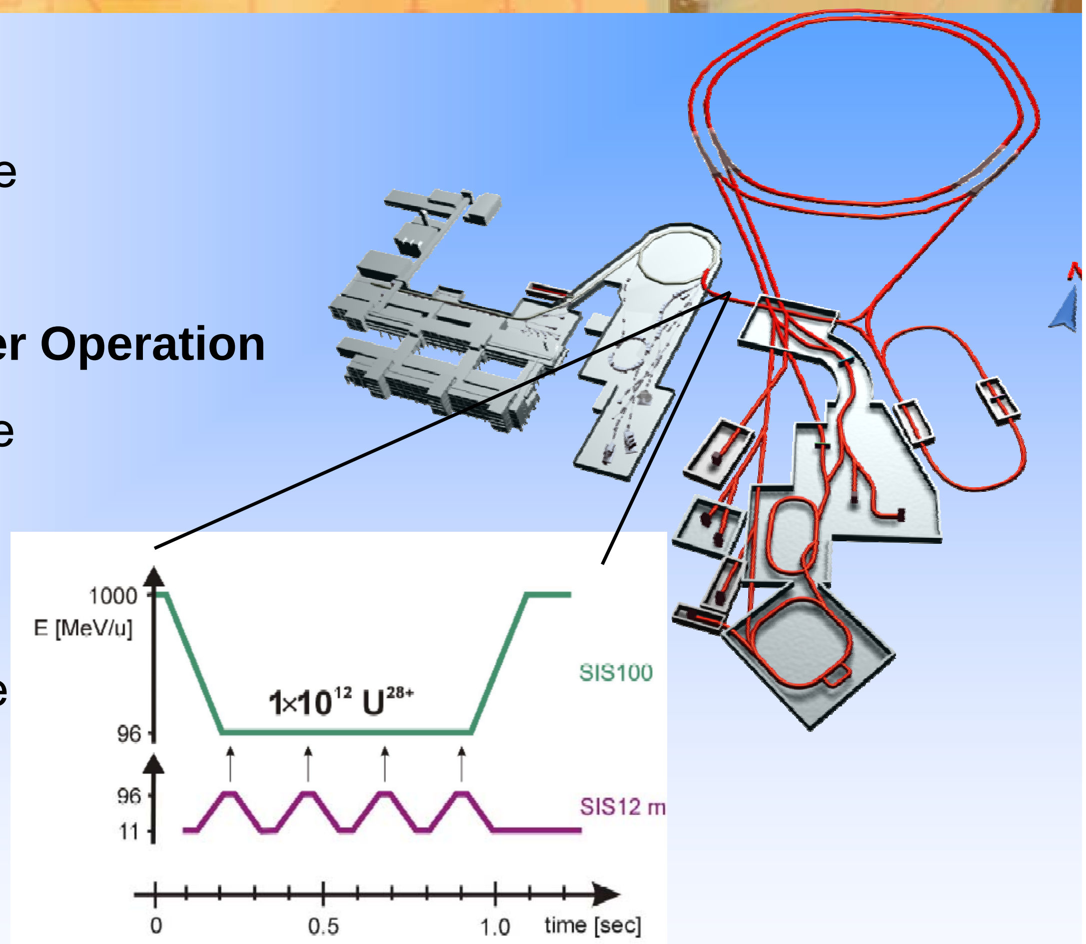
2.5 x 10^9 U^{73+} -ions /cycle

Planned Intensity in SIS12 Booster Operation

2.5 x 10^{11} U^{28+} -ions /cycle

Planned Intensity in SIS100/300

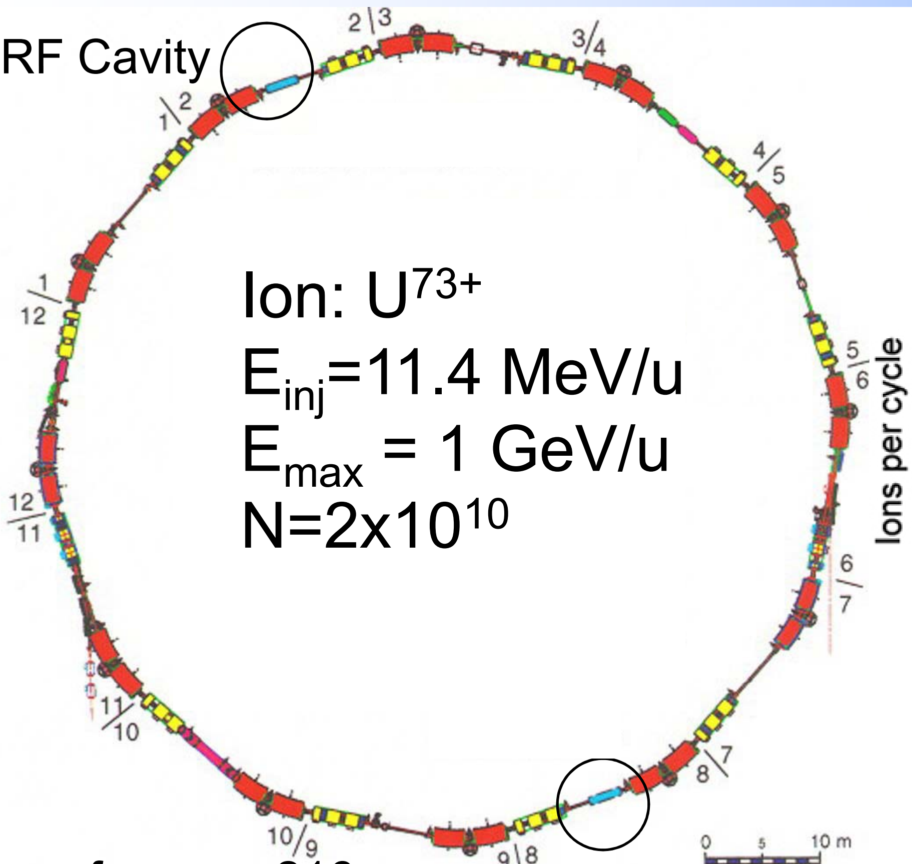
1 x 10^{12} U^{28+} -ions /cycle



Why U^{28+} ?

18 Tm (10 T/s)

RF Cavity



Ion: U^{73+}

E_{inj}=11.4 MeV/u

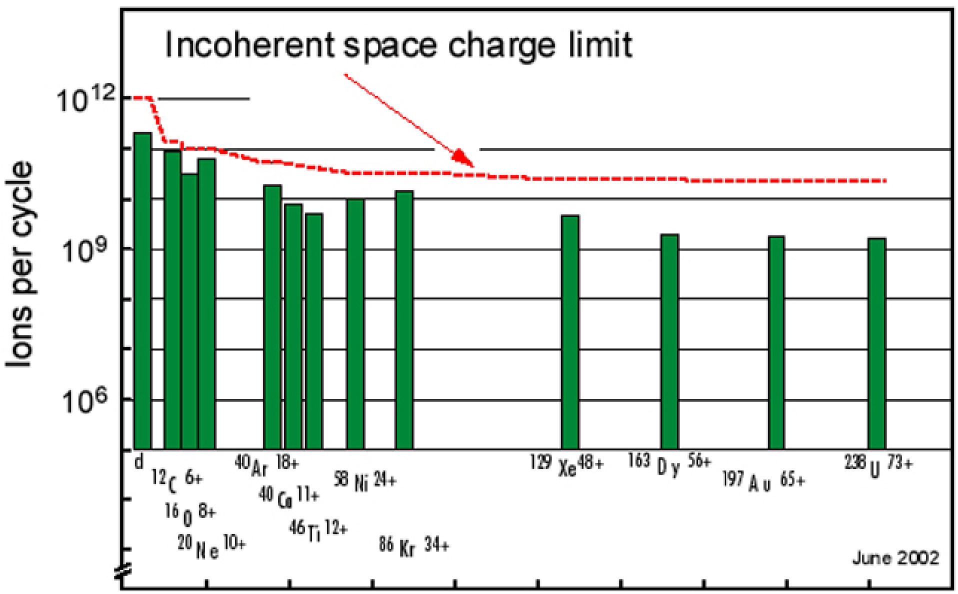
E_{max} = 1 GeV/u

N=2x10^{10}

Circumference: 216 m

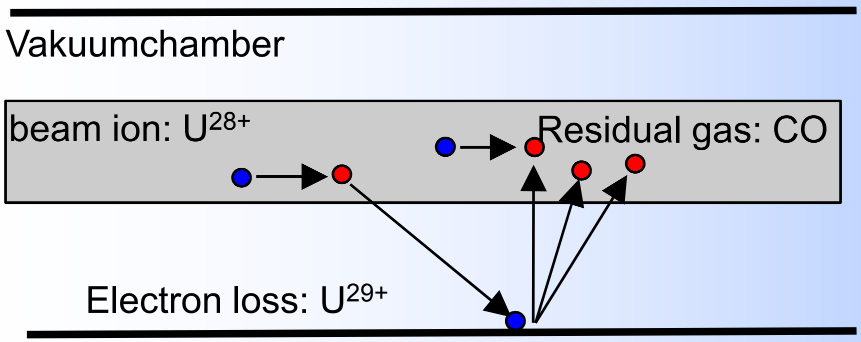
RF Cavity

Space charge limit

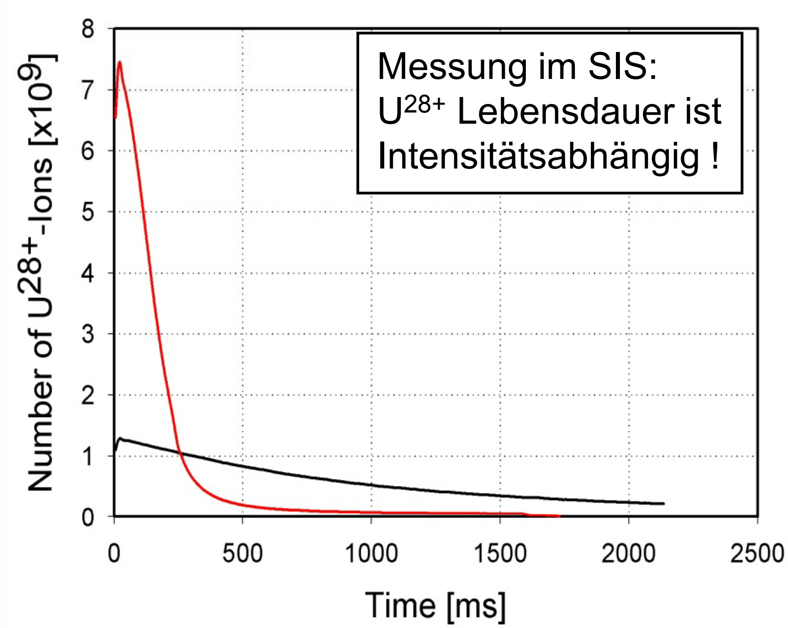


Development of SIS beam intensities

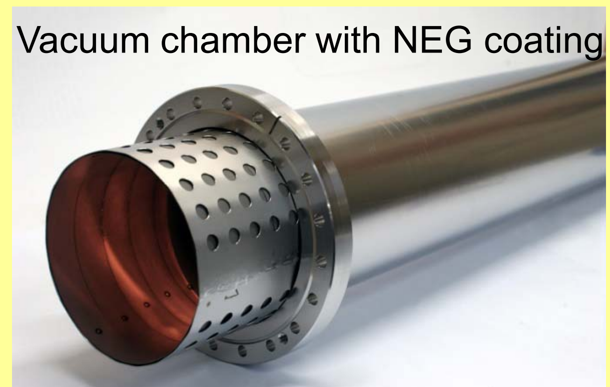
Dynamic vacuum



Desorptioncoefficient: $\eta \approx 10^4$!!!



Vacuum chamber with NEG coating



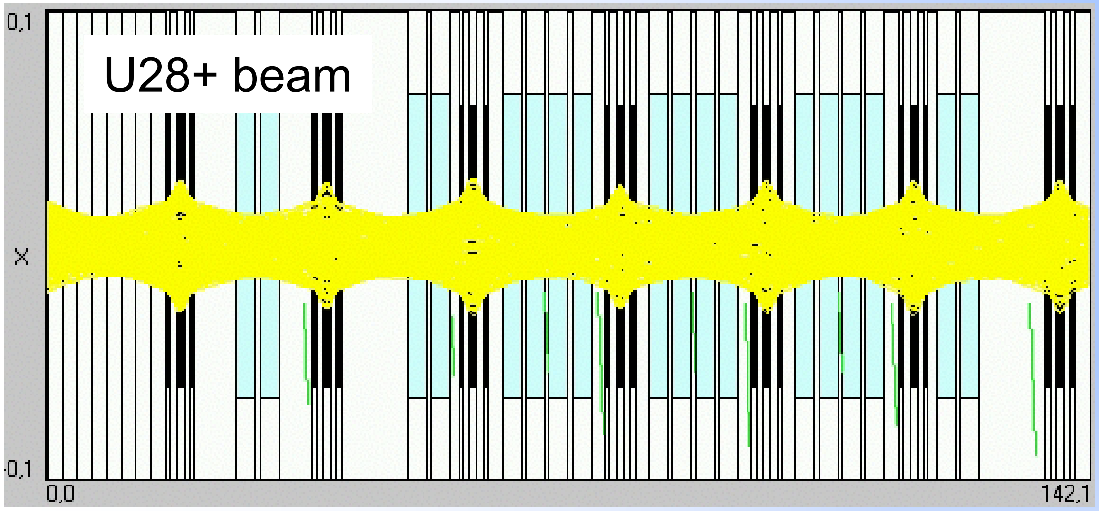
E. Mahner, LHC Division - Vacuum Group

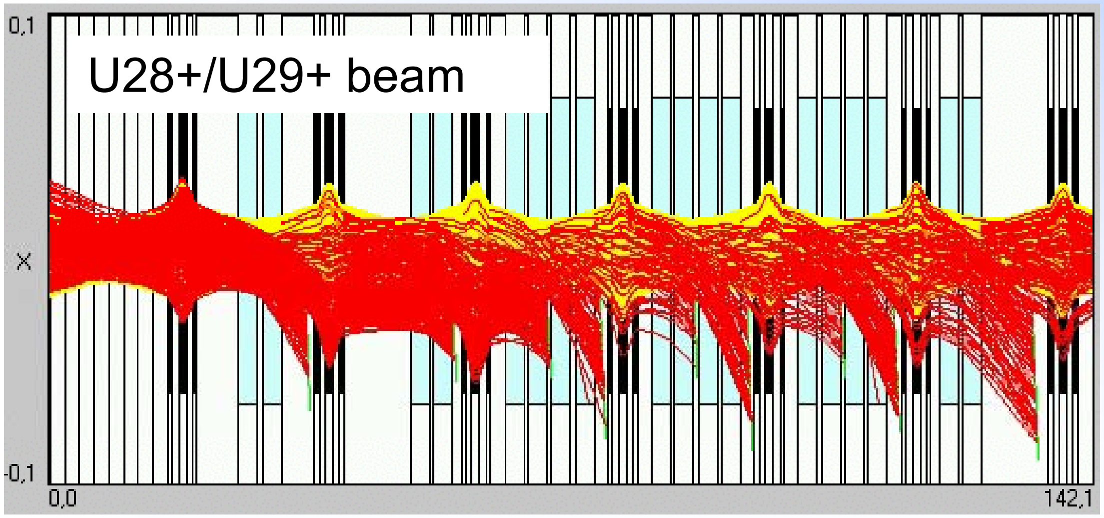
High pumping speed

S_{H_2}: 1000 l.s^{-1}.m^{-1} S_{CO}: 2000 l.s^{-1}.m^{-1}

S_{CO_2}: 1500 l.s^{-1}.m^{-1} S_{N_2}: 450 l.s^{-1}.m^{-1}

Beam losses due to Stippping in Residual Gas



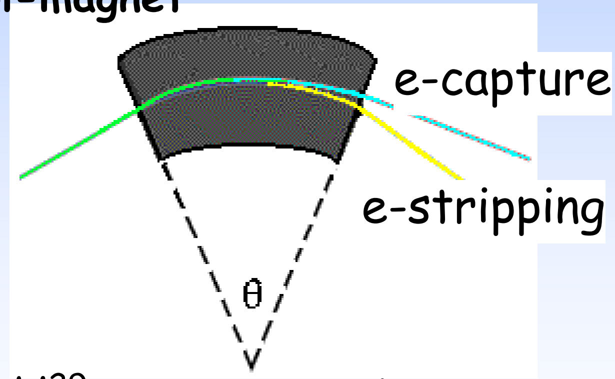


Projectile-Ion-Stripping in residual gas:

$$U^{28+} + X \rightarrow U^{(28+j)+} + X^{m+} + (m+j)e$$

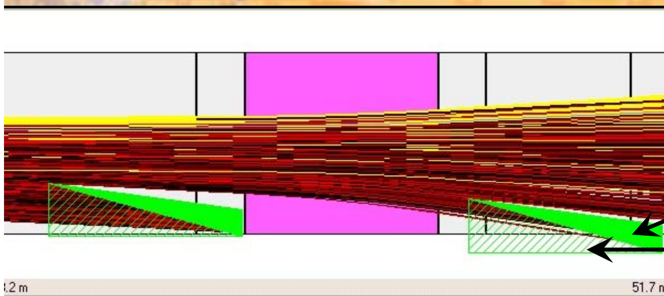
Limitation for SIS 18 at the moment 10^9 U^{28+} !

Dipol-magnet



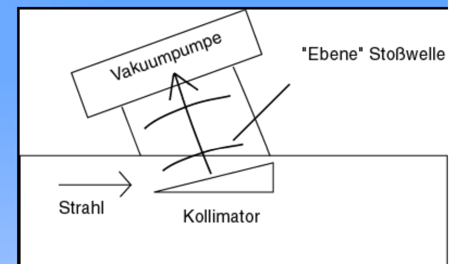
U^{29+} correspons to momentum spread of Δp/p=-3.5 %

Charge Separator Lattice and Collimation

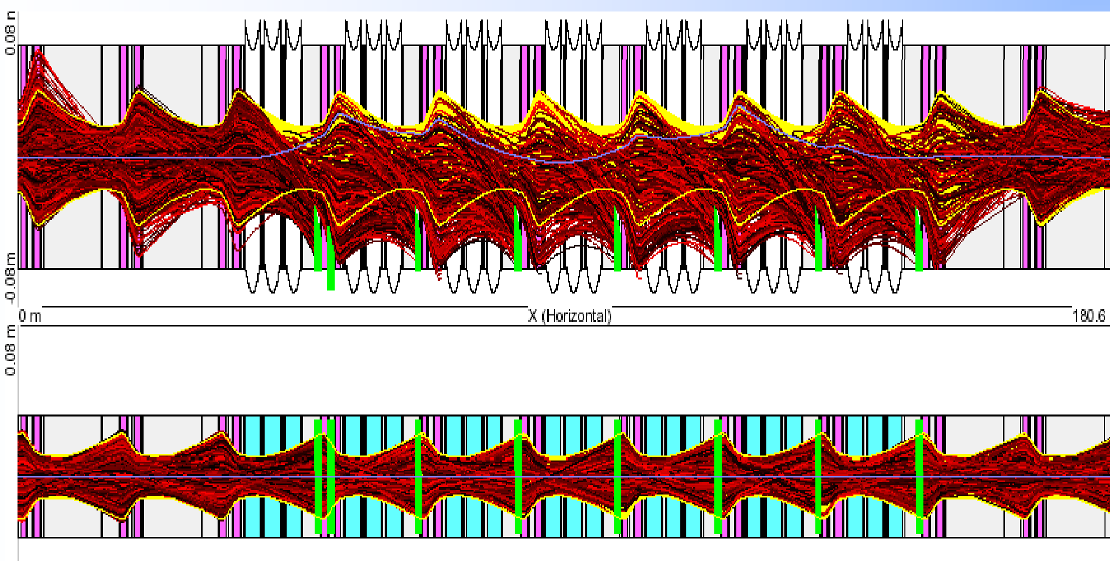


Wedge collimator at 80 K

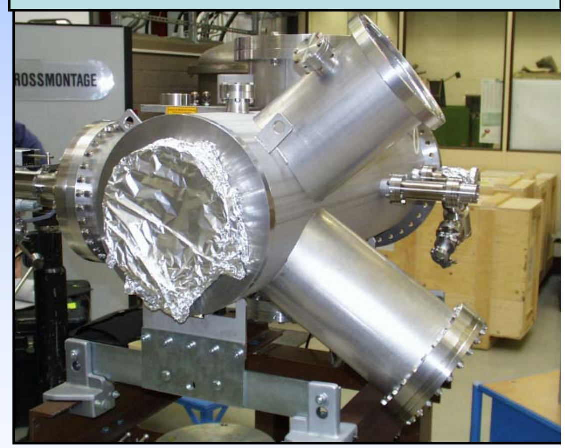
Pumping sec. chamber at 4 K



Principle



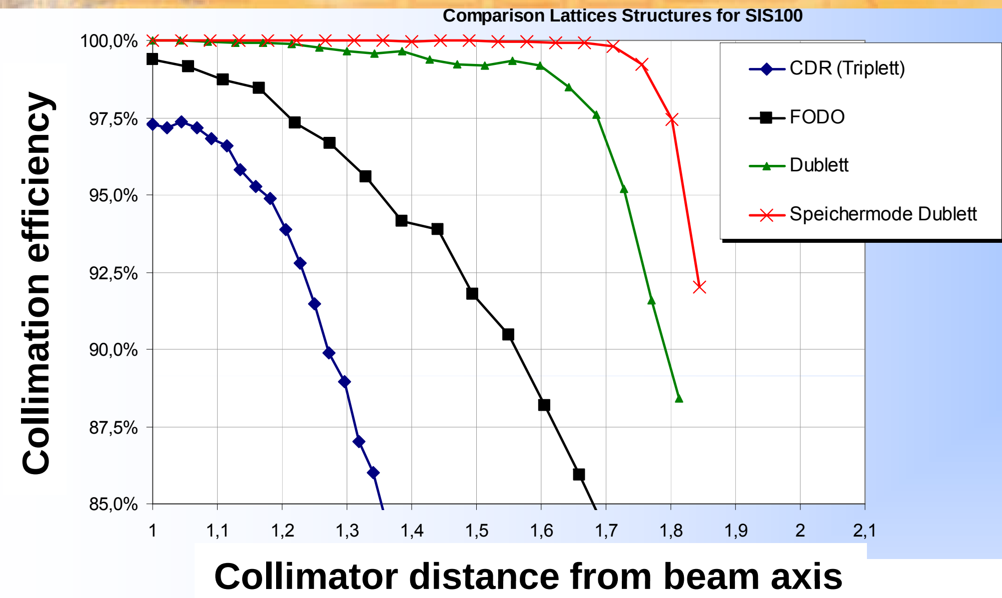
SIS18 warm prototype

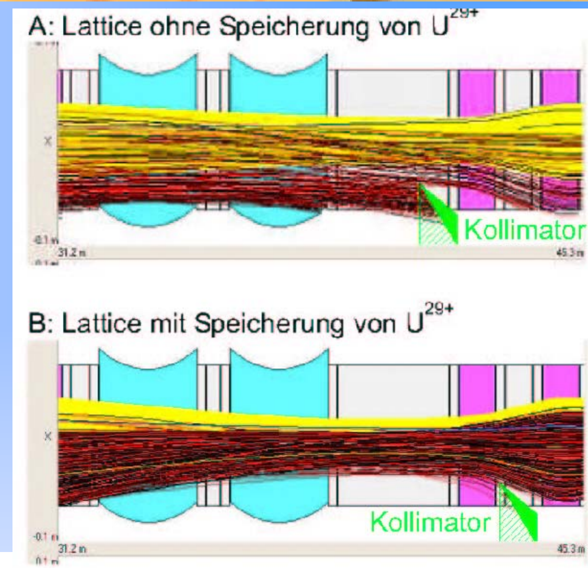


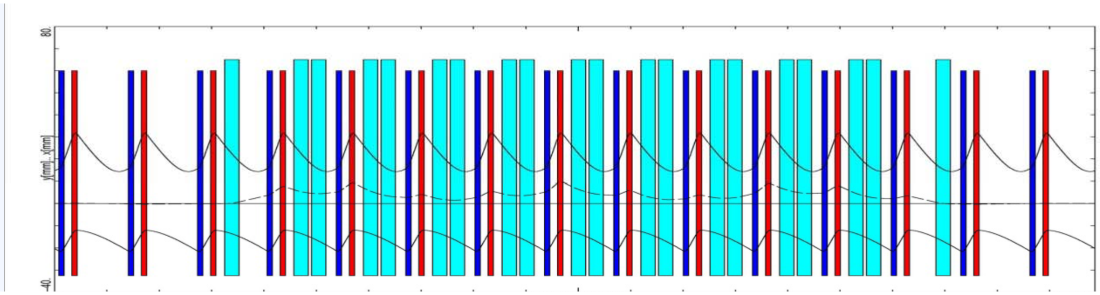
Lattice optimized according to peaked distribution of ionization losses

The collimations system must confine the desorbed gases ($\eta_{eff} = 0$)

SIS100 Storage Mode Lattice







Missing dipole concept creates flat minimum dispersion function

Storage mode lattices provide 100% collimation efficiency at maximum acceptance

Discussion

Some say accelerator physics is all about superlatives and "gigantomania".

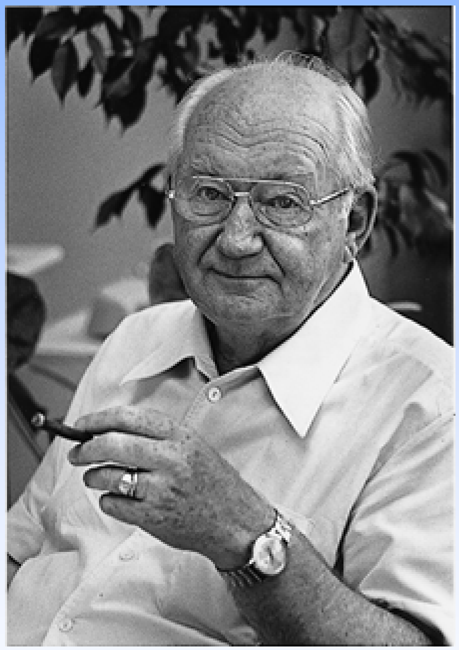
But isn't that exactly the definition of fun?

With this and some wise words I want to

END

Happiness is not to be found in knowledge, but in the acquisition of knowledge.

(Egar Allan Poe)



Professor Dr. Christoph Schmelzer,
First Director of GSI,
"father" of the UNILAC.