The Accelerator Facilities at the Paul Scherrer Institute (PSI) in Villigen, Switzerland

Werner Joho

January 2017


PSI East
Aare
SwissFEL
psi Forum
Auditorium
Exp. Hall
Neutron Source
SLS
PSI West
medical Annex

PSI has 4 Top-class Accelerators!

- Ring-Cyclotron : 590 MeV Protons (1974)

  => Neutrons, muons

- SLS: Storage Ring , 2.4 GeV Electrons (2000)

  => X-rays

- compact-Cyclotron COMET: 250 MeV Protons (1996)

  => Cancer Therapy

- SwissFEL, Electron Linac , 6 GeV (2016)

  => Femtosecond X-ray Flashes

3 Probes for Material Research

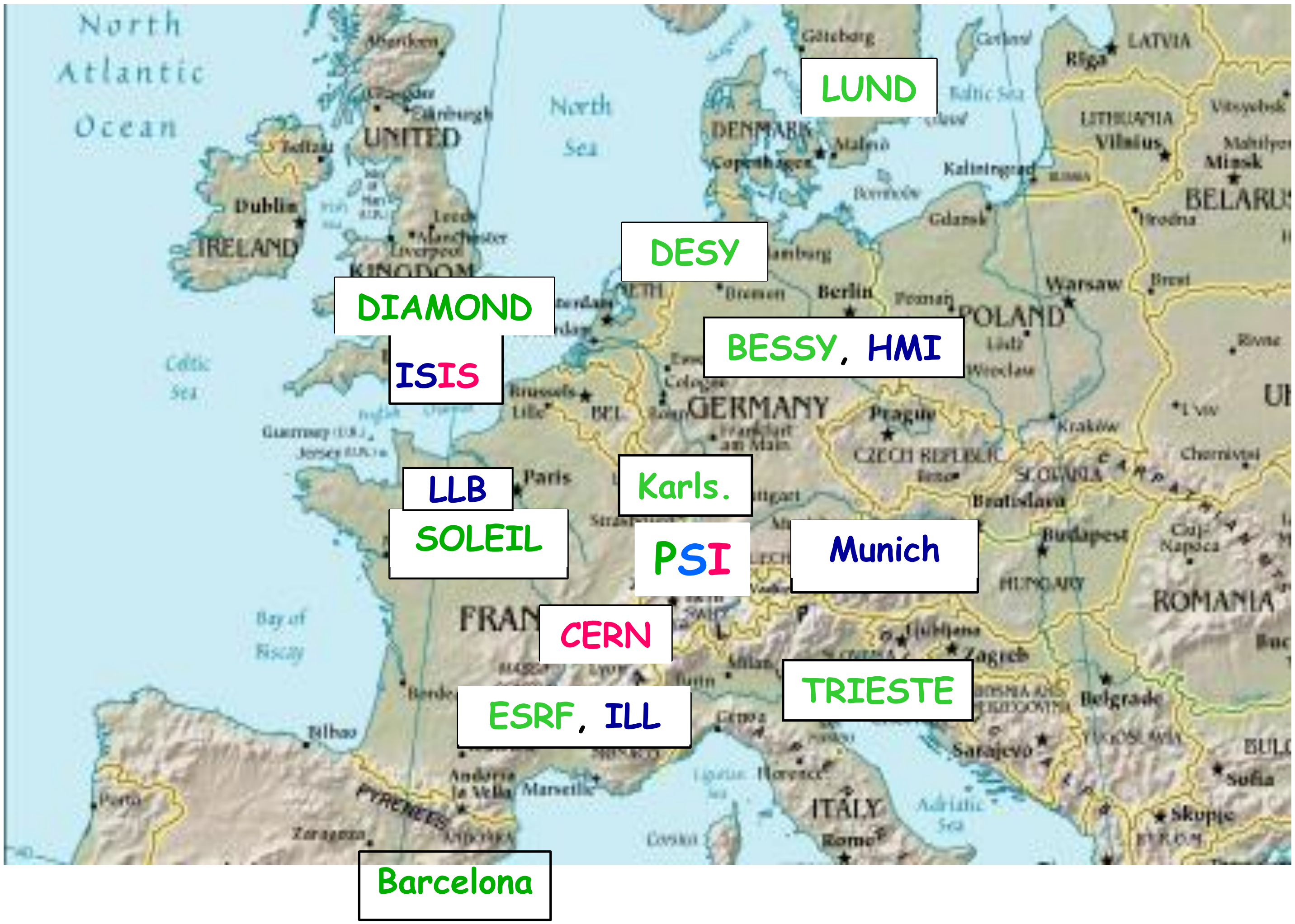
only at PSI and Rutherford Lab

Photons (SLS, SwissFEL) ⇨ Electron Cloud

Neutrons (SINQ) ⇨ Atomic Nuclei

Muons (μSR) ⇨ internal magnetic Fields in Crystals

Facilities in Europe for Material Sciences



X-rays
Neutrons
Muons

Ring Cyclotron
590 MeV Protons

2.4 mA, 1.4 MW average Beam Power
(World Record!)

most intensive
Muon Beams
$5 \cdot 10^8$ μ^+/s , 10^8 μ^-/s

Spallation-Neutron-Source
10^{14} n/s

equivalent to
medium Flux Reactor
(but without Uranium!)

Swiss Light Source (SLS)
2.4 GeV Electron Storage Ring

- constant beam current (400-402 mA)
  due to **top-up** injection every 2.5 min.

- extremely stable Photon Beams
  due to „**fast orbit feedback**" (< 0.2 μm)

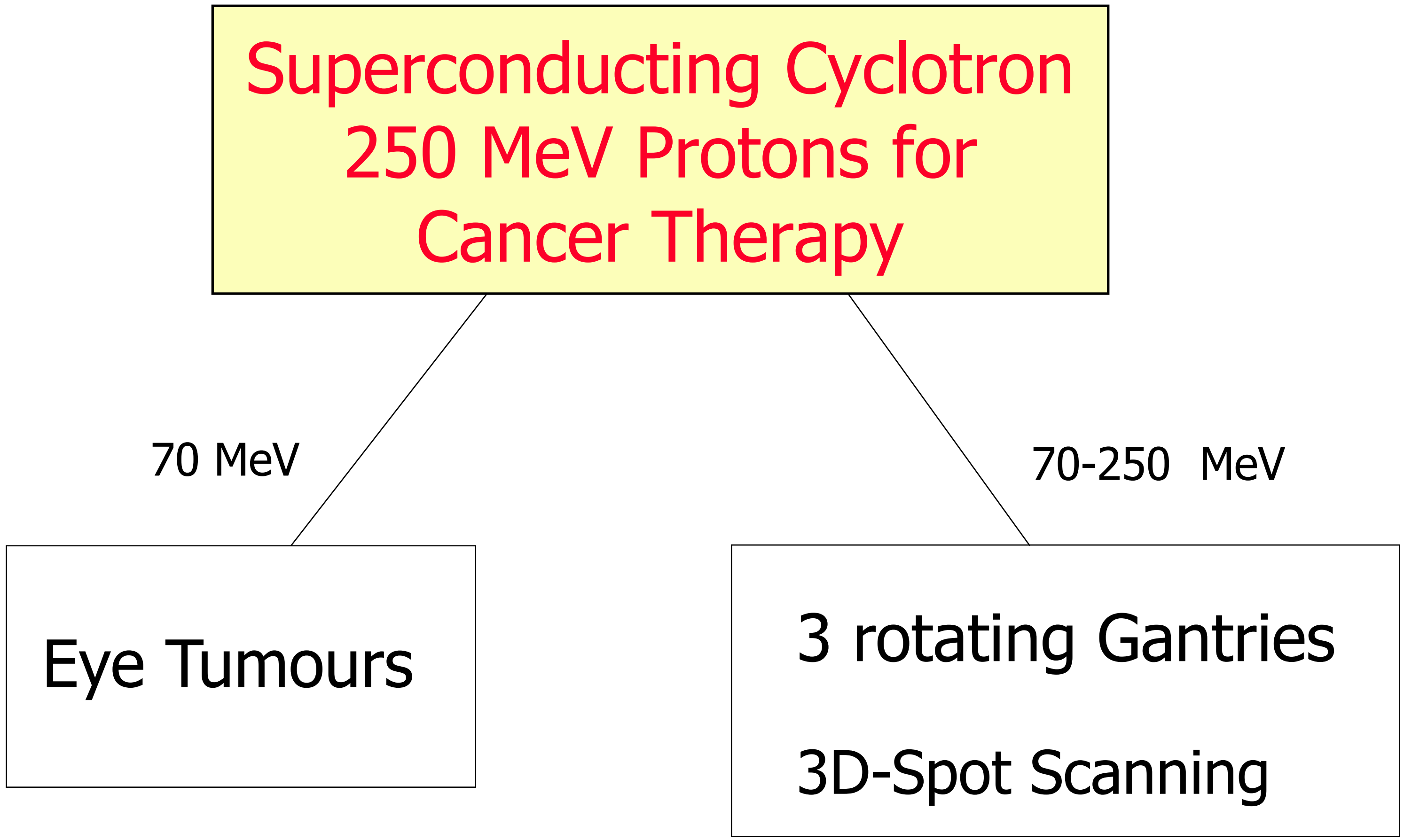
Nobel Prize in Chemistry 2009 !

V.Ramakrishnan won Nobel prize in chemistry

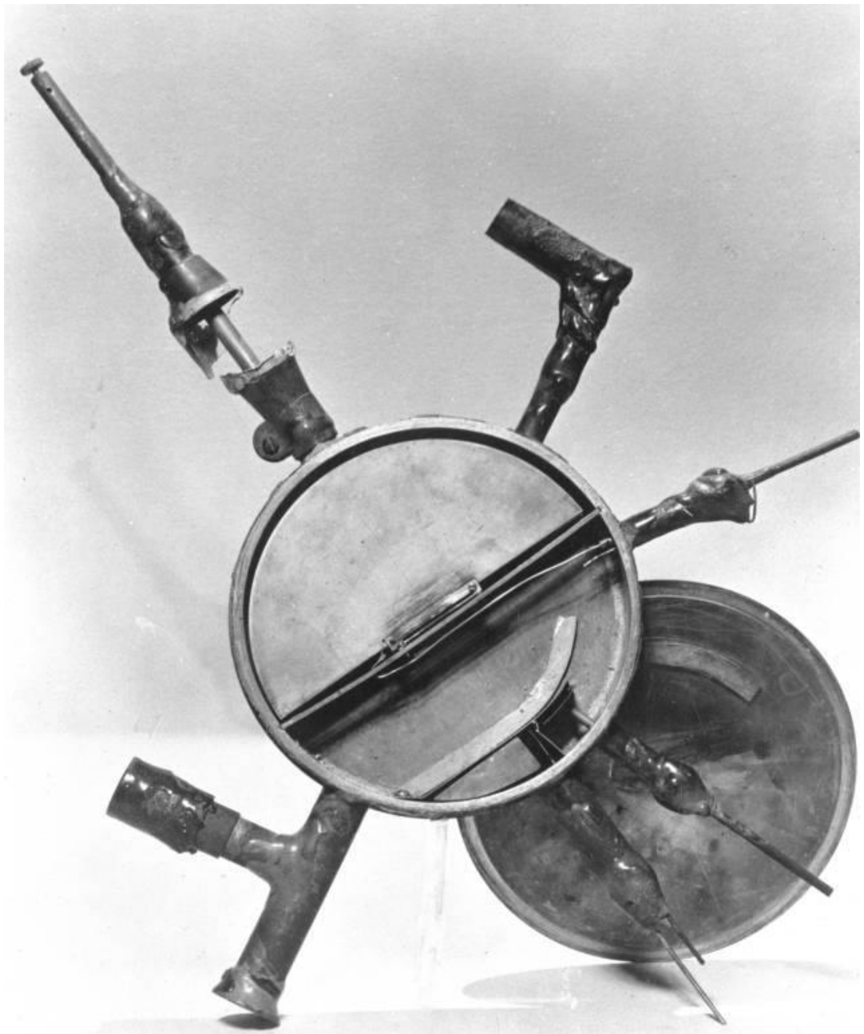
He was a user of a protein crystallography beam line at

the SLS at PSI

Investigation of Ribosomes with x-ray diffraction


Superconducting Cyclotron
250 MeV Protons for
Cancer Therapy
70 MeV
70-250 MeV
Eye Tumours
3 rotating Gantries
3D-Spot Scanning

The first Cyclotron 1931



E.O.Lawrence,

M.S.Livingston

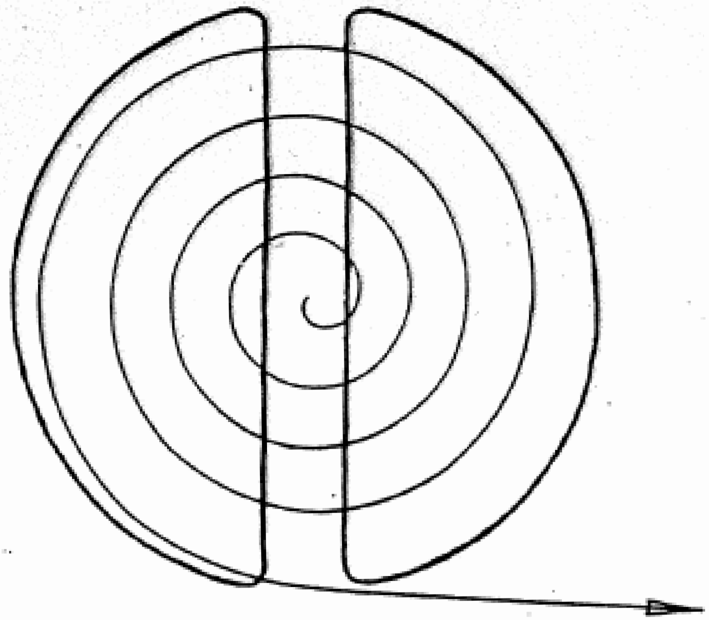
Berkeley, California

4 inch diameter

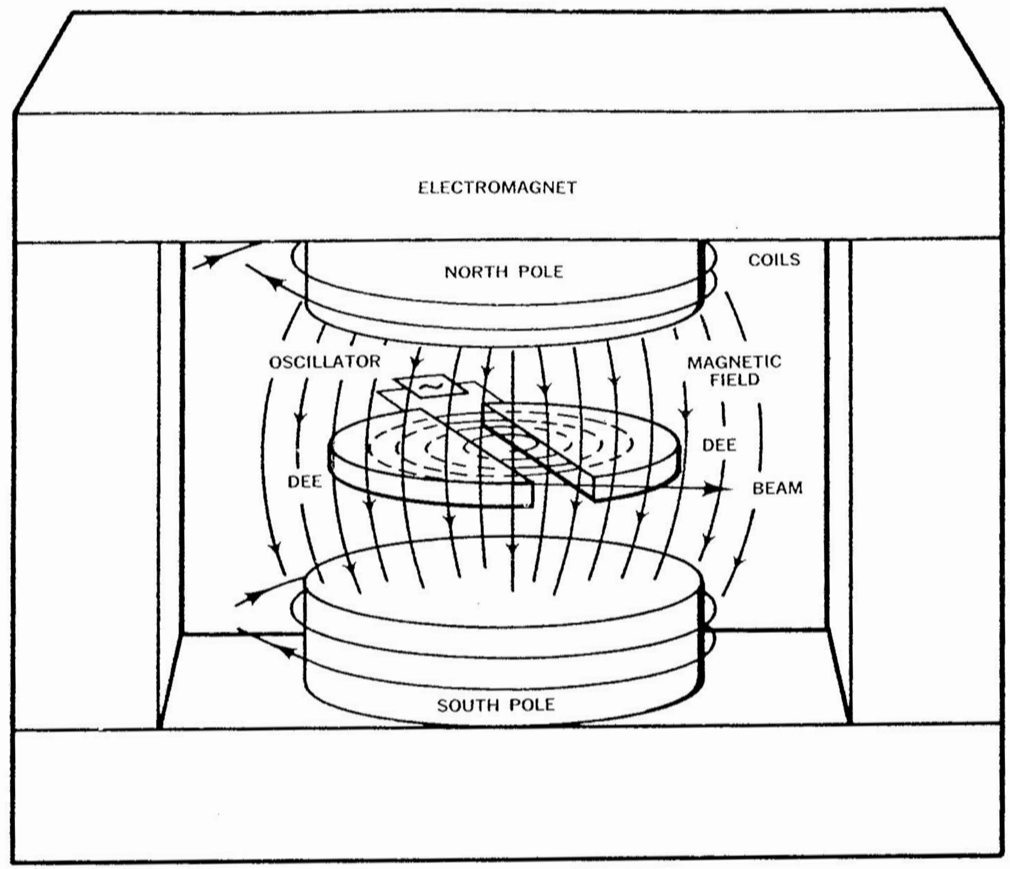
1 kV on the Dee

80 keV Protons

original Cyclotrons

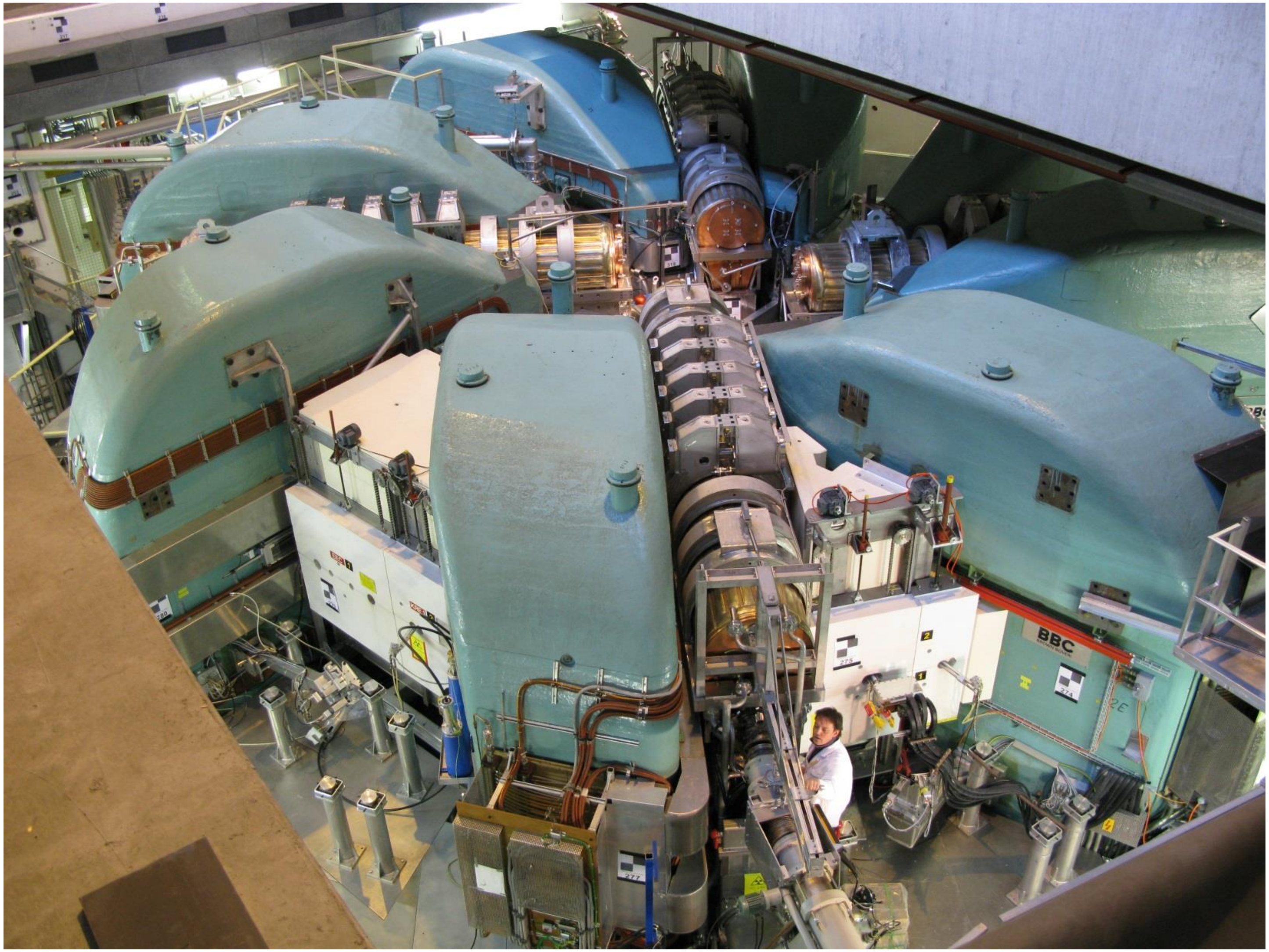


the cyclotron as seen by the inventor



the first classical cyclotrons

4 new Cu Cavities in Ringcyclotron (2008)



590 MeV Protons

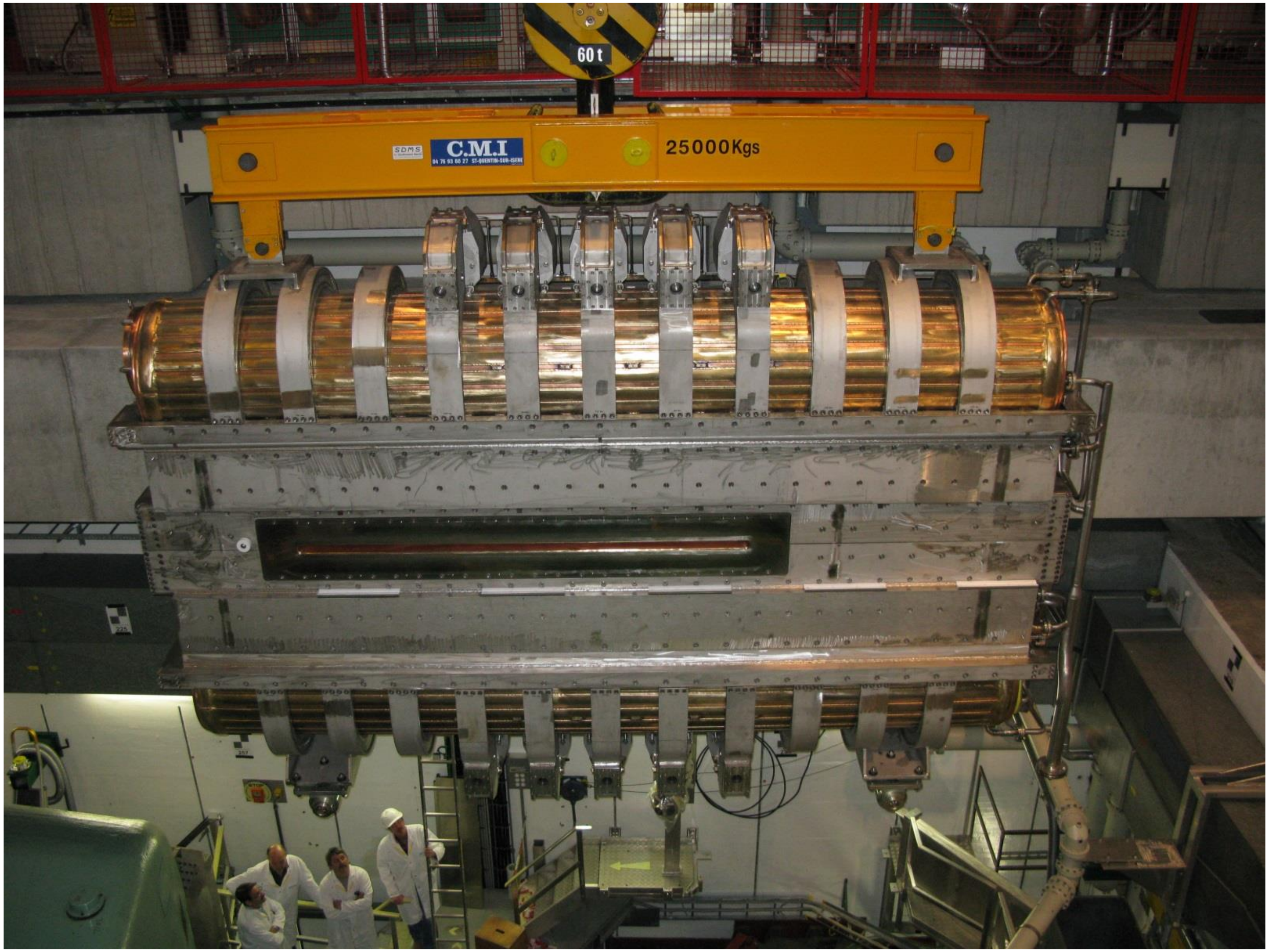
1.4 MW Beam Power
(world record!)

8 Magnet à 250 Tons

4 Cavities à 850 kV

Extraction ≈ 99.98 %

New Copper Cavity (5.6m long)



50 MHz, CW

Voltage limit 1 MV

(old cavity 0.72 MV)

at 850 kV and 2.4 mA:

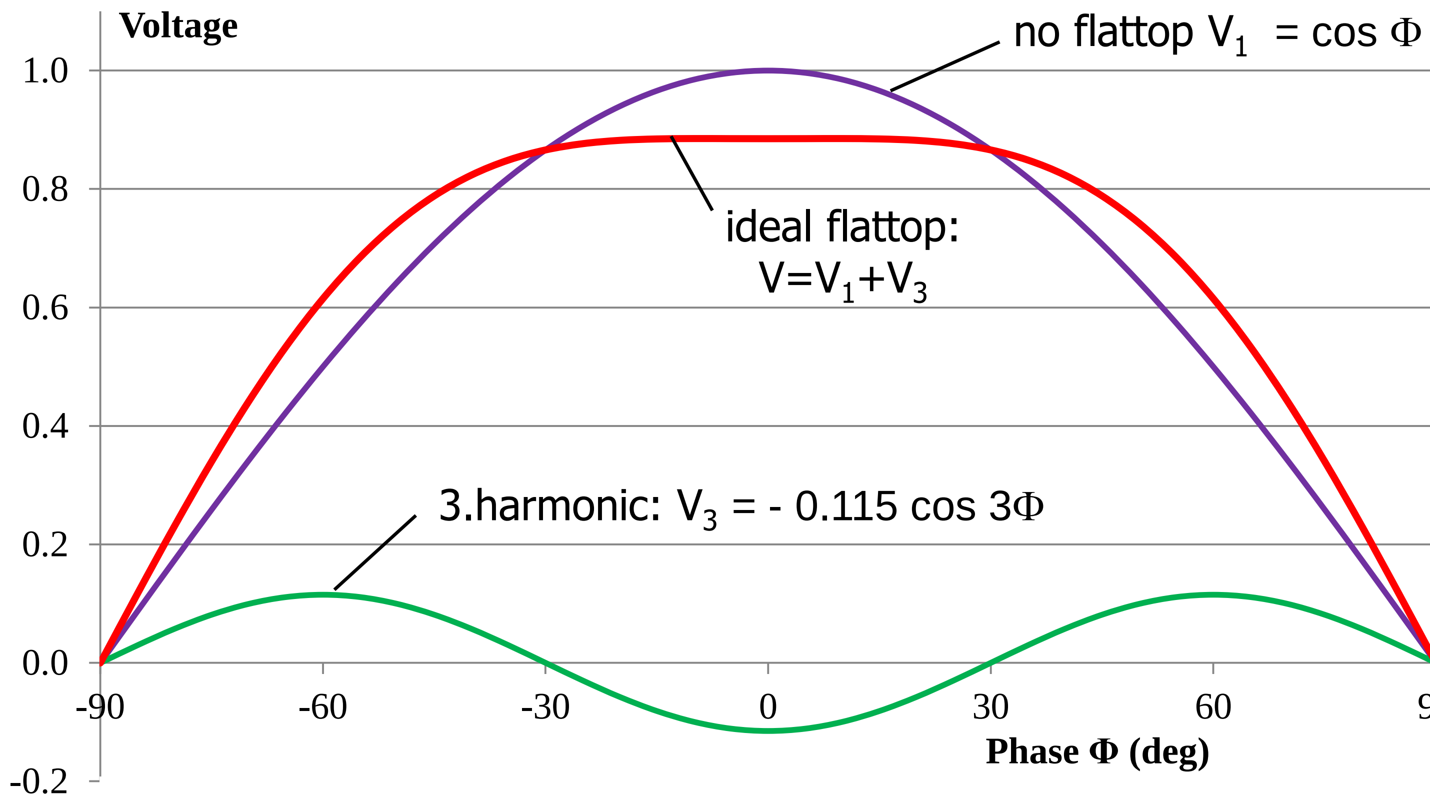
250 kW loss in cavity

350 kW goes
to the beam

Beam limit 3 mA ?

Flattop Voltage gives minimum energy spread

Flattop RF-Voltage with addition of a 3.harmonic



Advantages of Ring Cyclotrons
(Hans Willax 1963)

magnetic field and RF system are decoupled

many high voltage cavities

flattop cavity

strong vertical focusing

straight sections

fast crossing of resonances,

good turn separation

monoenergetic beam

single turn extraction

small magnet gap

low power consumption

(magnet weight as low as for compact magnet!)

easy construction of extraction and injection elements

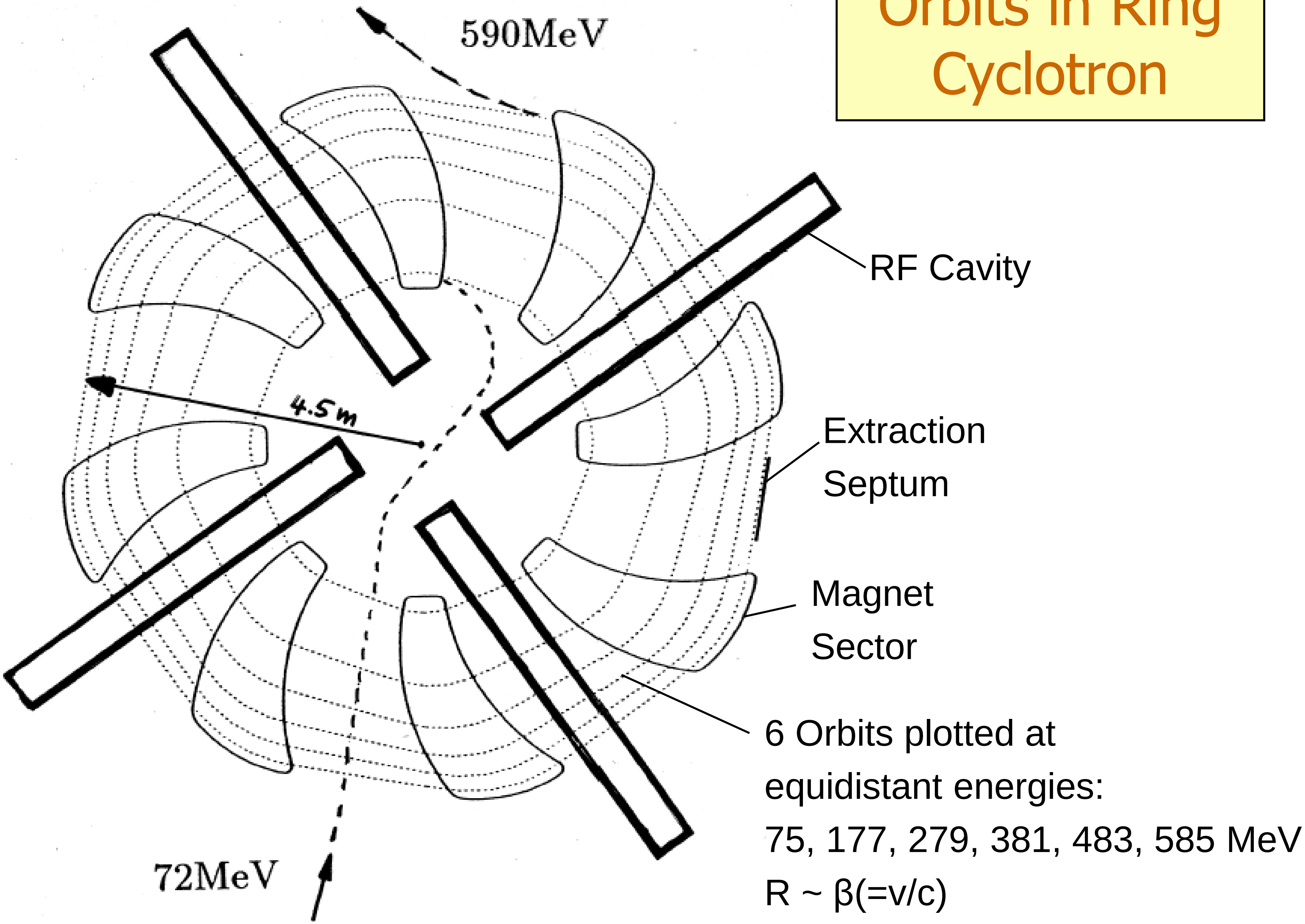
lots of space for diagnostic and correction elements

low extraction losses

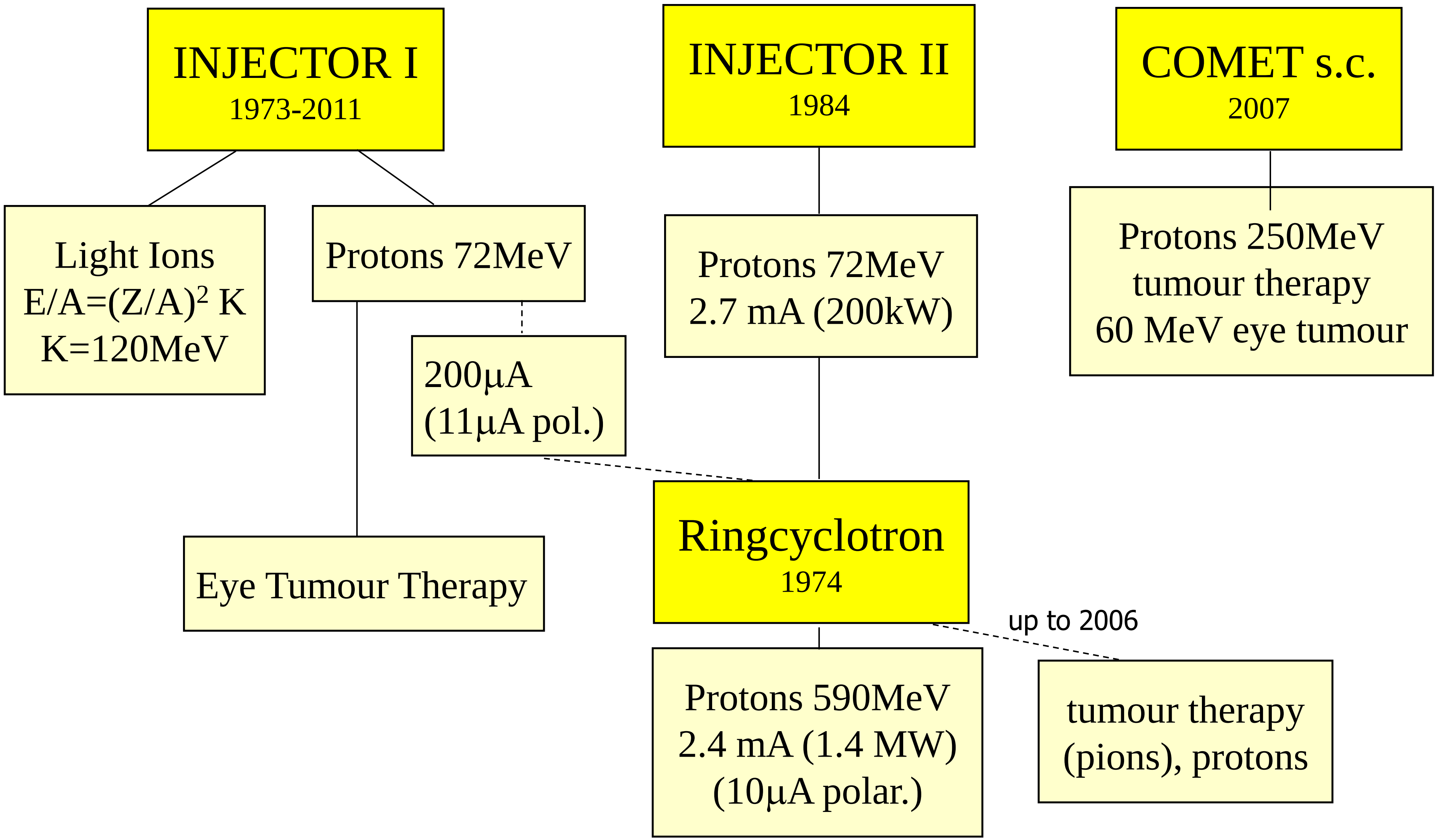
=> high intensity

requires injector!

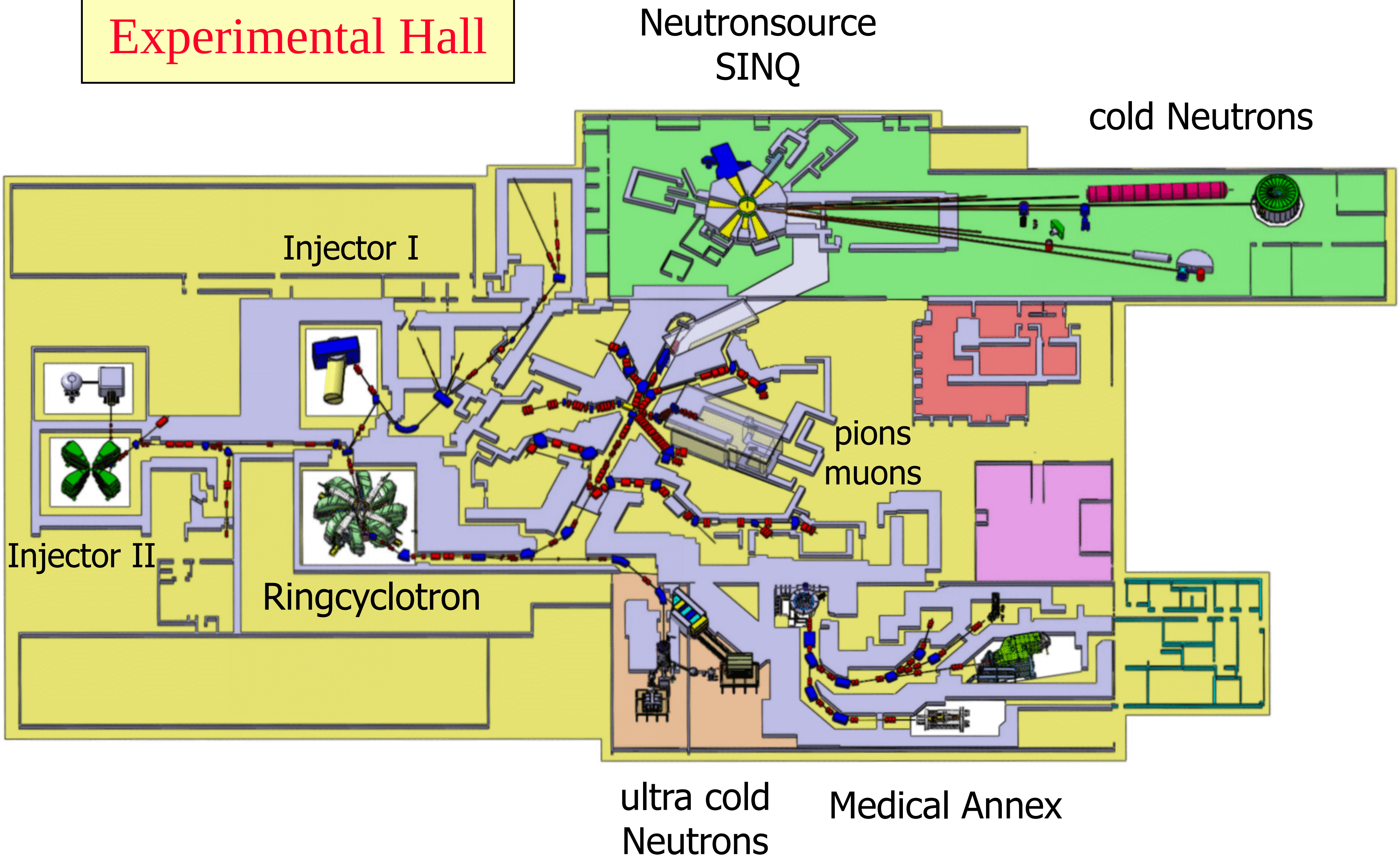
Orbits in Ring Cyclotron



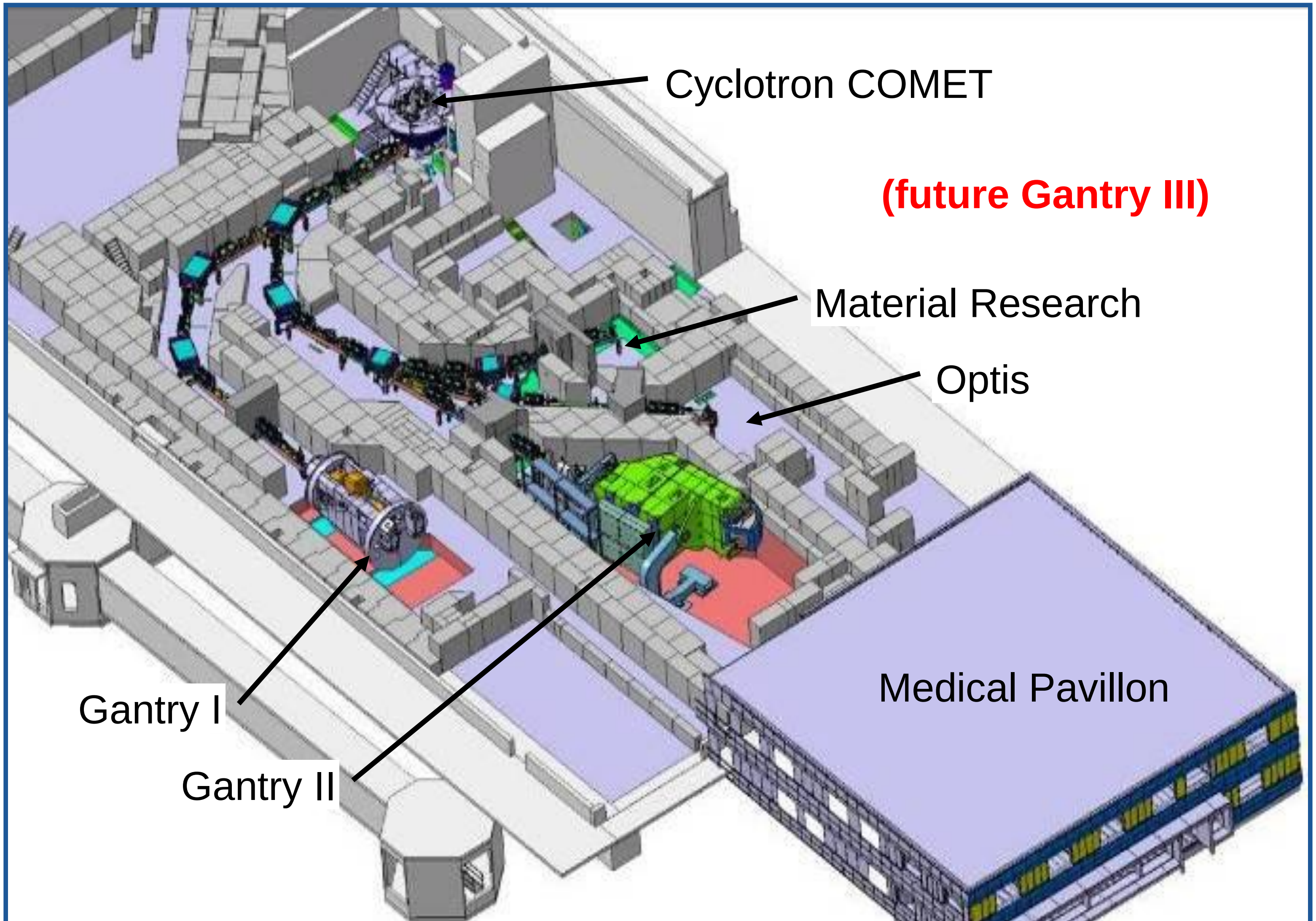
The PSI Cyclotrons



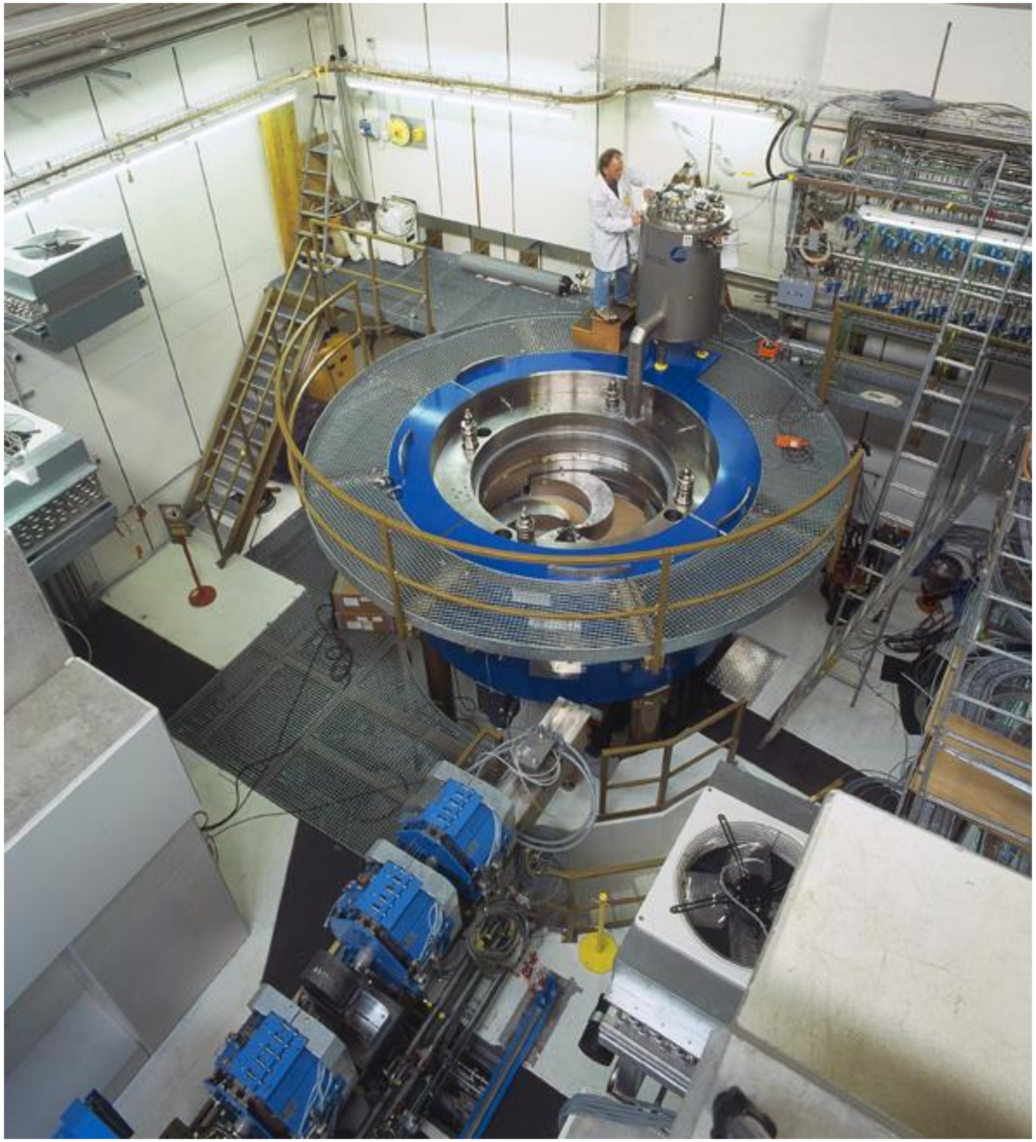
Experimental Hall



The PROSCAN Medical Annex



Comet Cyclotron



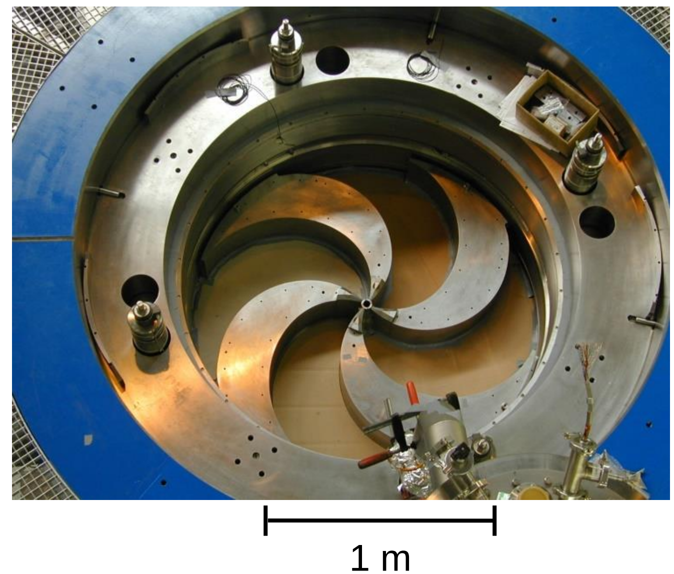
Radiation Therapy with

250 MeV Protons

superconducting Cyclotron:

Magnet, 3m Ø

Collaboration: ACCEL & PSI



The spiral structure is responsible for the vertical beam focusing

OPTIS, Eye Tumour Therapy with Protons

1984-2016

ca. 6’000 Patients

Tumour Control:

> 98%

(Collaboration with
Hospital Lausanne)

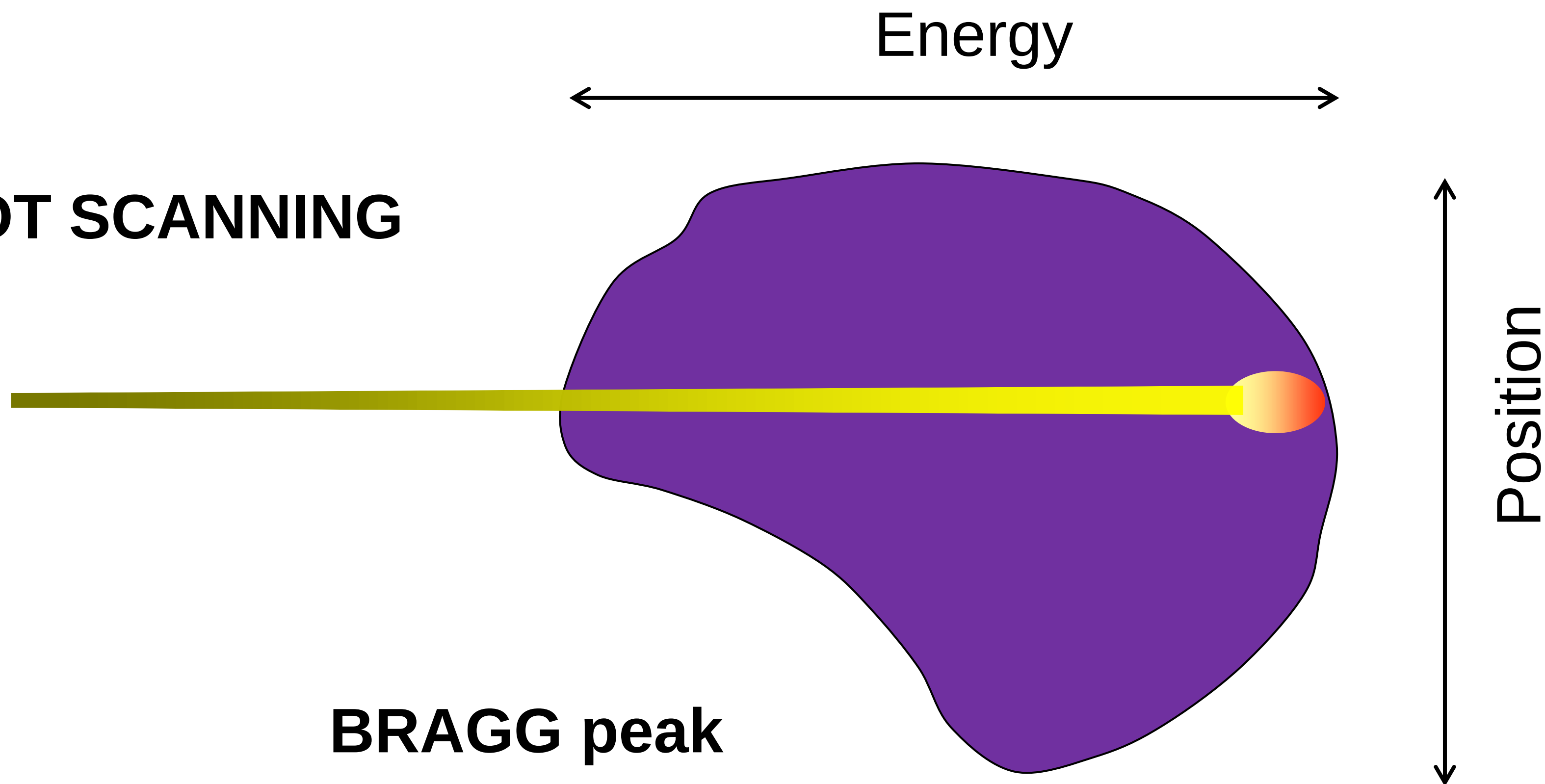
Irradiation on 4 Days

Proton Therapy

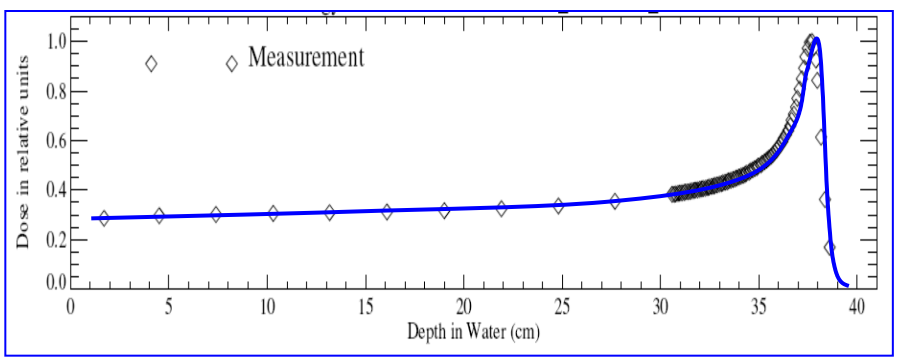
Irradiation of Tumour from different Directions with Gantry

⇒ minimal Dose at Surface

SPOT SCANNING

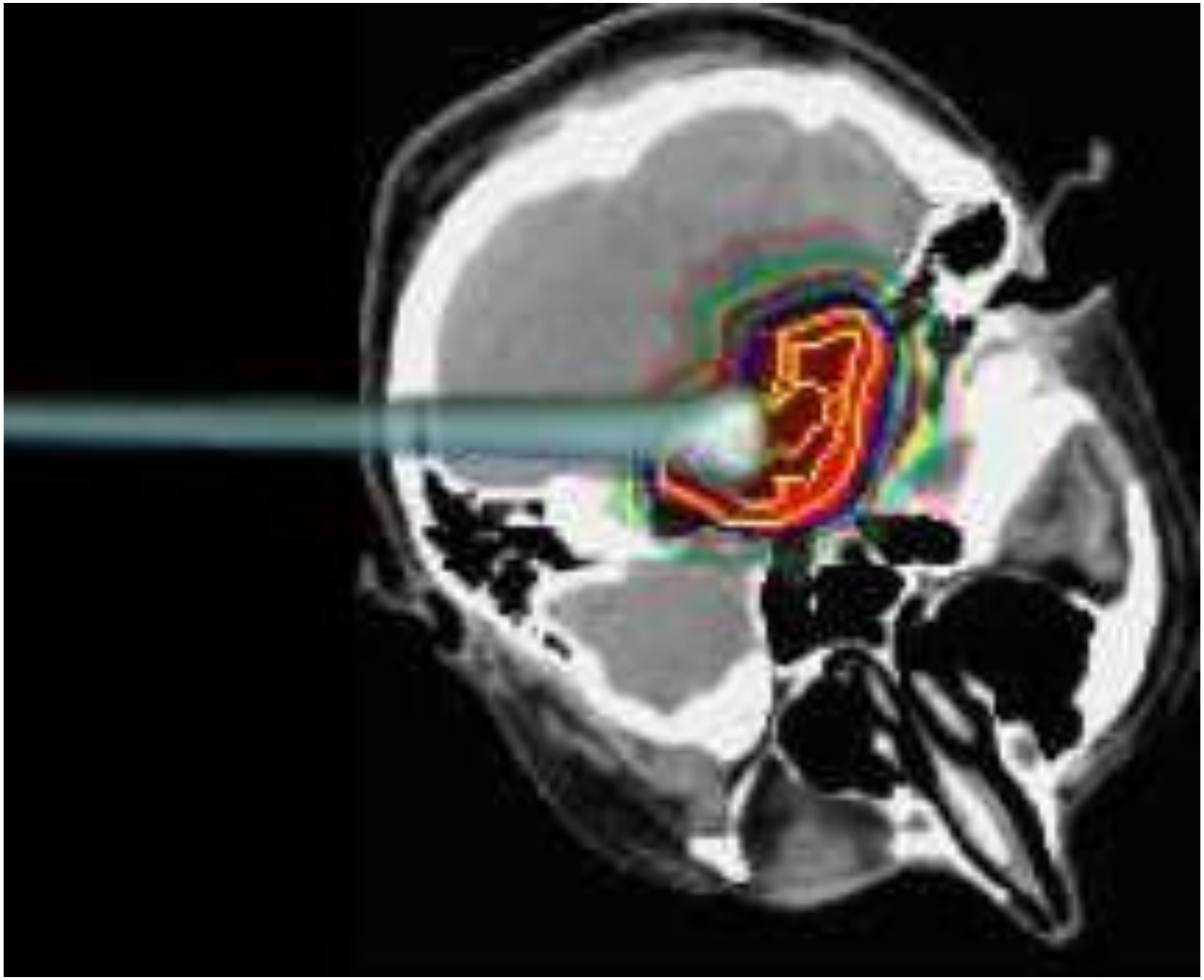


BRAGG peak



Irradiation of deep seated tumours; minimal damage to neighbouring tissues

Brain Tumour



Irradiation with

Protons by

Spot-Scanning

(E.Pedroni, PSI)

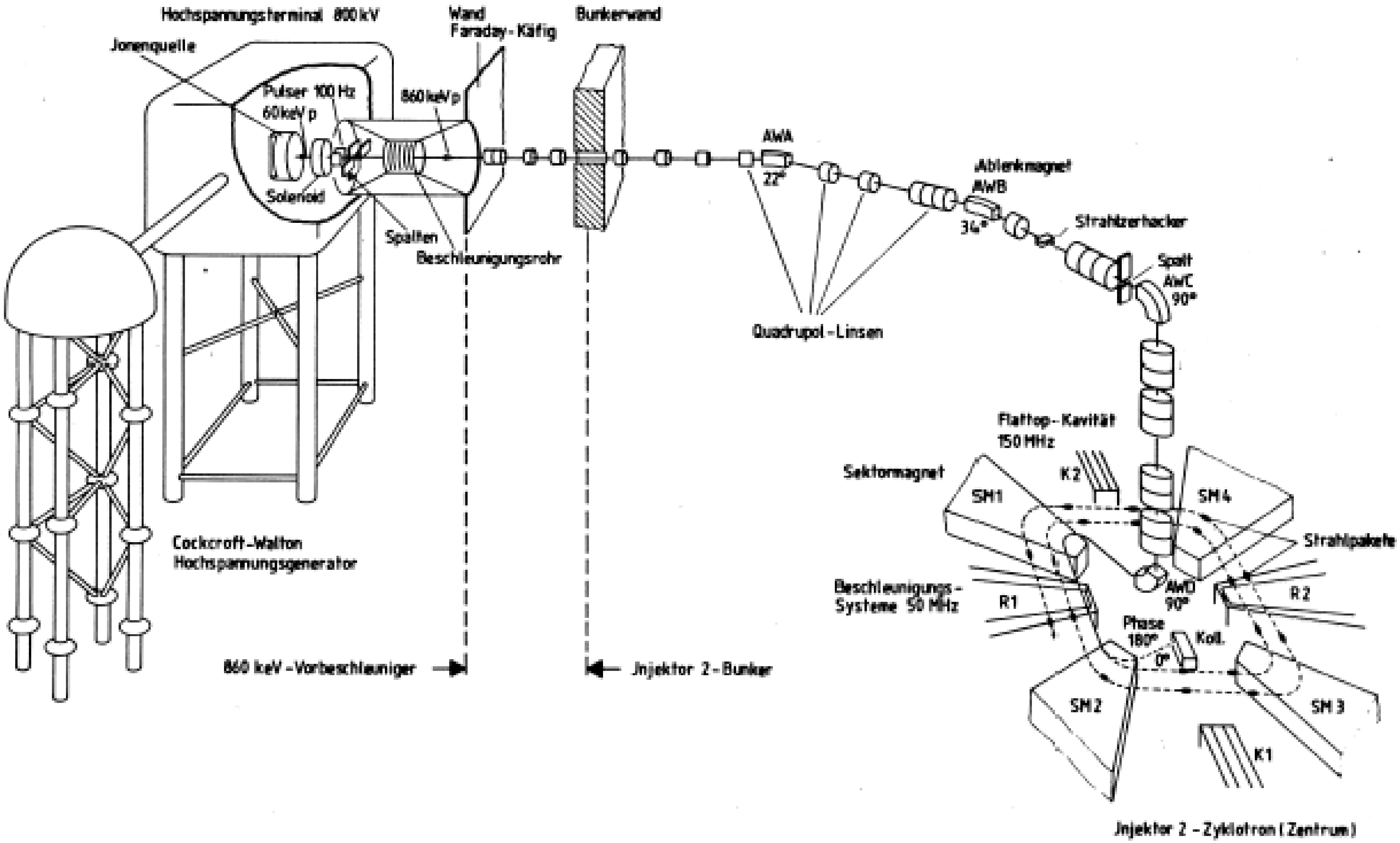
Cockkroft-Walton Pre-Accelerator

Voltage: 810 kV

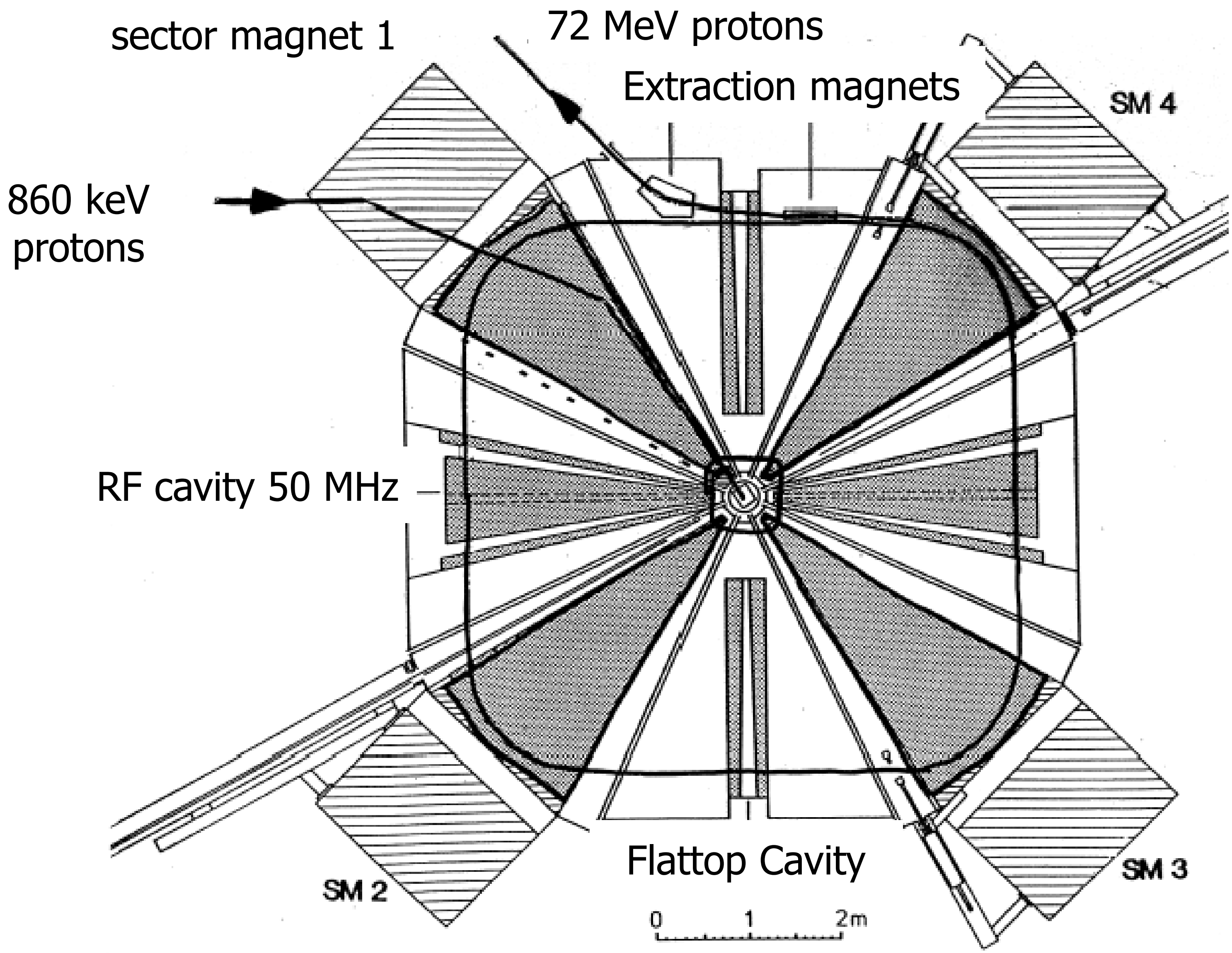
Acceleration Tube

Proton Source inside Faraday Cage on 60 kV

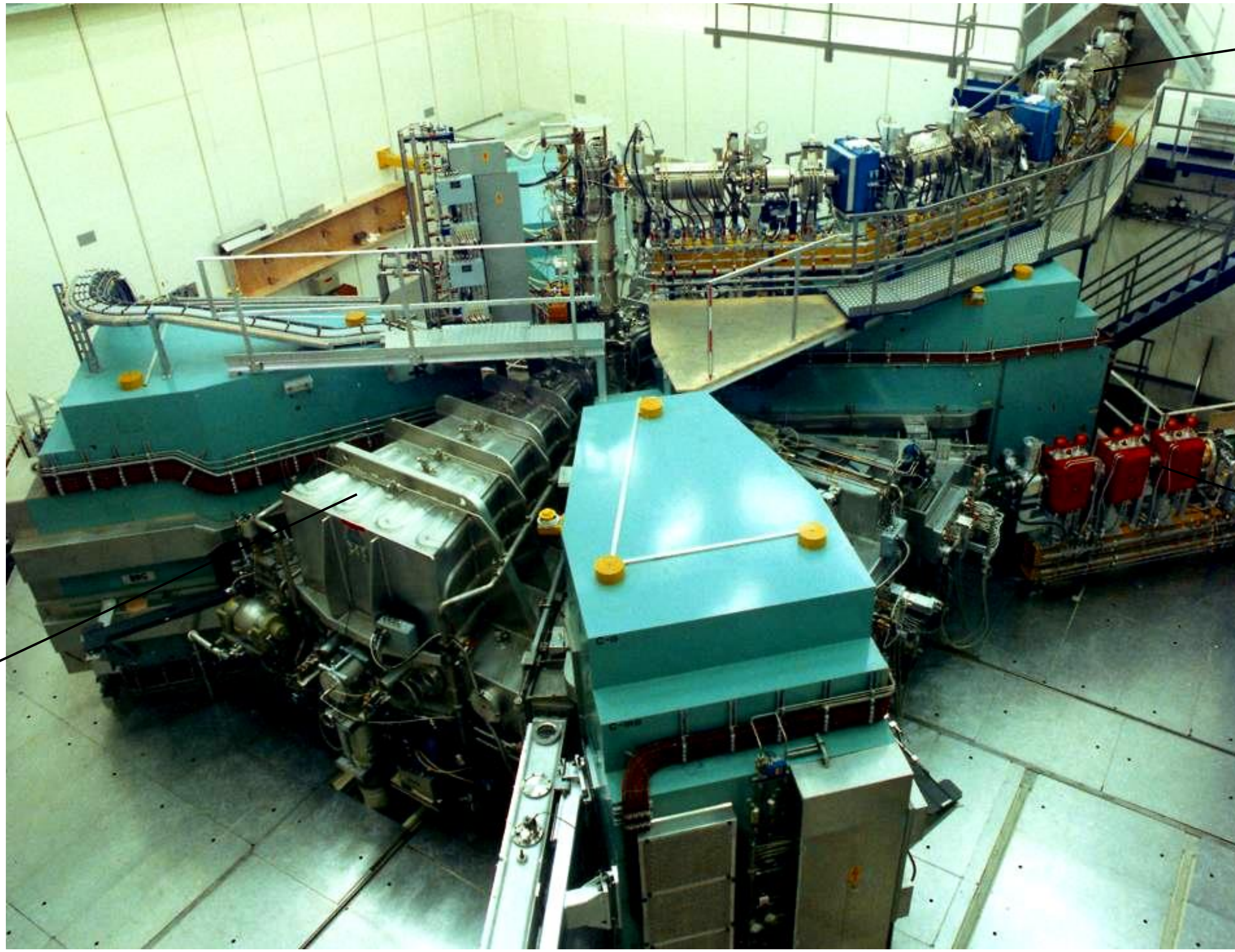
Injection of 870 keV Protons into Injector II



Layout Injector II



Injector II



Injection Line

870 keV

Extraction Line

72 MeV Protons

(after 100 turns)

Resonator

50 MHz

Recipe for high Intensity

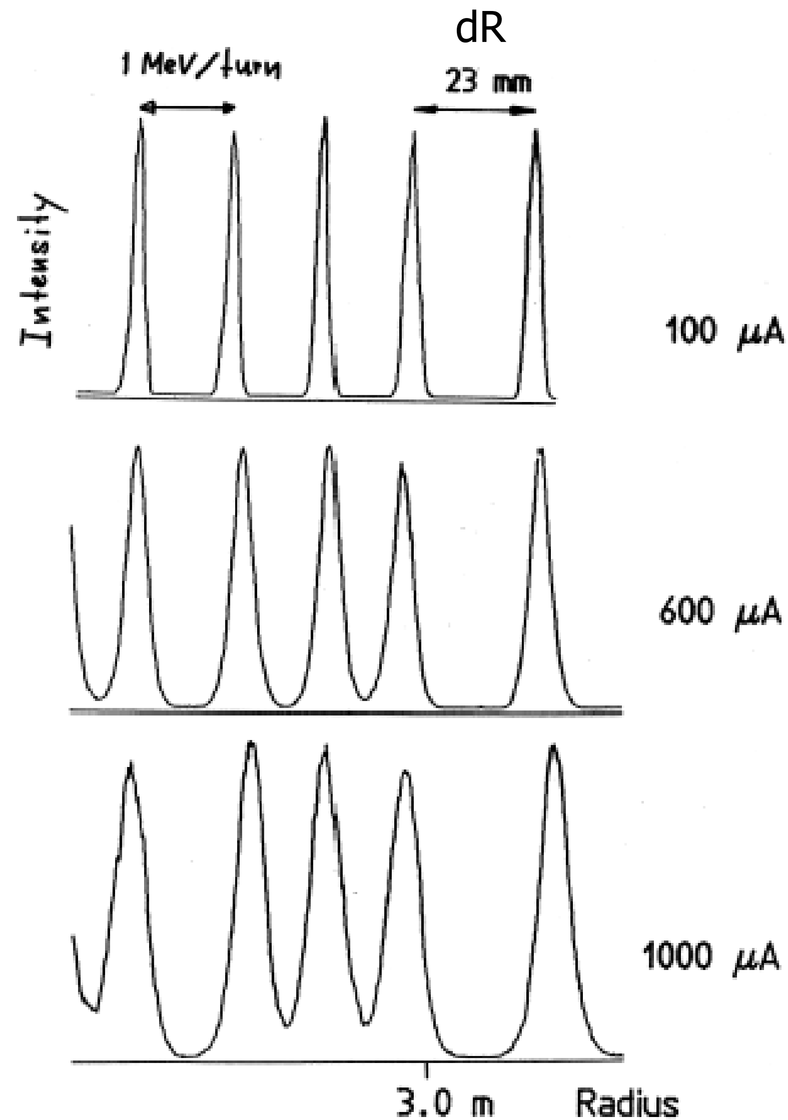
- continuos beam (cw)
- very low extraction losses

=> separated turns with
large turn separation dR
at extraction

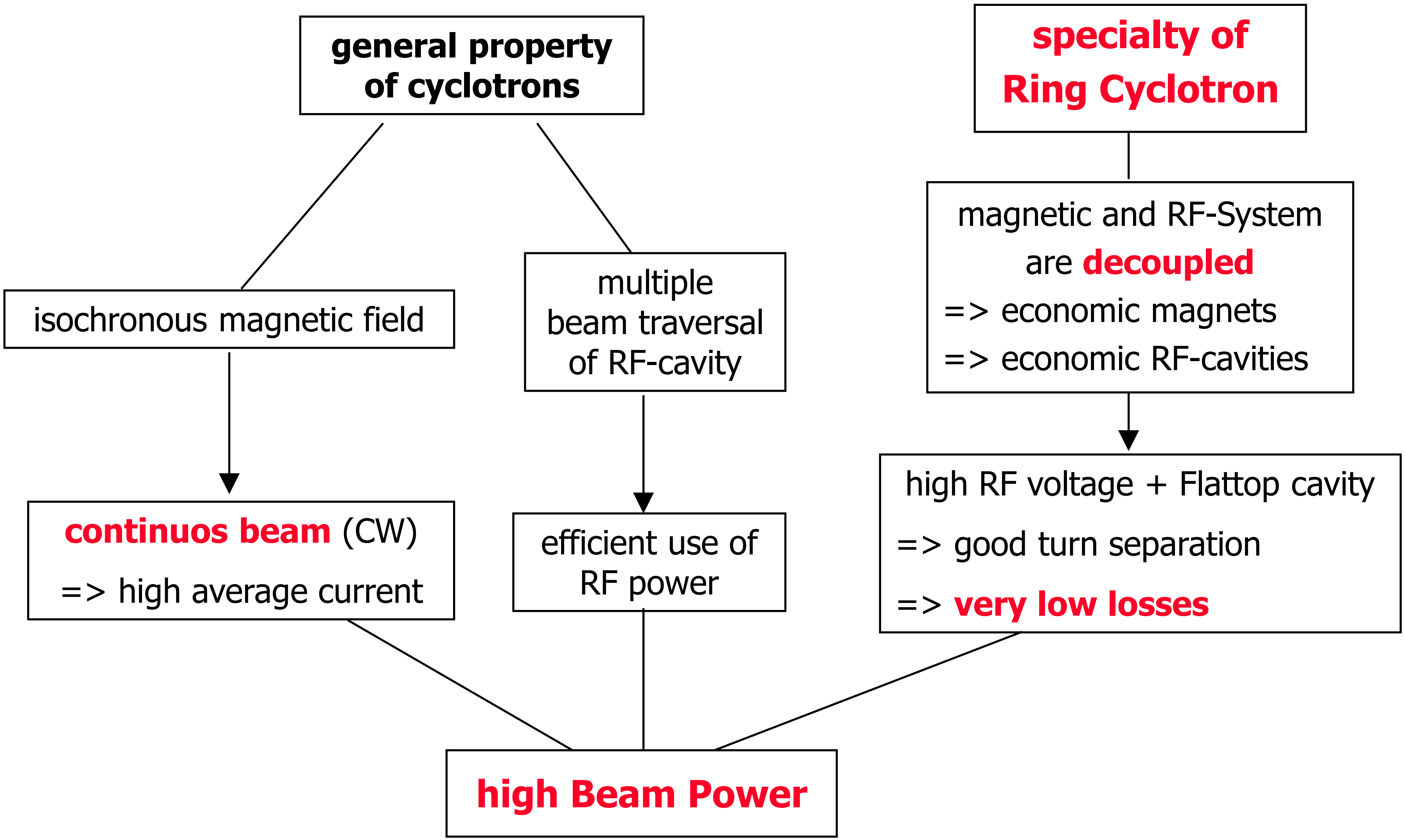
=> high energy gain per turn,
powerful RF-system with
high voltage cavities

dR ~ Radius R
=> **large machine radius** !!

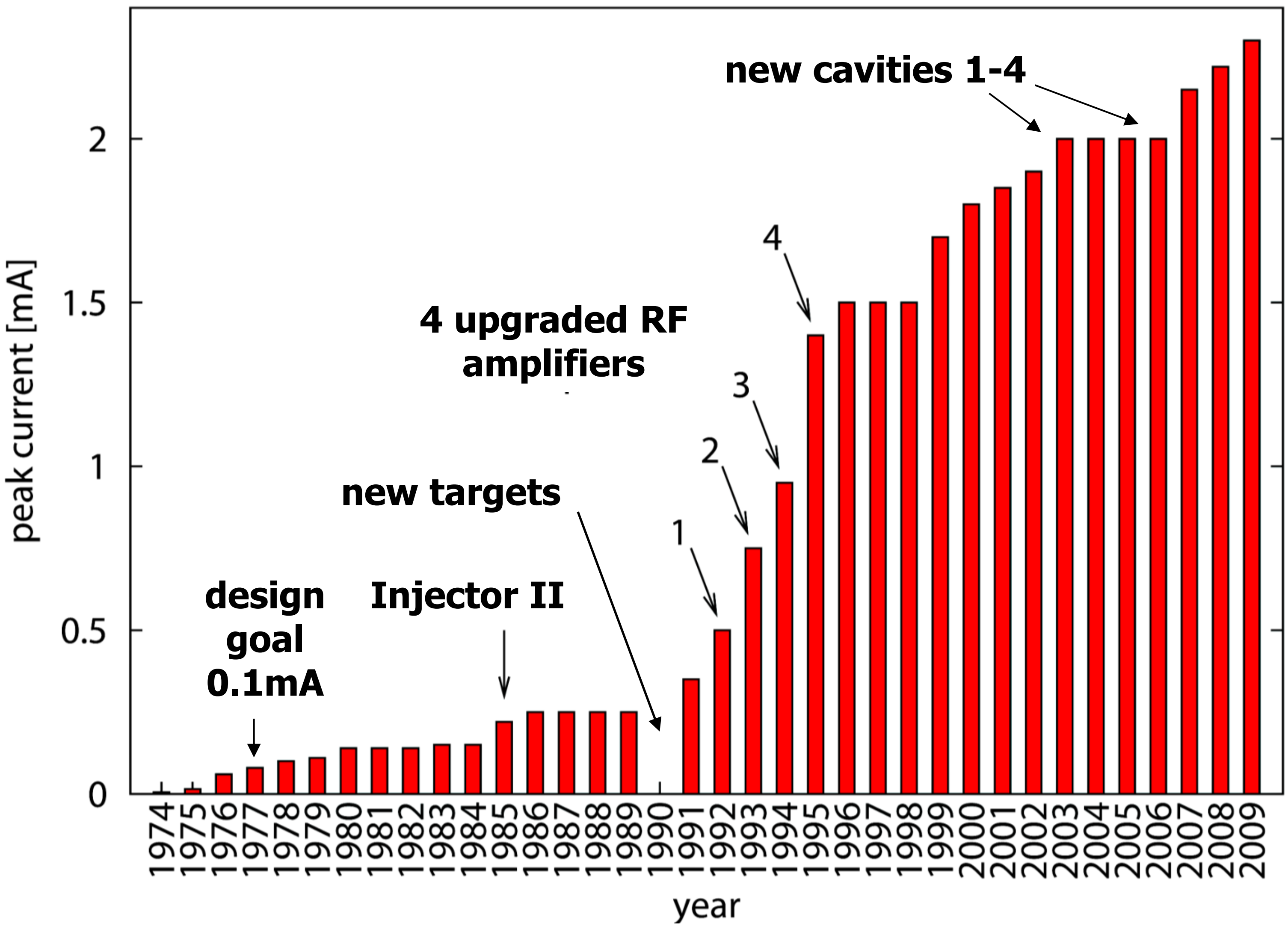
the last 5 turns in the Injector II



why is the PSI Ring Cyclotron such an efficient accelerator ?



History of the Peak current in the 590 MeV Ring Cyclotron

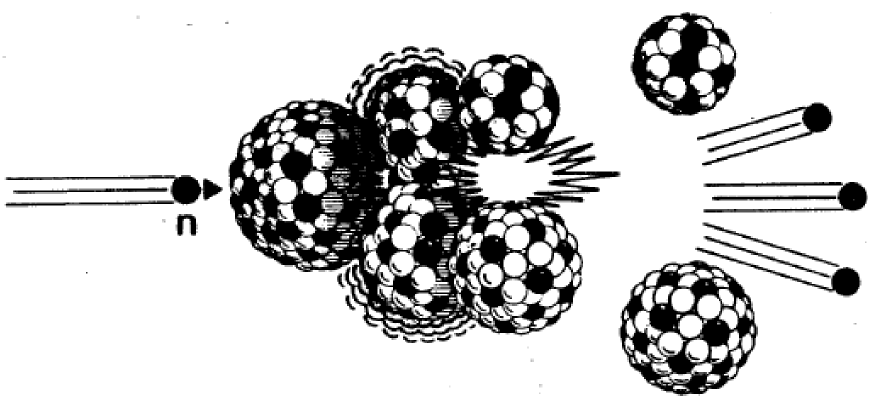


Courtesy Mike Seidel

„slow“ Neutrons for Material Research

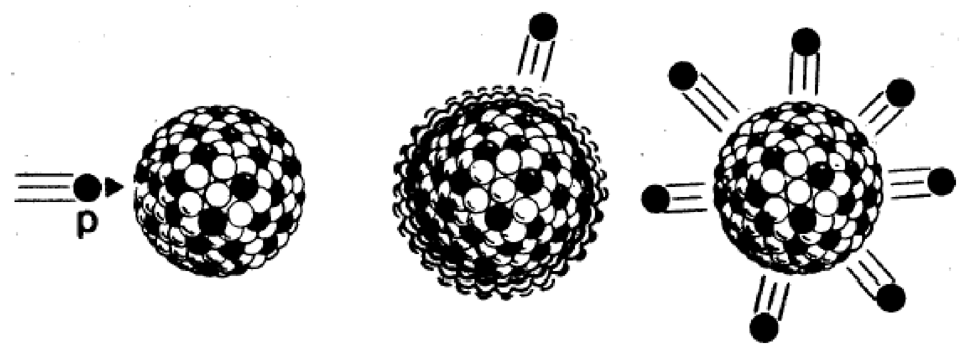
- Production of fast Neutrons
- slowing down in Moderator

1. Fission of Uranium (U^{235})
   in a Reactor

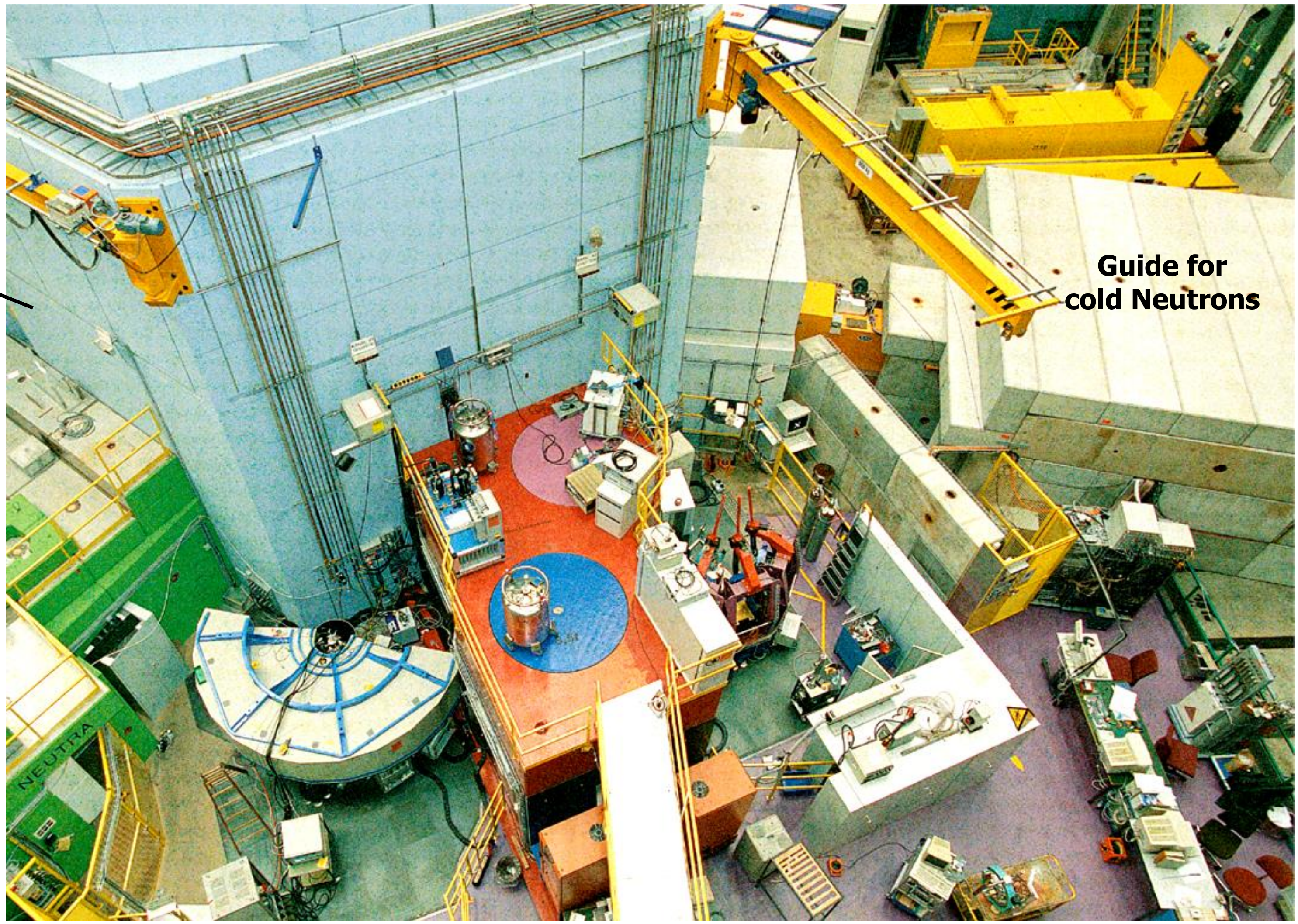


2. Spallation of heavy Nuclei
   (e.g. lead) by Bombardment with
   Protons from an Accelerator

=> safe and fast turning off !



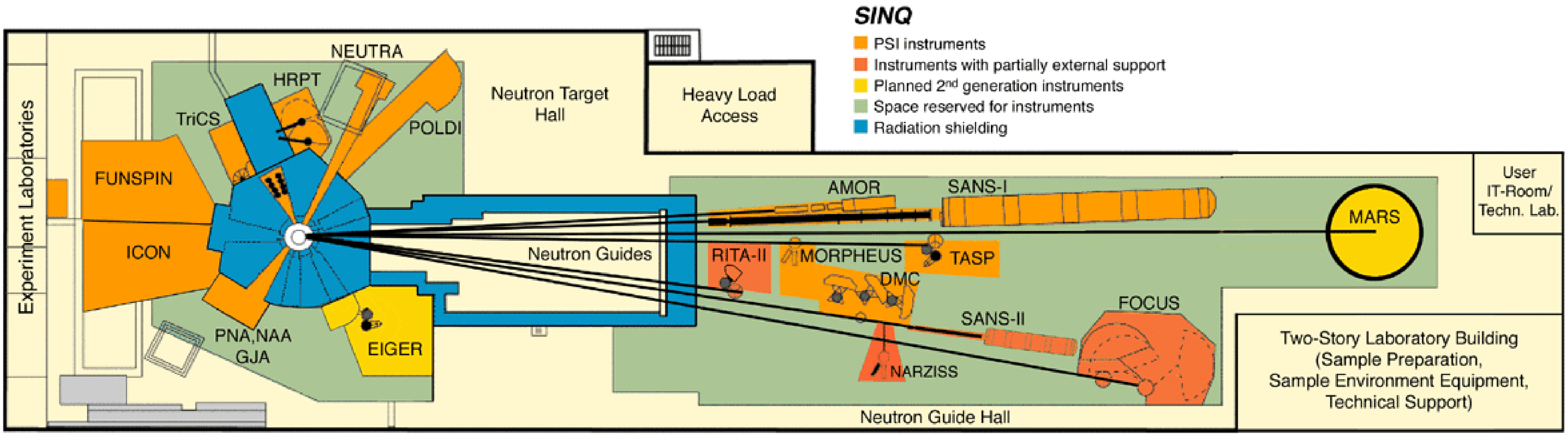
SINQ
Neutron Spallation Source



cold Neutrons

Proton (590 MeV) => Lead Nucleus => ca. 10 Neutrons

=> Moderation to < 0.025 eV => Diffraction on Material Probes



Spallation Neutrons

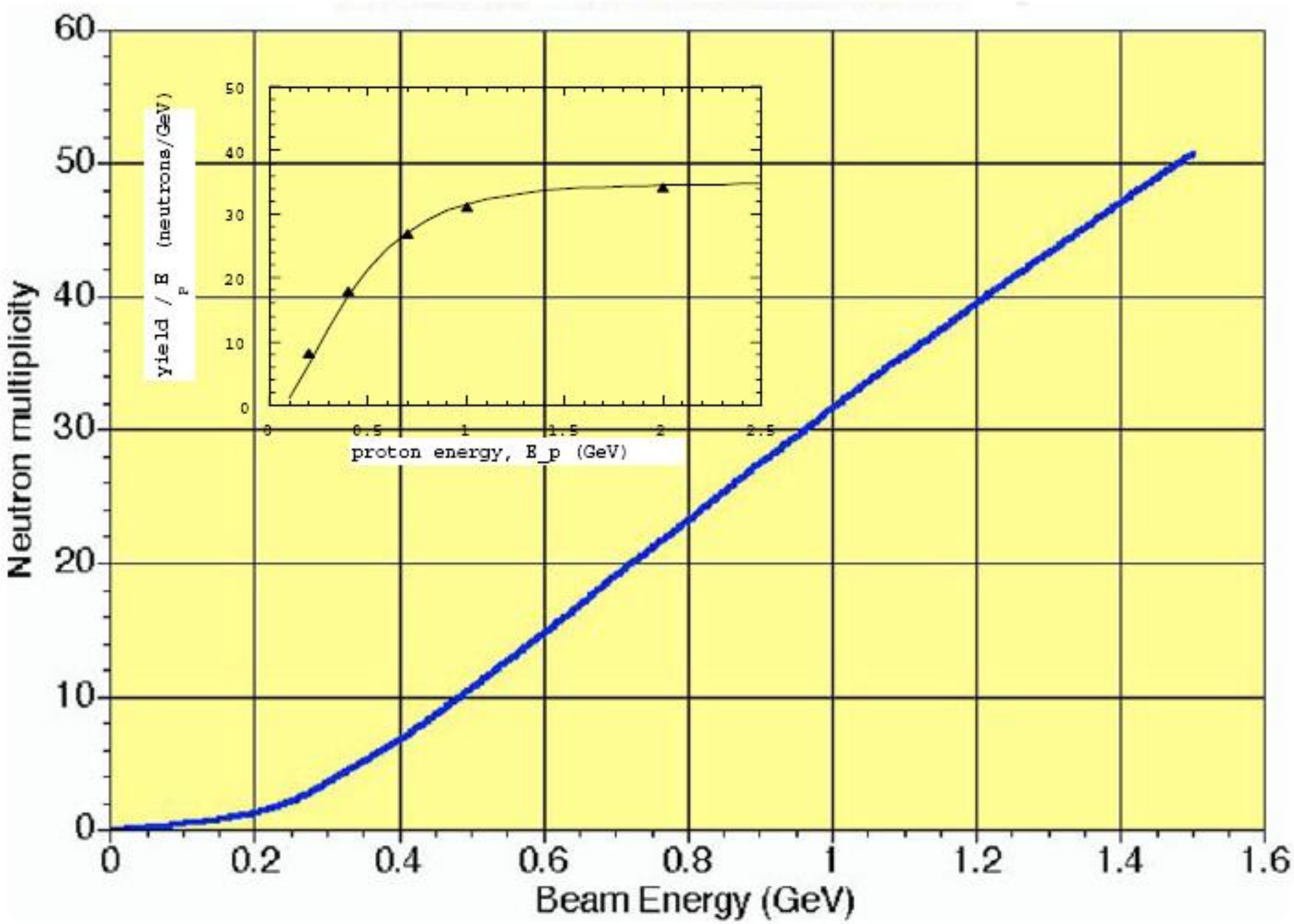
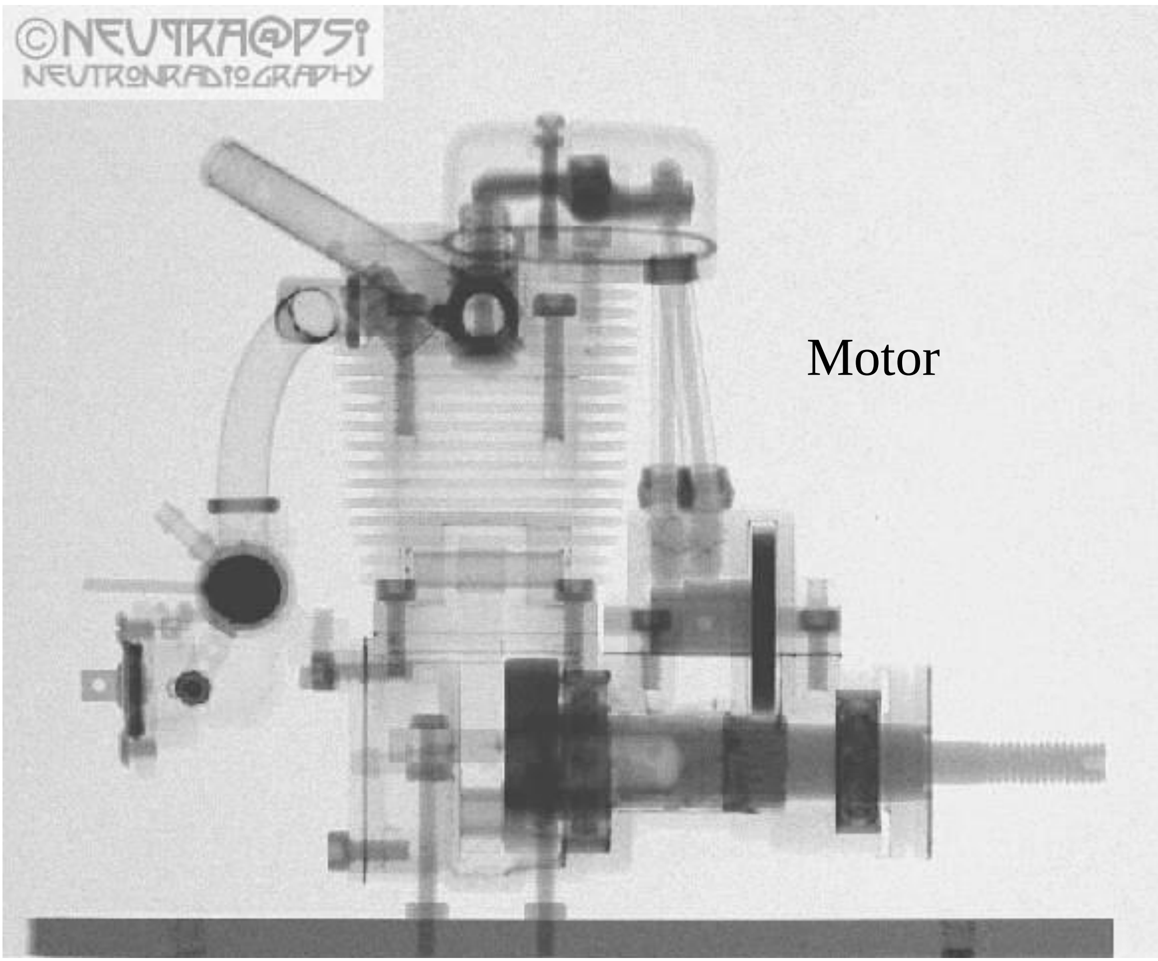
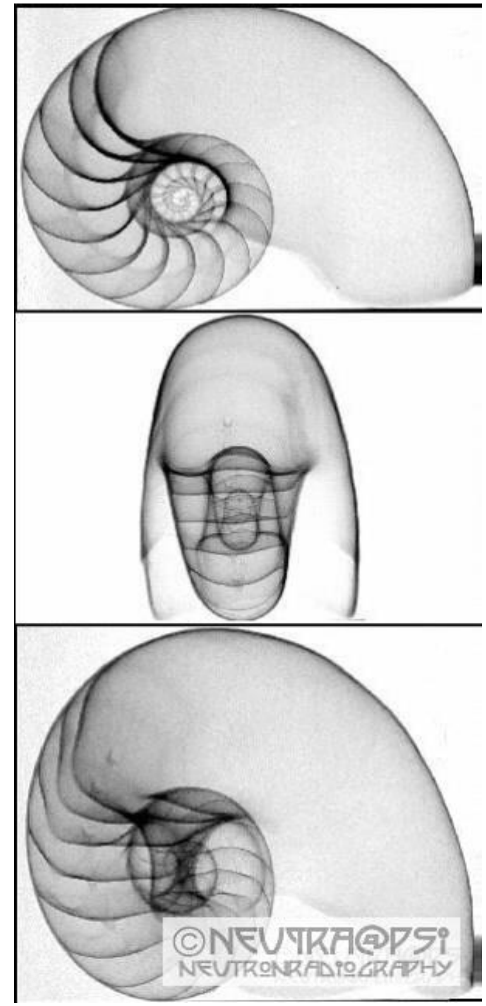


Figure 1. Calculated neutron multiplicity on lead as a function of proton energy[5]; the insert shows a calculated energy-normalised yield.

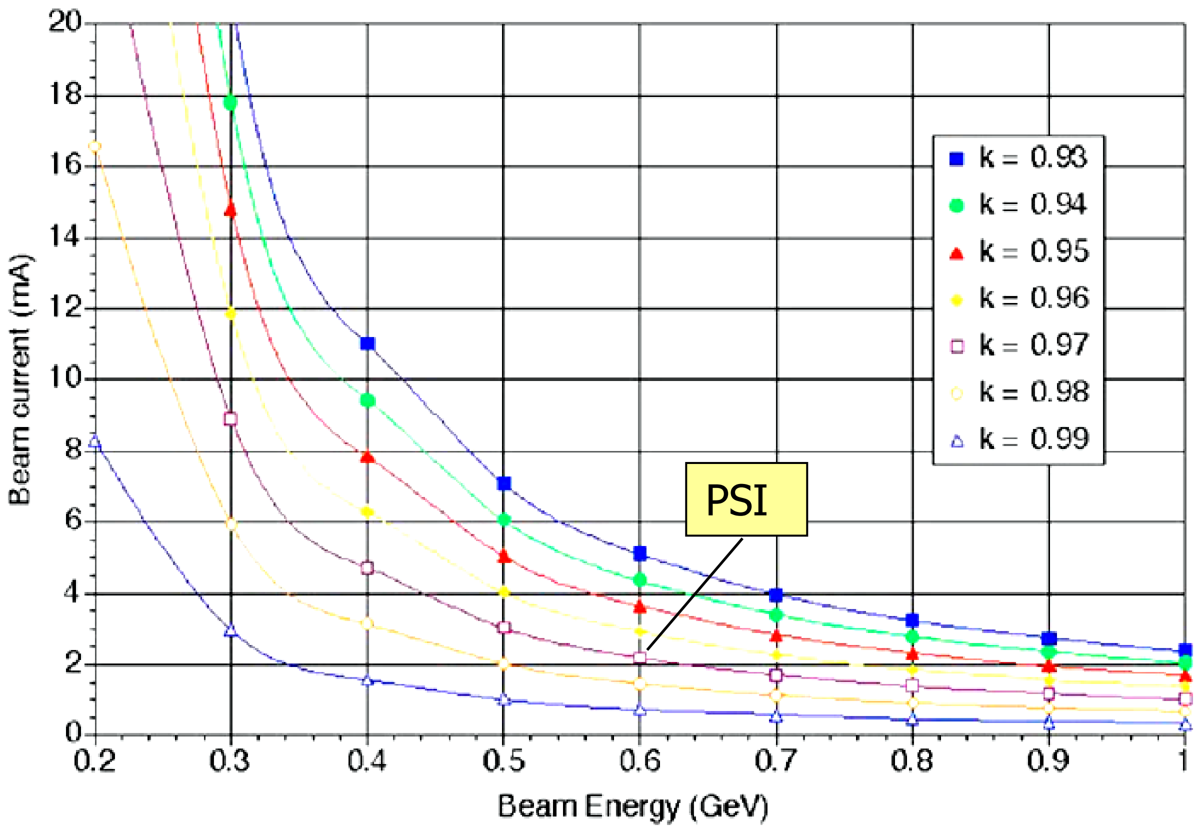
Radiography with Neutrons

=> the interior of big objects becomes visible





Energy Amplifier Concept (C.Rubbia)



Beam current needed to produce 80 MW_{th} with protons for different criticality factors k (ref. Ansaldo 2001)

example: 600 MeV PSI Cyclotron

in future with 3 mA => **1.8 MW**

=> production of neutrons in subcritical reactor **(e.g. k=0.97)**

=> 110 MW_{th} => **40 MW_{el}**

=> power plant with 1 GW_{el} needs 35 mA protons at 1 GeV => s.c. Linac

- inherently safe
- use of **Thorium** (big reserves)
- no production of Plutonium for weapons

reduction of lifetime of nuclear waste !

chem. separation of long lived actinides

⬇

high intensity proton beam
≈ 40 MW (30*PSI) , ca. 2050 ?

⬇

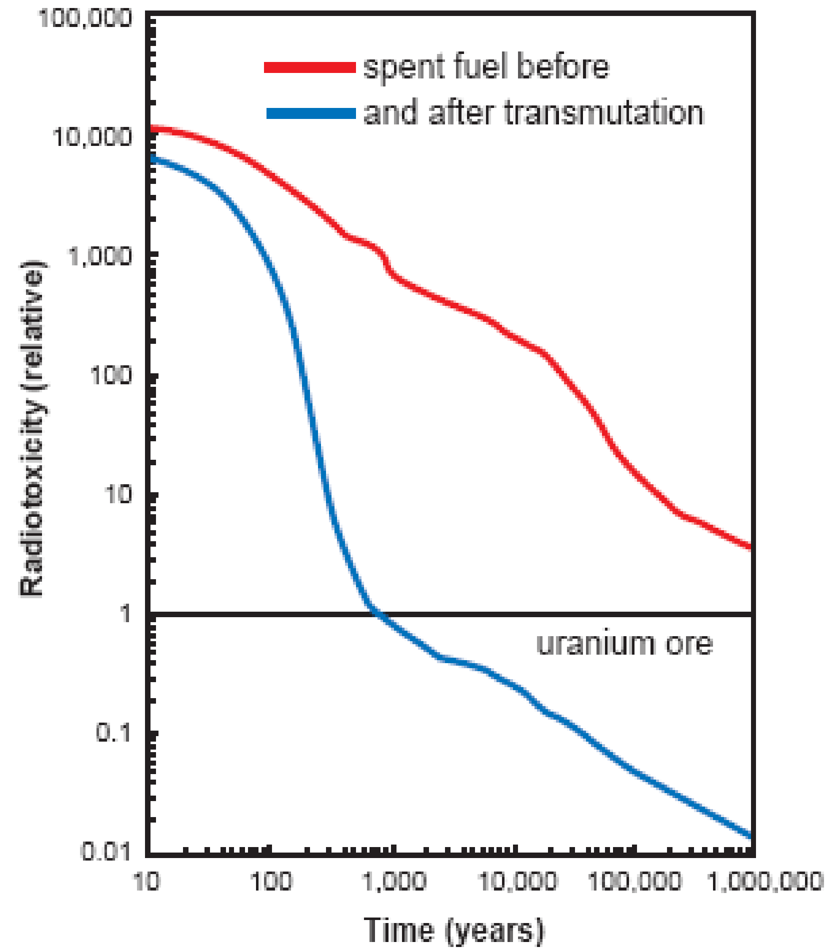
production of neutrons

⬇

transmutation of aktinides

⬇

Reduction from 1 Mill. years to 400 years



European Roadmap for Accelerator Driven Systems ... ENEA Italien 2001

Ring Cyclotron September 1973

1 Hans Willax
2 Miguel Olivo
3 Thomas Stammbach
4 Werner Joho
5 Christa Markovits

First 600 MeV Protons on Target 25.2.1974

Richard Reimann
Manfred Daum

Thomas Stammbach
Werner Joho
Francesco Resmini
Hans Willax
Paul Rudolf
Urs Schryber
Jean Pierre Blaser

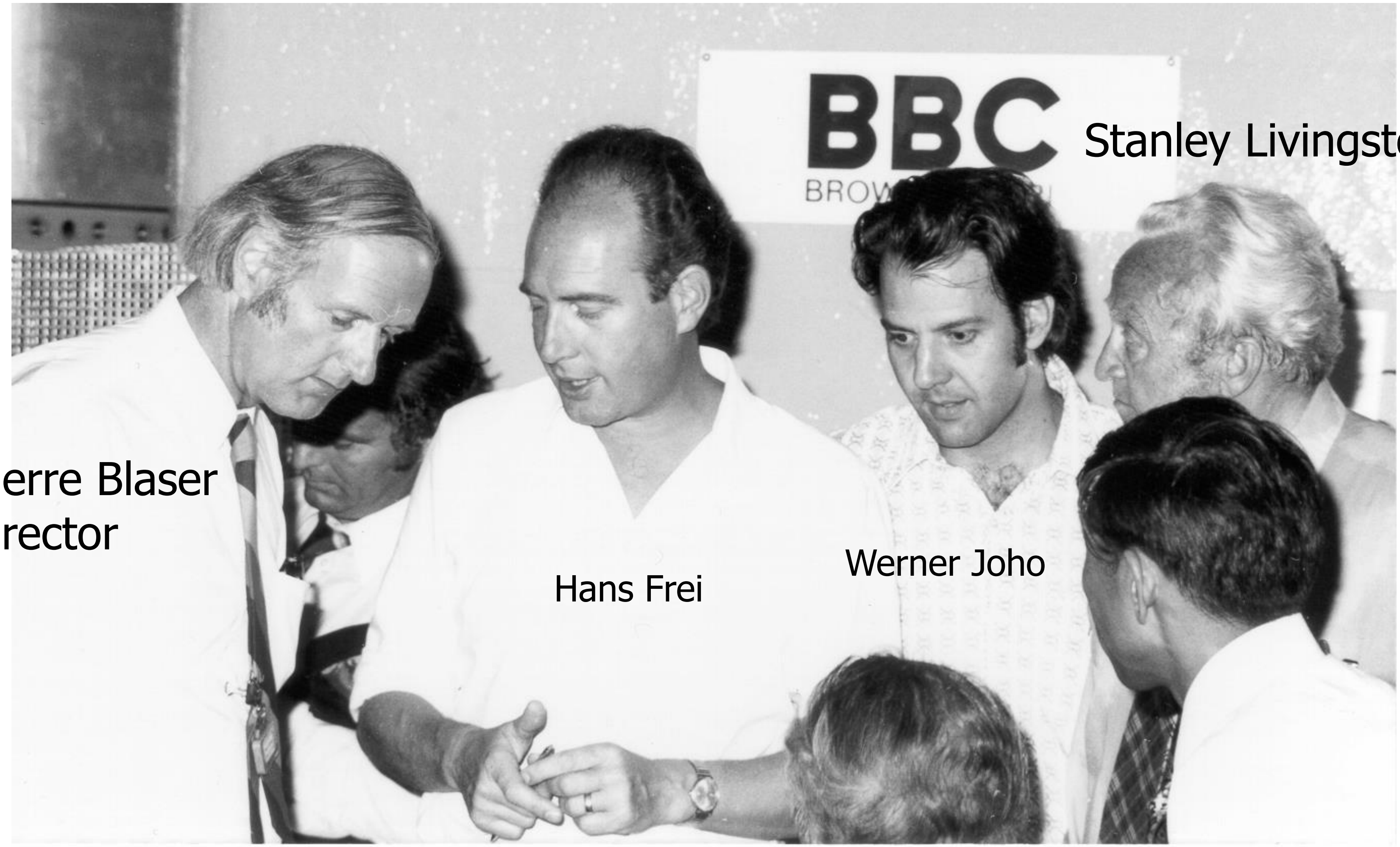
Das Dream Team von 1974

Old Sinners Villigen, 24. 2. 1974

Stehend v. l. n. r.: Gerber, Blaser, Willax, Joho, Schryber, Lanz
Vorne v. l. n. r.: Daum, Olivo, Steiner, Frosch, Tschalär

Courtesy Manfred Daum

Int. Cyclotron Conference 1975 Zürich



Success Factors for PSI Ring Cyclotron

1	Magnets and RF-System are decoupled	
2	4 high voltage cavities	→ **I max ~ V^3**
3	large Radius R	→ high turn separation dR/dn ~ R·V
		fast acceleration into fringe field, where Qr drops: dR/dn ~ $1/Qr^2$
4	excellent beam from Injector	→ separated turns
5	Flattop Cavity	→ high phase acceptance ΔΦ
6	eccentric Injection	→ Qr at extraction 1.75 => 1.5
		wins factor 3 in dR/dn: 6 => 17mm
7	straight electrostatic Septum with 0.1mm strips	→ Losses at extraction ≈ 10^{-4} ↓
8	Continuous Beam (CW)	→ **1.4 MW Beam Power**

History of the Cyclotron

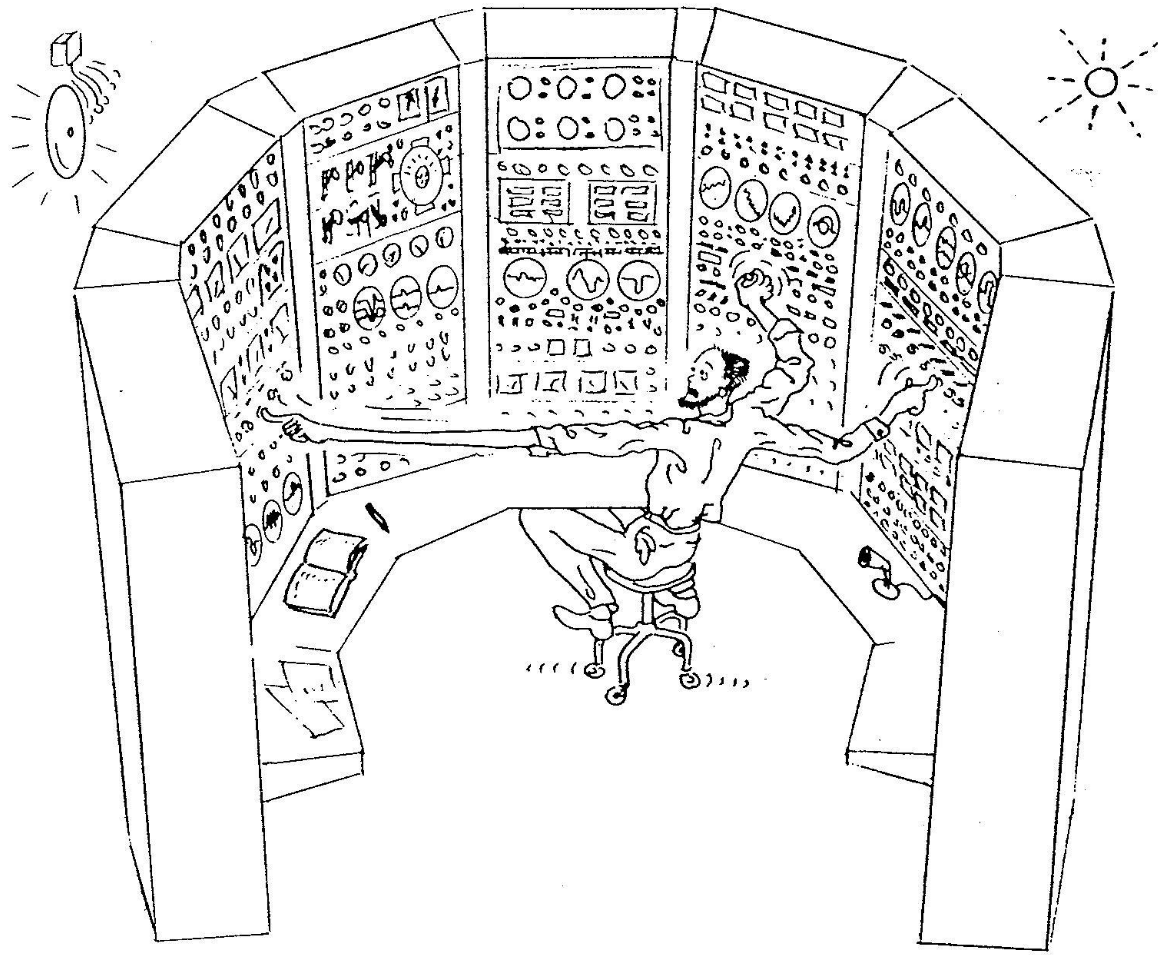
1929	Idea by E.O.Lawrence in Berkeley (inspired by R.Wideroe!)		
1931	4 inch cyclotron	80 keV	p
1932	10 inch cyclotron	1.2 MeV	p
1934	26 inch cyclotron	7 MeV	p
1939	60 inch cyclotron	16 MeV	d
1946	184 inch synchrocyclotron	200 MeV	d
		400 MeV	α

1938 Idea for sectored cyclotron (AVF) by Thomas

1962	88 inch sector cyclotron	K=160 MeV	ion
1974	SIN/PSI Ringcyclotron	590 MeV	p
1982	supercond.cyclotron MSU	K=500 MeV	ion

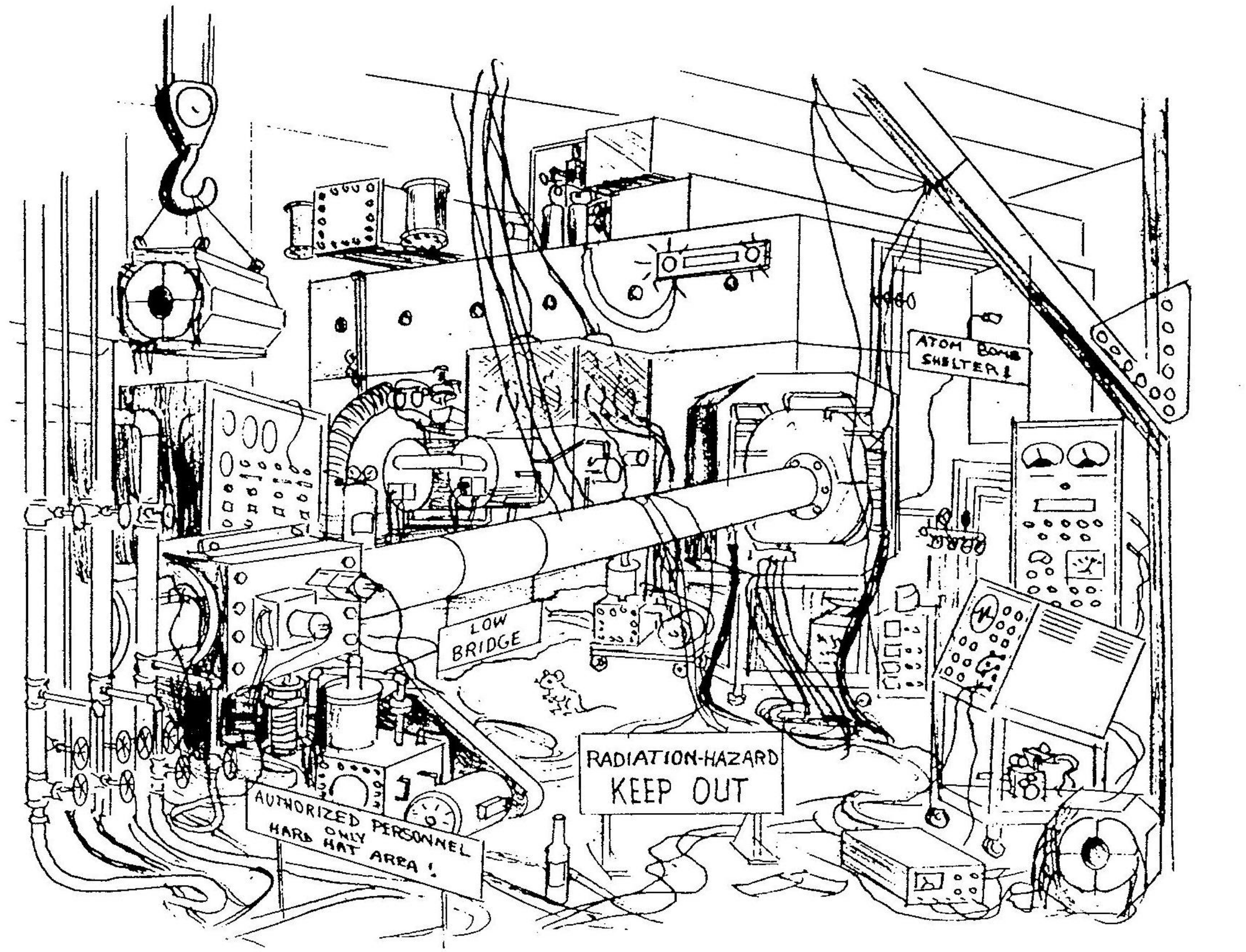
2008: ca. 90 indiv. cyclotrons, ca. 200 commercial cyclotrons

The Cyclotron as seen by the **Operator**



Dave Judd
1966

The Cyclotron as seen by the **Visitor**



SLS

(140m Diameter)

Swiss	**L**ight	**S**ource
Synchrotron	**L**ichtquelle	**S**chweiz
Source	**L**umière	**S**uisse
Sorgente	**L**uce	**S**vizzera

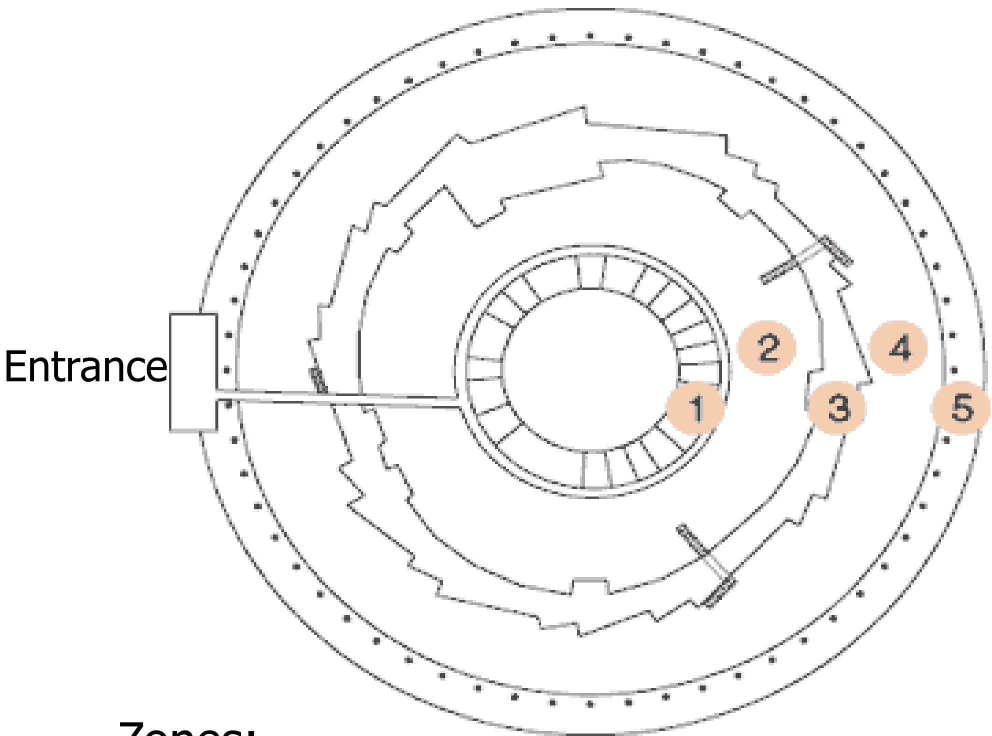
SLS Building

an architectural Juwel !

Team of Architects from Bern
(Gartenmann, Werren, Jöhri, Marchand)

SLS interior Area

Building Concept



Zones:

1. Office Building (3 Floors)
2. Technical Galery
3. Tunnel (Storage Ring, Linac and Booster)
4. Area for Beam Lines
5. Outer Ring (60 Columns, Air Inlet System)

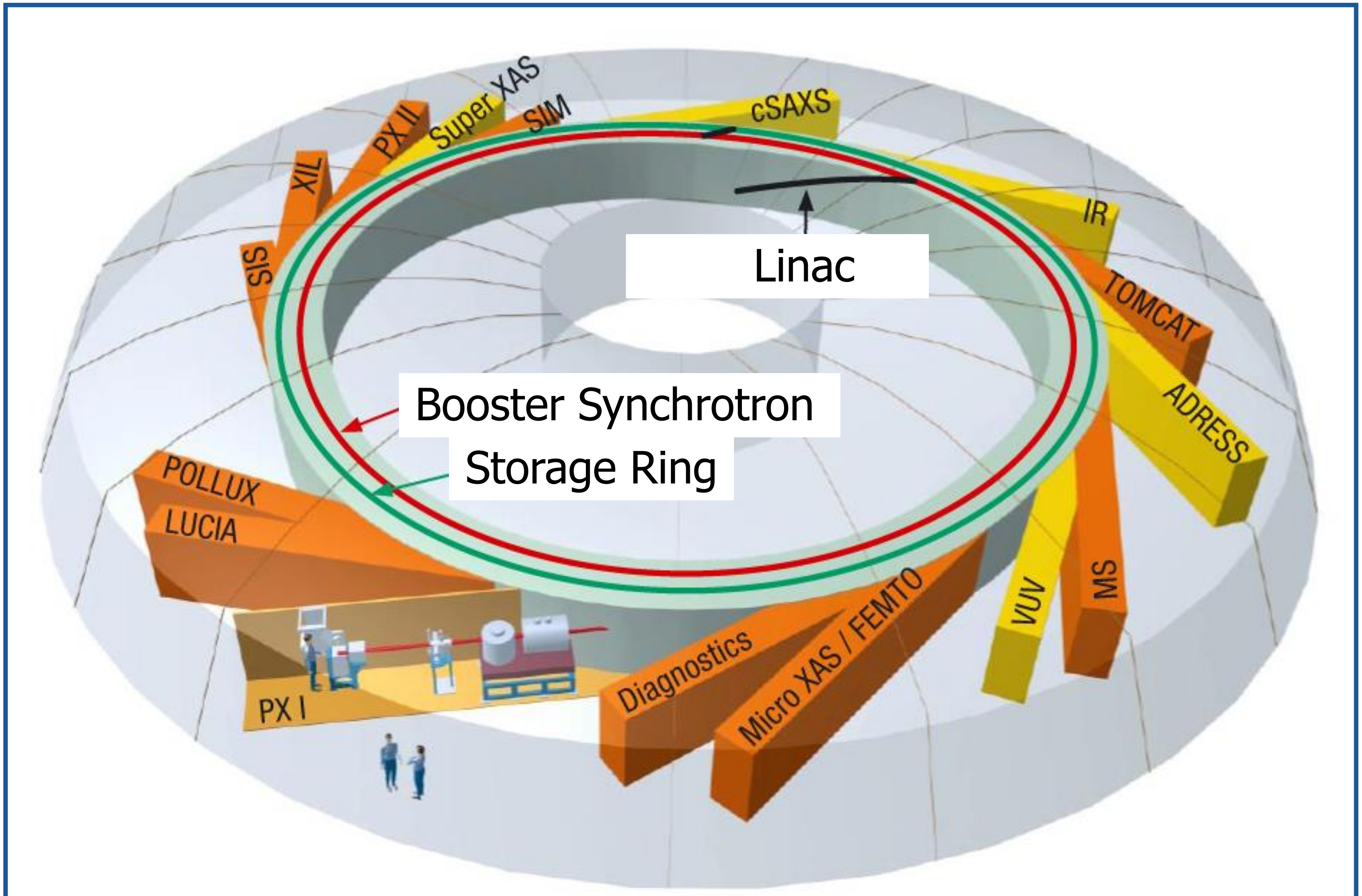
- separate annular Ring (40 cm) for Floor of Tunnel und Beam Lines (Zones 3, 4)

  => decouples Tunnel and Exp. Floor from rest of Building

- very stable Temperatures in Tunnel und Hall

=> stable Conditions for Electron Beam and Beam Lines

SLS Layout



Super XAS
SIM
PX II
cSAXS
XIL
IR
SIS
Linac
TOMCAT
ADRESS
Booster Synchrotron
Storage Ring
POLLUX
LUCIA
MS
VUV
Micro XAS / FEMTO
Diagnostics
PX I

SLS Beamlines

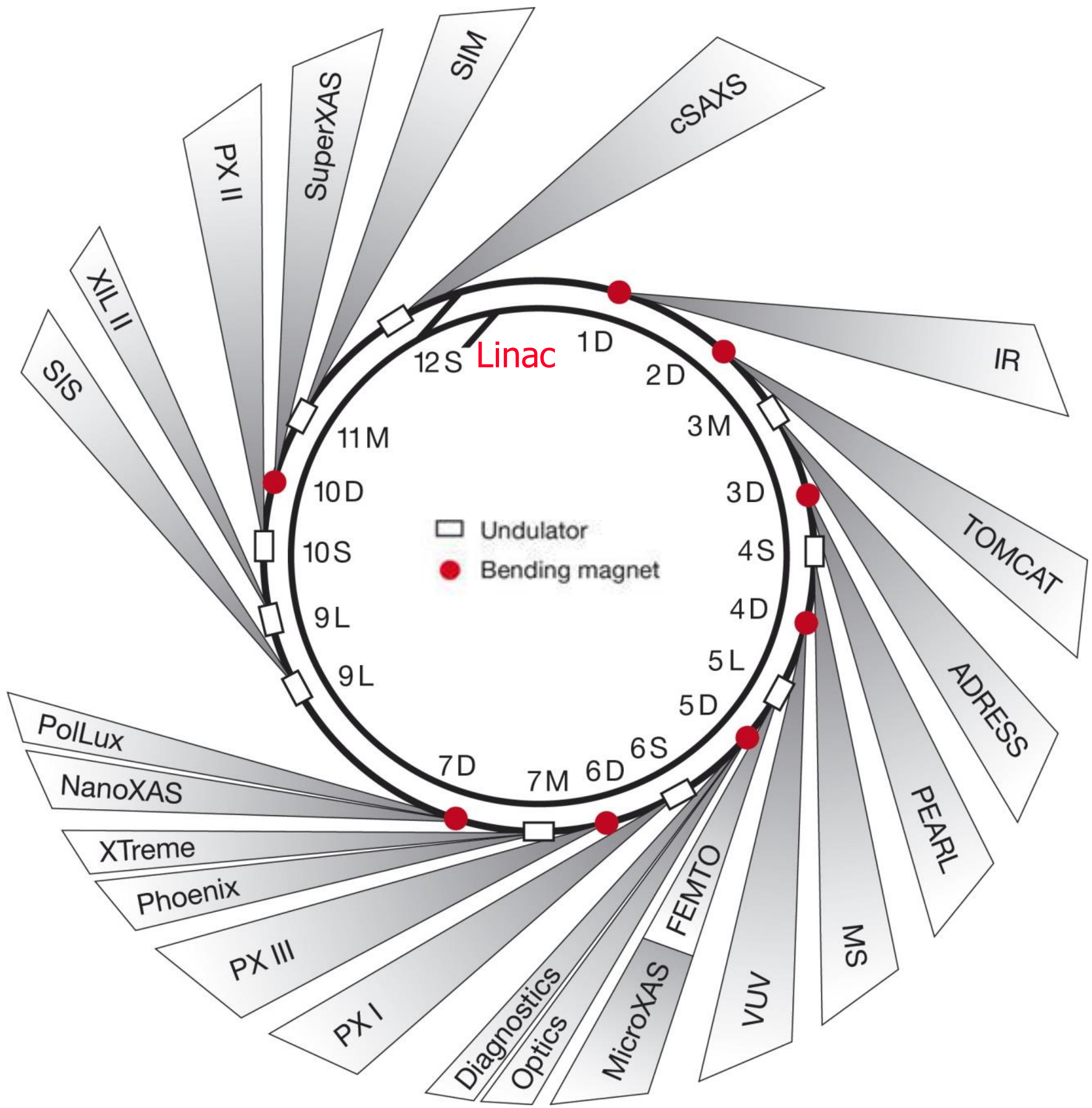
2013:

21 Beamlines in Operation:

10 with Undulators

3 from Superbends

8 from Dipoles



Synchrotron Radiation

- laser-like Beams (polarised),
  generated by high Energy **Electrons**
- very high Intensity (Brightness)
- free choice of Wavelength
  from infrared to hard X-Rays

what is needed?

$\Rightarrow$ a **Storage Ring** (with many Magnets), where Electrons can circulate for hours

SLS Strategy

Quality

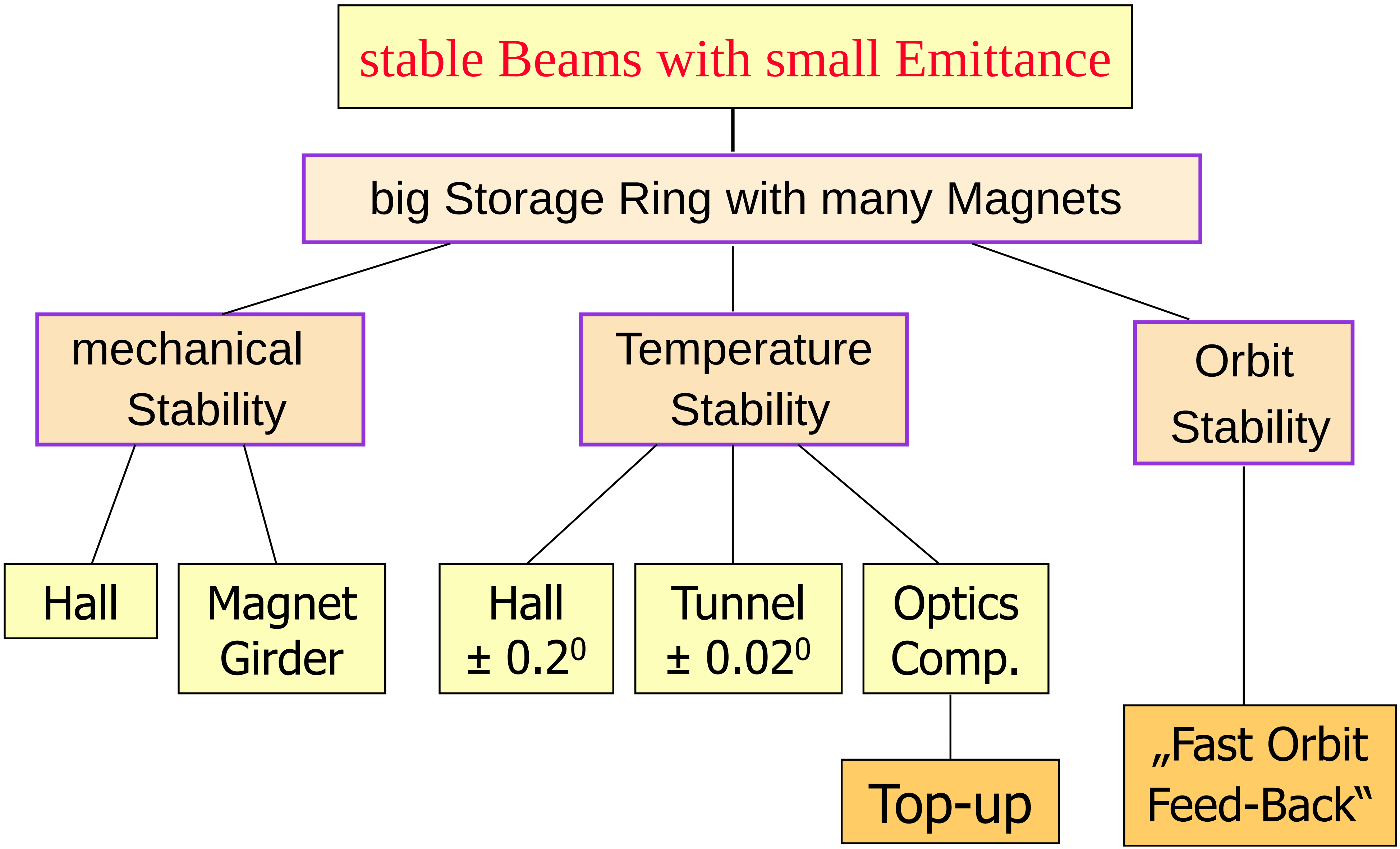
- high brightness , small emittance,
  ⇒ large circumference with many magnets

Flexibility

- large spectral range (VUV to hard x-rays)
- straights of 4 m, 7 m and 11 m => choice for undulators

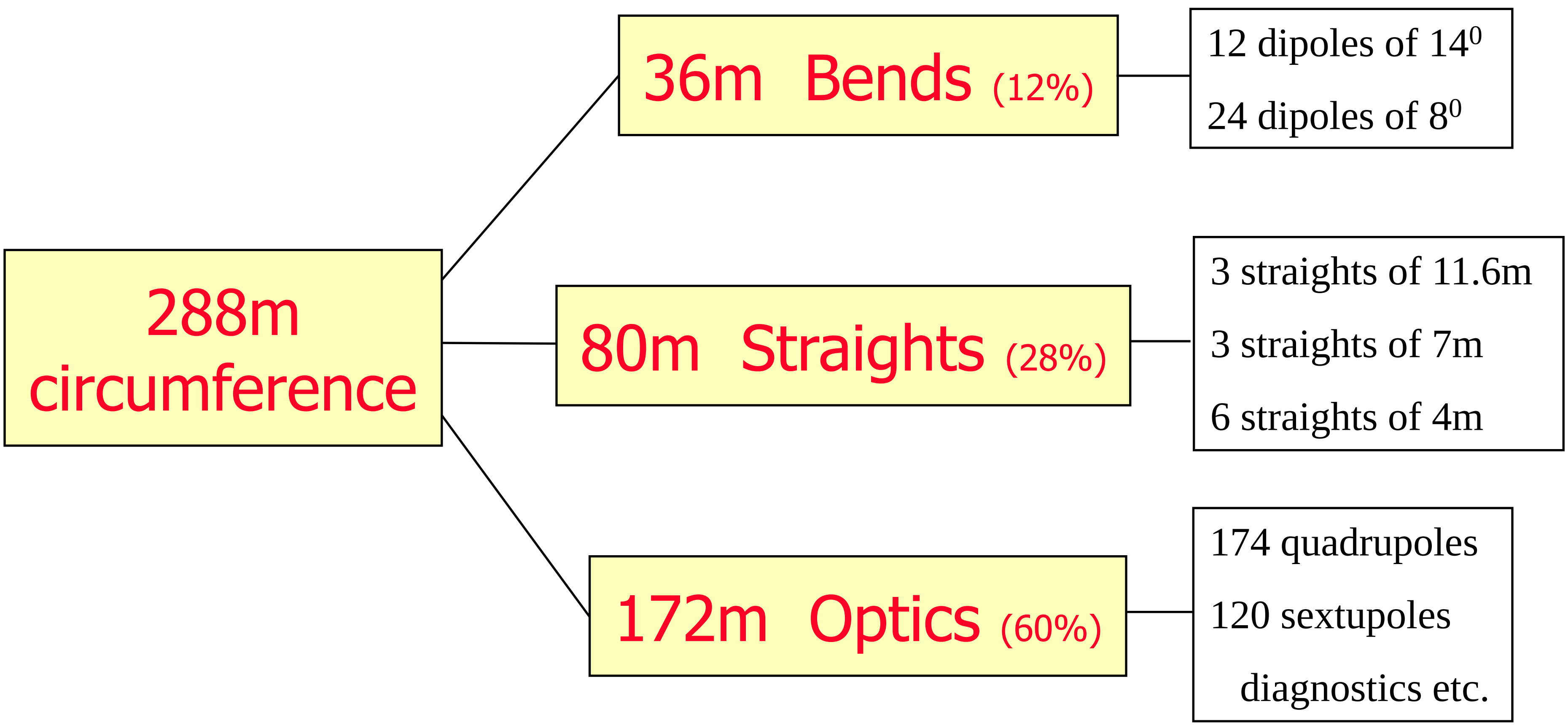
Stability

- separation of building structure from floor
- stable temperature in tunnel and experimental hall
- positioning of the magnets on rigid girders
- fast orbit feedback (up to 100Hz)
  with high accuracy (< 0.5 μm)
- constant beam current with **top-up injection** (every 2 min)
  ⇒ constant heatload on optical components

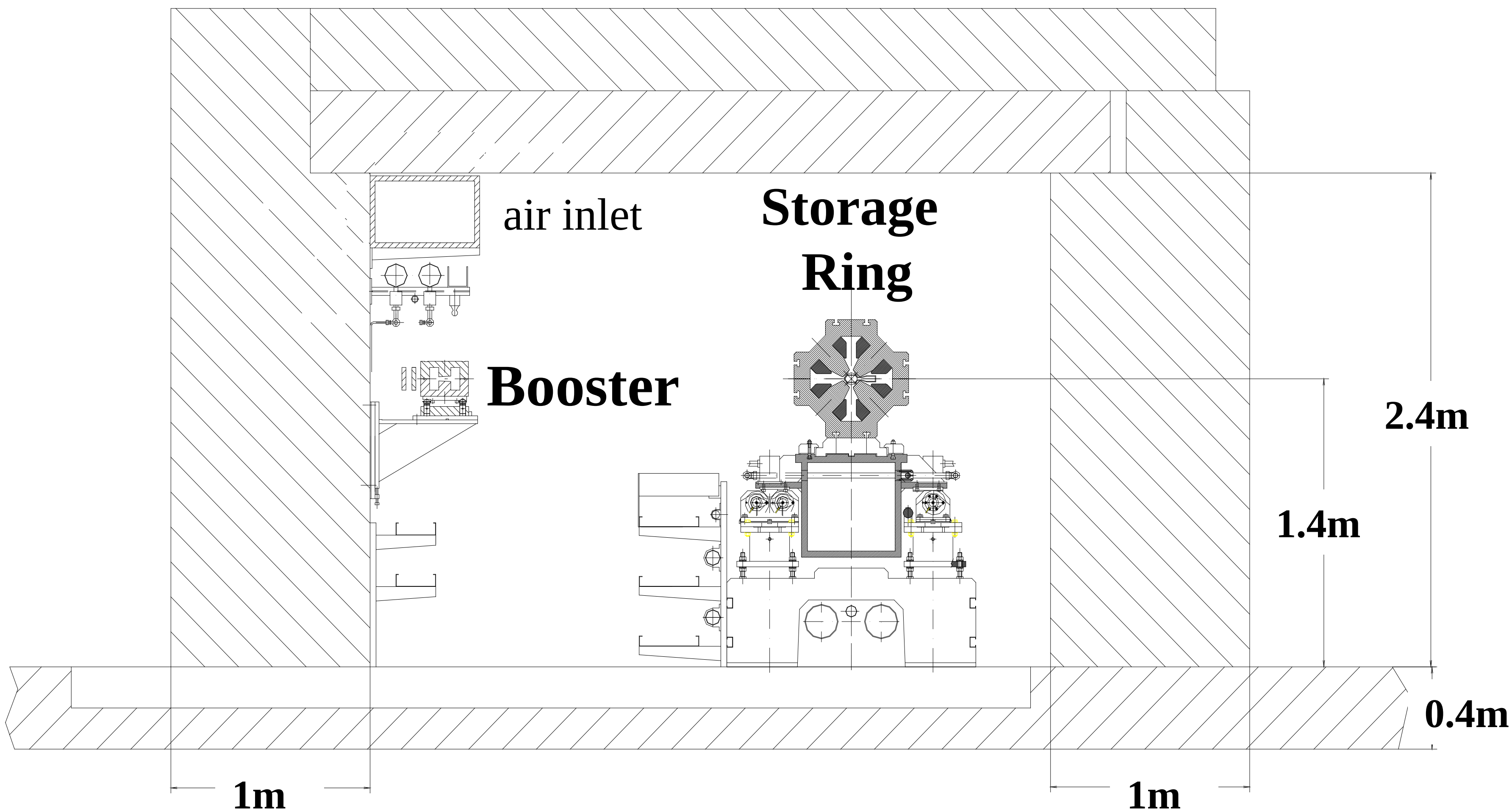


stable Beams with small Emittance
big Storage Ring with many Magnets
mechanical Stability
Temperature Stability
Orbit Stability
Hall
Magnet Girder
Hall ± 0.2⁰
Tunnel ± 0.02⁰
Optics Comp.
Top-up
„Fast Orbit Feed-Back“

Allocation of Space for Storage Ring



SLS Tunnel



Parameter of 2.4 GeV Storage Ring

circumference	288 m
12 straights	3x11.7m, 3x7m, 6x4m
current	400 mA
emittance	5 nm
lattice	Triple Bend Achromat
tunes Q_x , Q_y	20.44 , 8.74
momentum compaction	$0.6 \cdot 10^{-3}$
RF frequency	500 MHz
peak RF voltage	2.6 MV
radiation loss / turn	500 keV
energy spread (rms)	$9 \cdot 10^{-4}$
damping times (x, y, E)	9 , 9 , 4.5 ms

SLS-Components

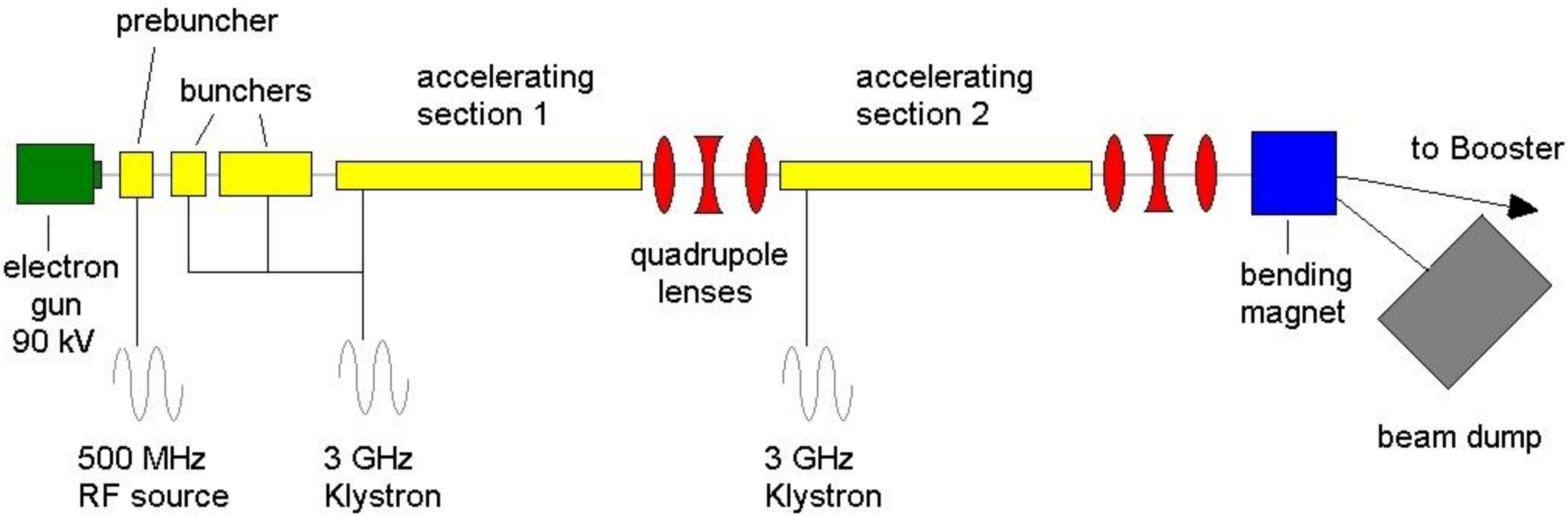
Accelerators

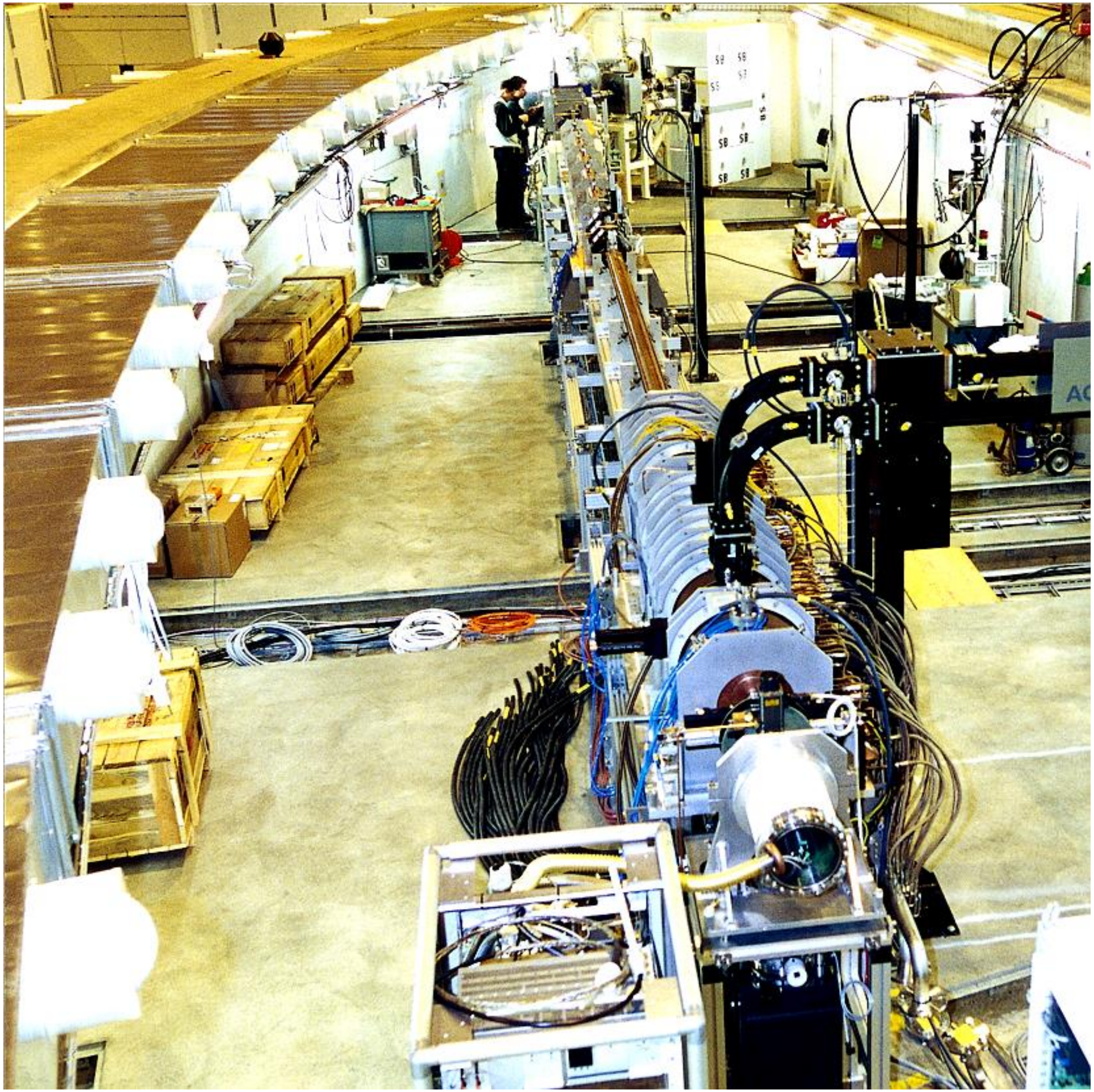
- Electron gun **90 keV**
- LINAC **100 MeV**
- Booster, 3 Hz **0.1-2.4 GeV**
- Storage Ring, 288m **2.4 GeV**

Beamlines

- Protein Cristallography
- Material Sciences
- Surface Microscopy
- Surface Spectroscopy
- environment sciences

Layout 100 MeV Linac





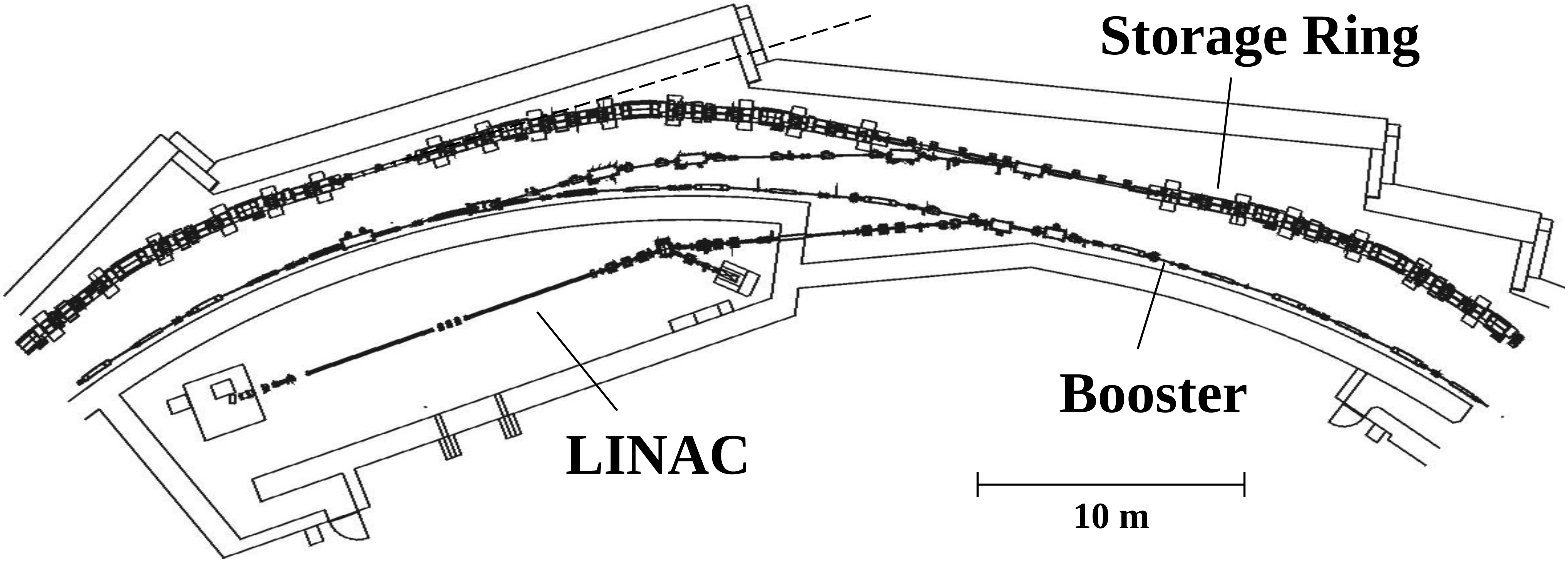
Linac

Electron Gun 90 keV

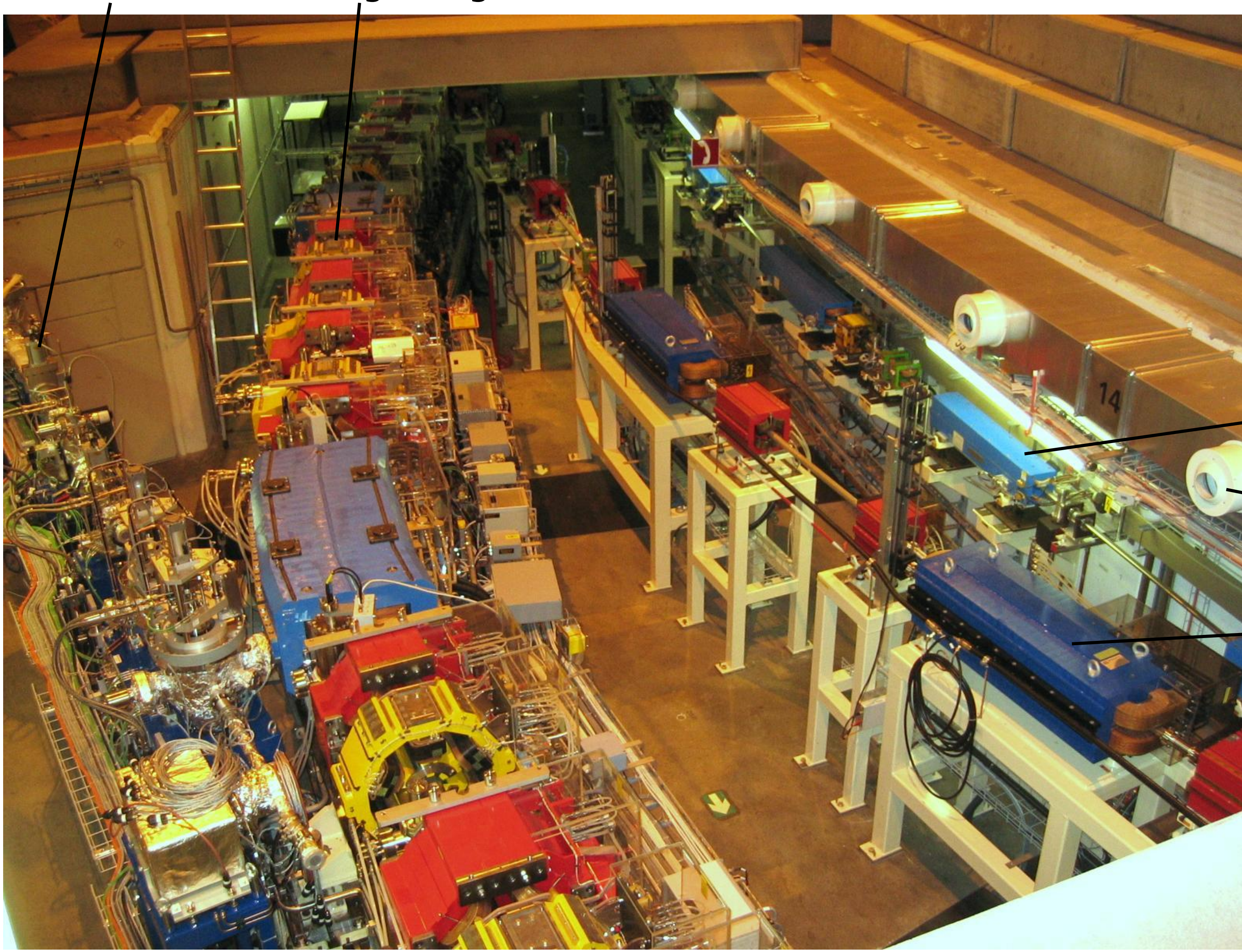
Linac 100 MeV

(11m long)

Injection Region



SLS Tunnel


Beamline
Storage Ring
Booster
Cooling Air Inlet
Transferline
14

what is special at SLS ?

1. very good beam quality , high brightness

   (requires large circumference, many magnets)

- microscopy (ca. 30 nm) , spectroscopy
- small probes (microcrystals, 5-10µm)
- beamstability < 0.2 µm (with fast orbit feed back)

2. large spectral range :

   infrared to hard X-rays (6 decades !)

what is special at SLS ?

3. Short, Medium and Long Straights

(6 à 4 m, 3 à 7 m, 3 à 11.5 m)

- flexibel undulator schemes

(e.g. variation of the polarization in the kHz-region)

4. Top-up Injection :

- constant beam intensity over days (beam lifetime is irrelevant !)

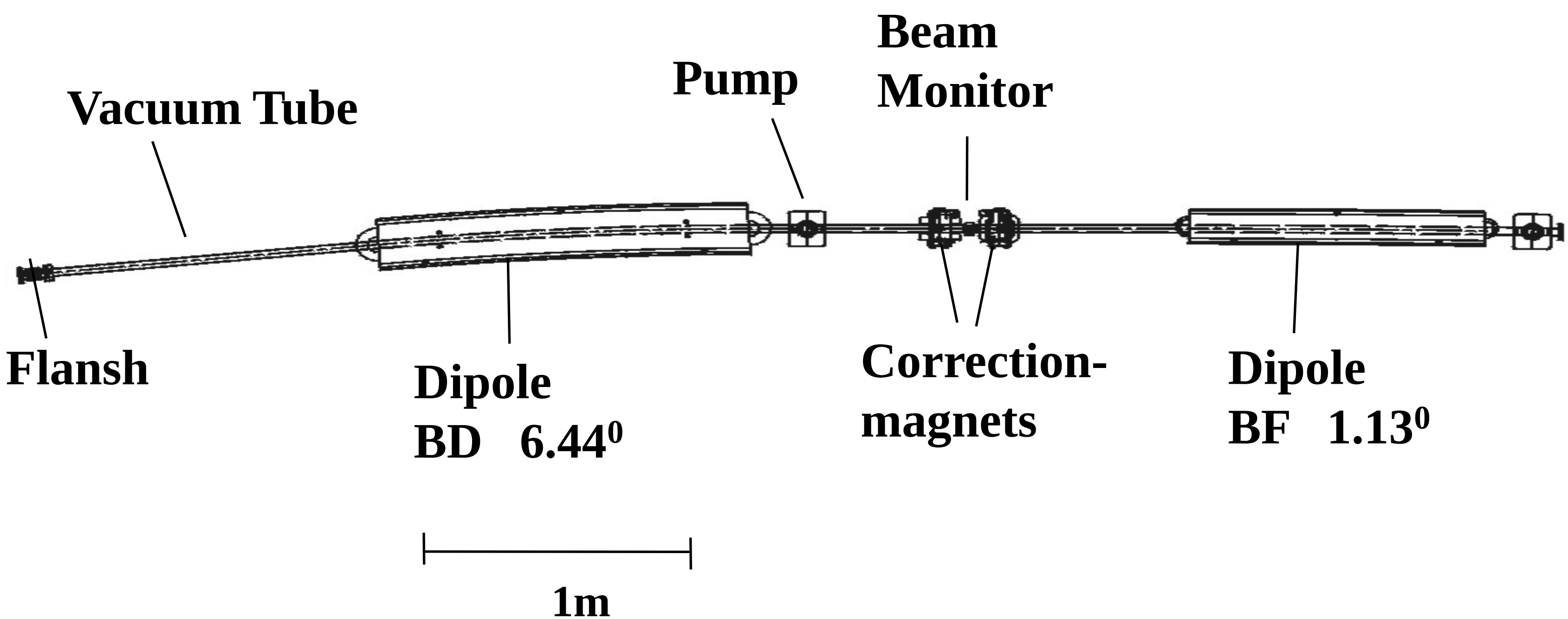
=> constant heat load on optical components

Booster Specialty

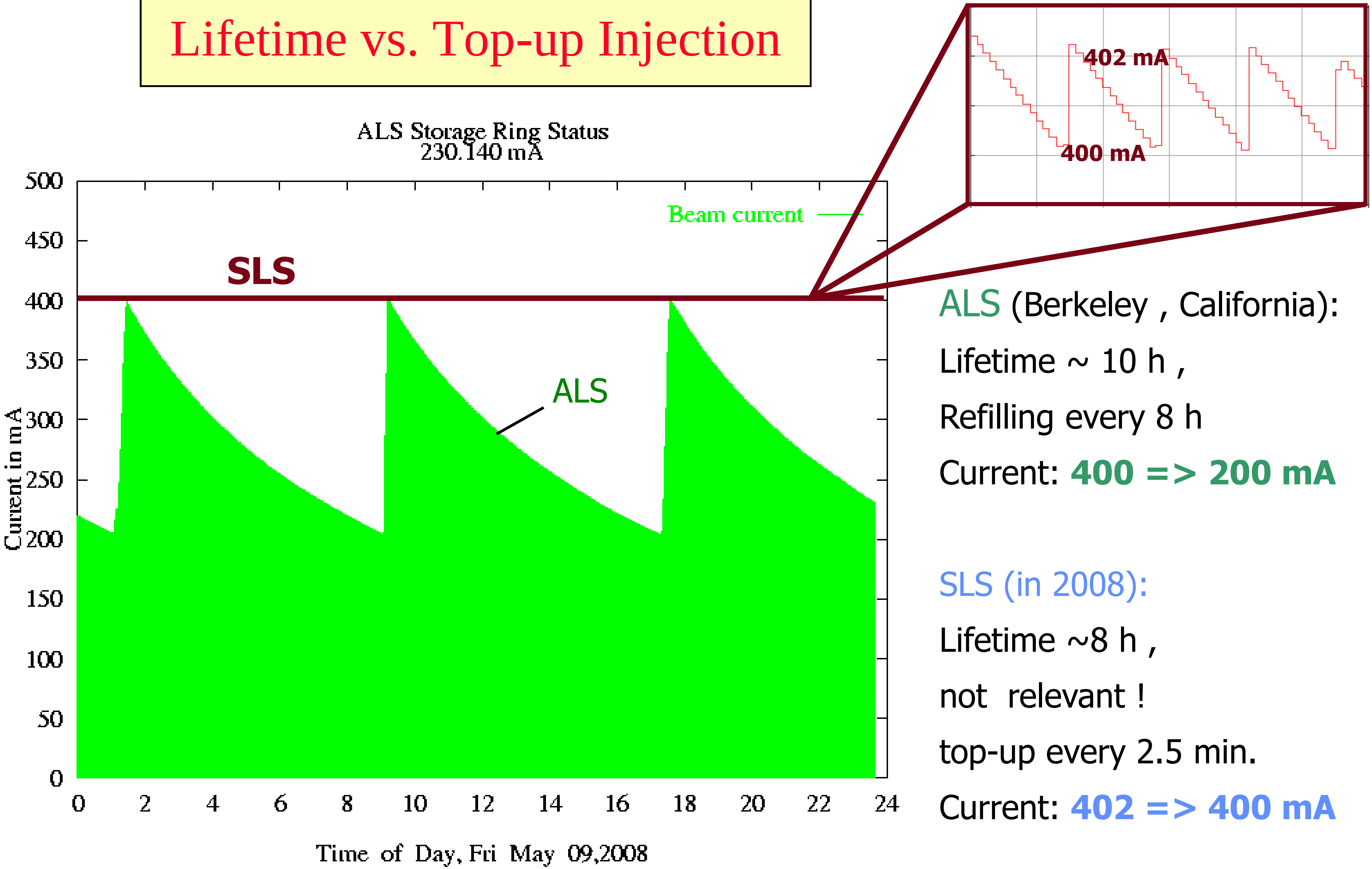
- **Booster in same Tunnel as Storage Ring**
- => large Circumference
  => small Emittance
- efficient Injection into Storage Ring, filling in 6 min.
- compact, economic Magnets
- simple Vacuum Chamber (30 x 20 mm)

- **Top-up Injection**
- short refill (2s) every 2.5 min.
  => constant Beam Current
- => stable Temperatures on optical Components
- Energy Consumption < 20 kW !

Booster
FODO-cell
5.4m long



Lifetime vs. Top-up Injection



ALS (Berkeley , California):

Lifetime ~ 10 h ,

Refilling every 8 h

Current: **400 => 200 mA**

SLS (in 2008):

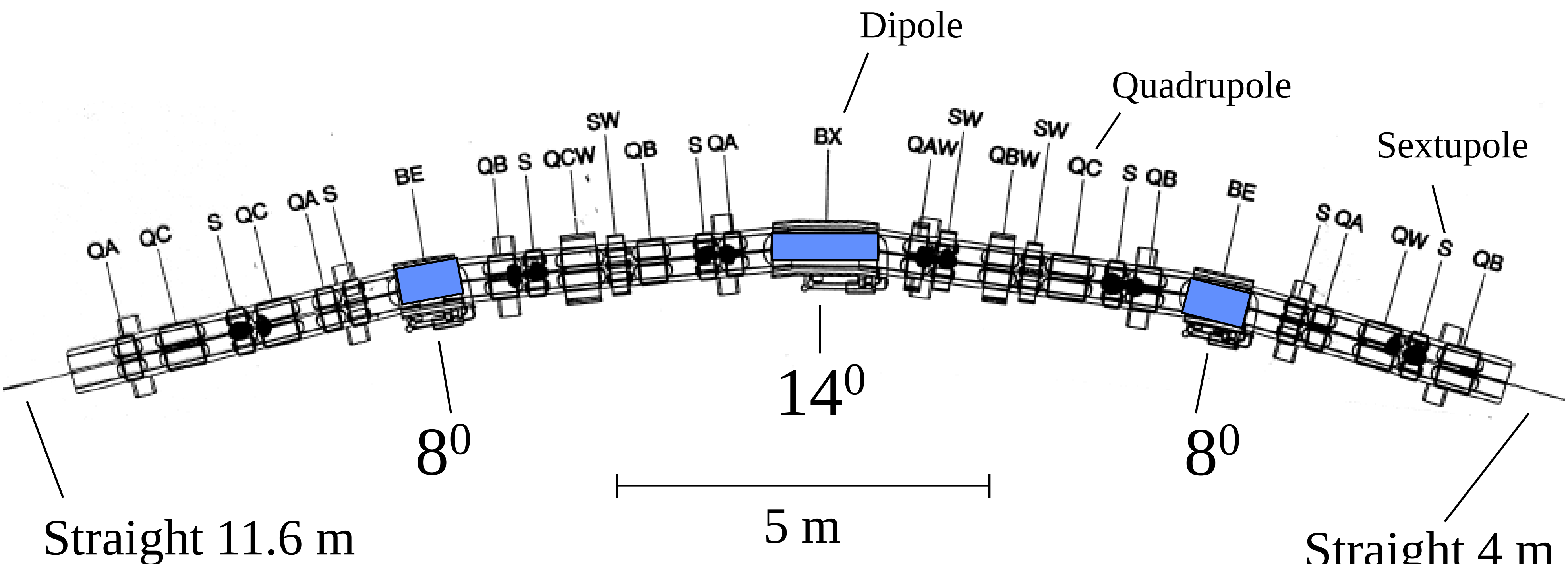
Lifetime ~8 h ,

not relevant !

top-up every 2.5 min.

Current: **402 => 400 mA**

SLS 30^0 Arc



TBA-lattice

(Triple Bend Achromat)

Parameter Storage Ring

Storage ring

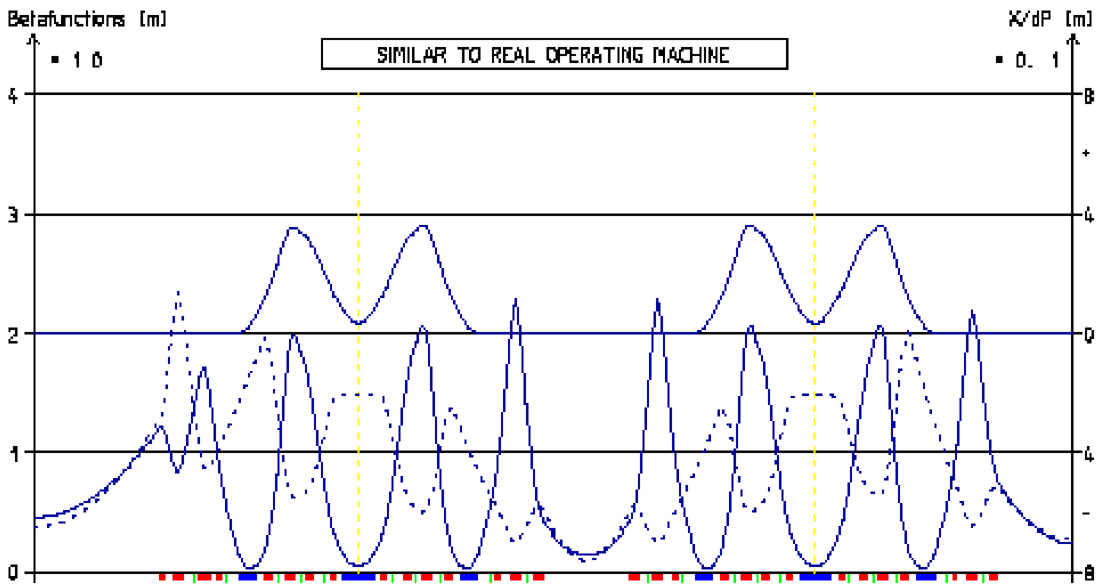
12 TBA: 8°/14°/8°

12 straights:

3 x 11 m

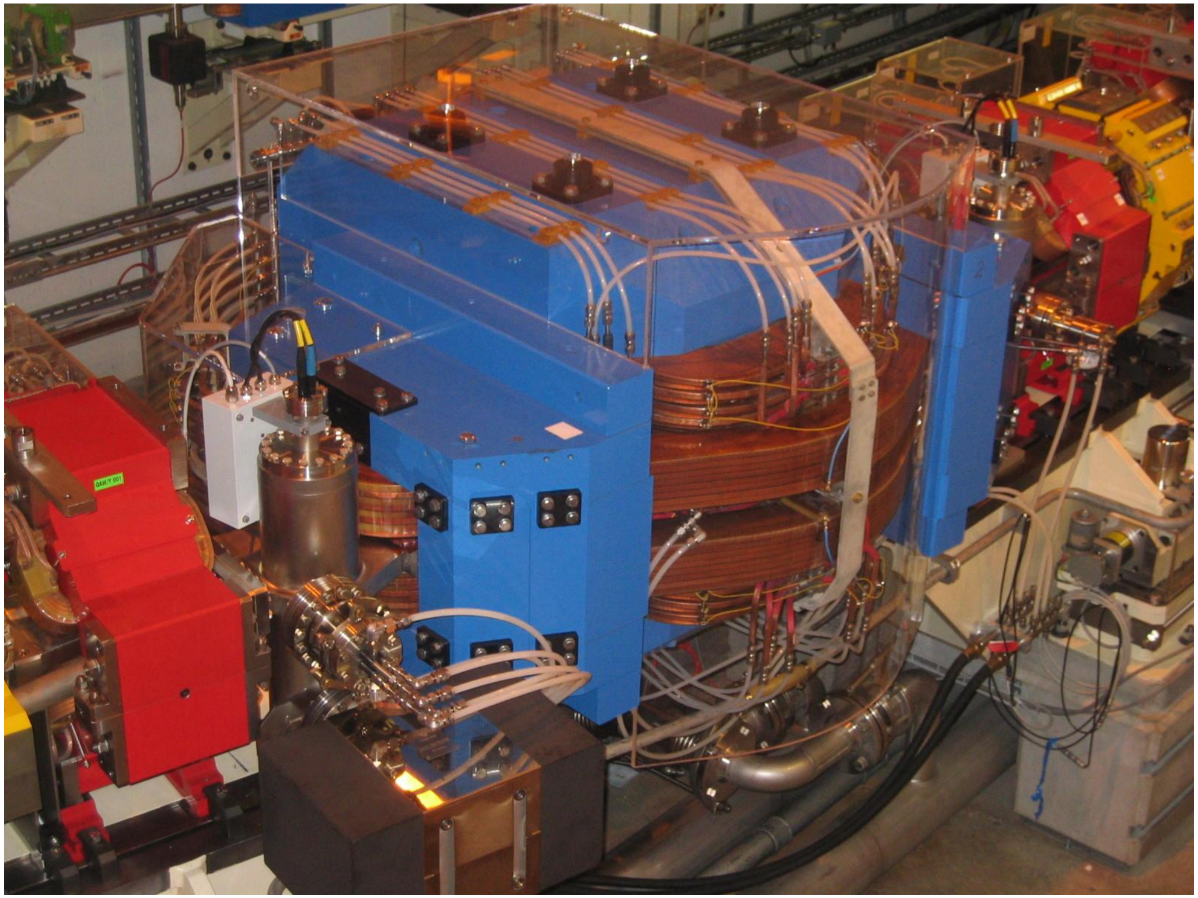
3 x 7 m

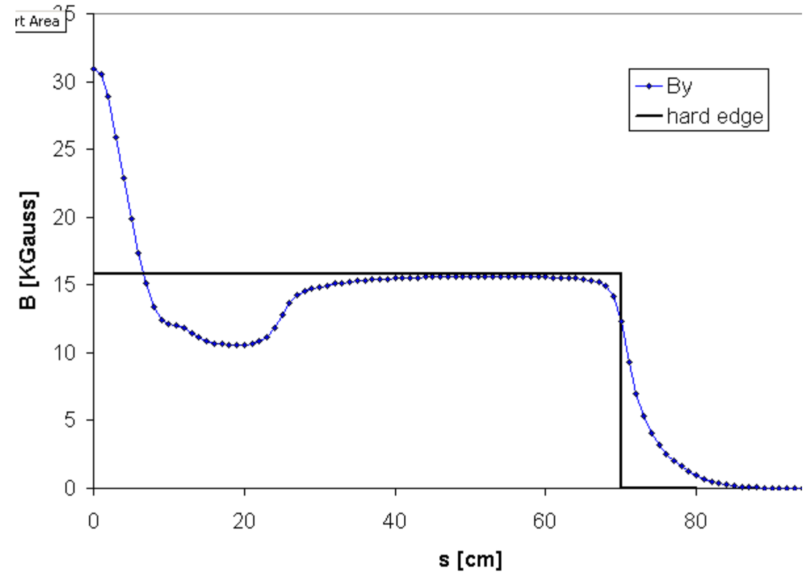
6 x 4 m



Energy	**2.4 GeV**	Momentum compact.	$6.3 \cdot 10^{-4}$
Emittance	**5 nm rad**	Radiation loss per turn	512 keV
Circumference	288 m	Damping times	9 / 9 / 4.5 ms
RF frequency	500 MHz	Relative energy spread	$8.9 \cdot 10^{-4}$
Tunes	20.41 / 8.17	Bunch length (rms)	3.5 mm
Chromaticities	-66 / -21	Beam current	**400 mA**

Superbend





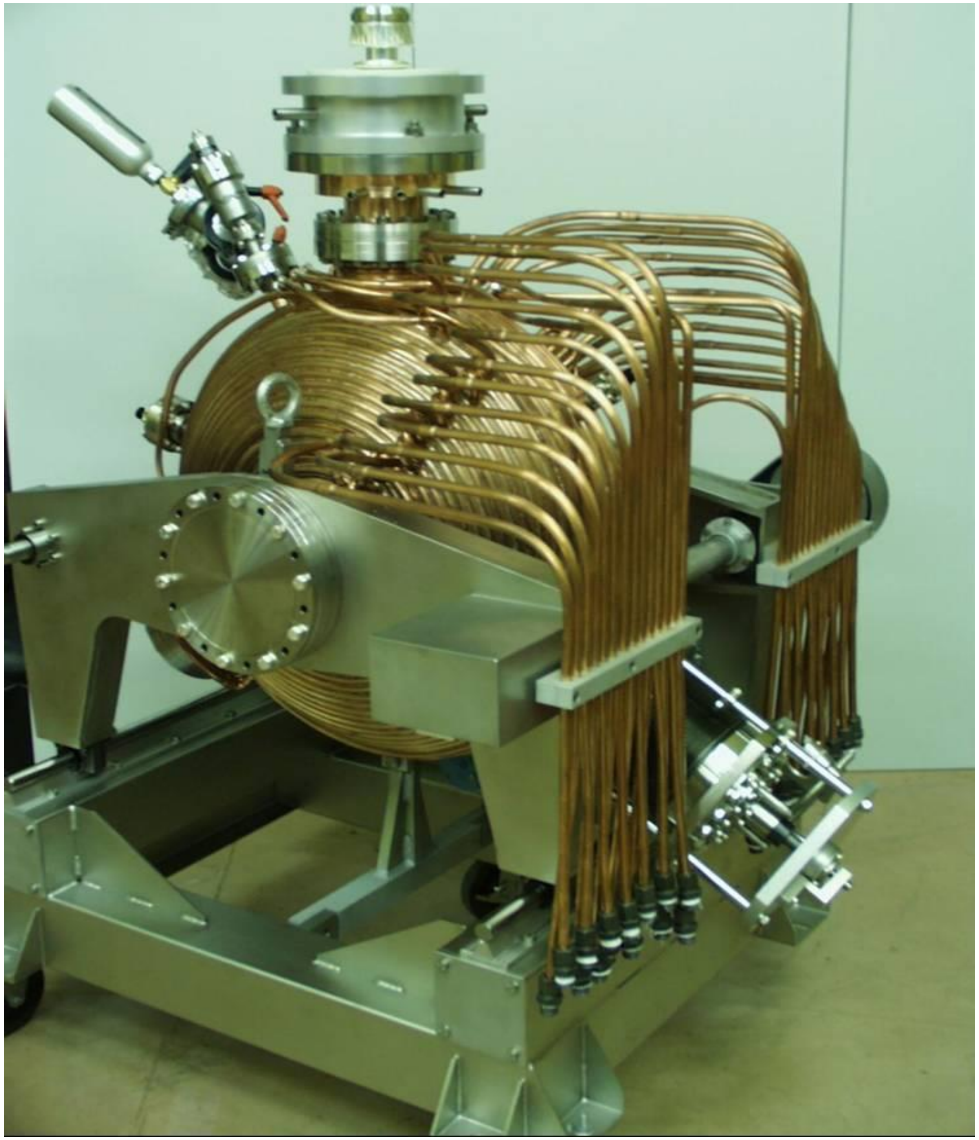
bending angle 14^0

center cone with 3 T

critical energy = 11.5 keV

end regions with 1.5 T

RF-Cavity



circulating Electrons generate

200 kW of X-Rays

this power has to be

refurbished by an RF-System

Cavity = Resonator, made of Copper,

Frequency 500 MHz

4 Cavities in Storage Ring,

1 Cavity in Booster

600 kV Voltage

55 kW Power Loss/Cavity

fast Electrons in magnetic field
generate Synchrotron Light

moving light source

⇓

Doppler effect

shift to higher frequencies

=> short wavelenth λ

narrow light cone

=> strong collimation (laserlike)

slalom course in undulator

⇓

positive Interference

period λ_u gives sharp spectral lines at harmonics n

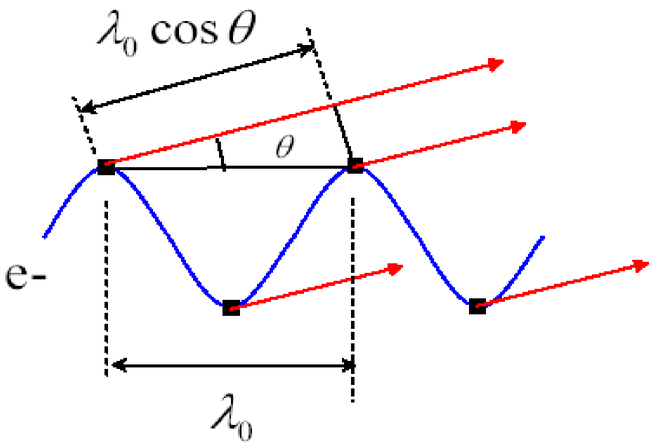
=> high brightness

$$\lambda \sim \lambda_u (c - v_e) \sim n\, \lambda_u / E_e^2$$

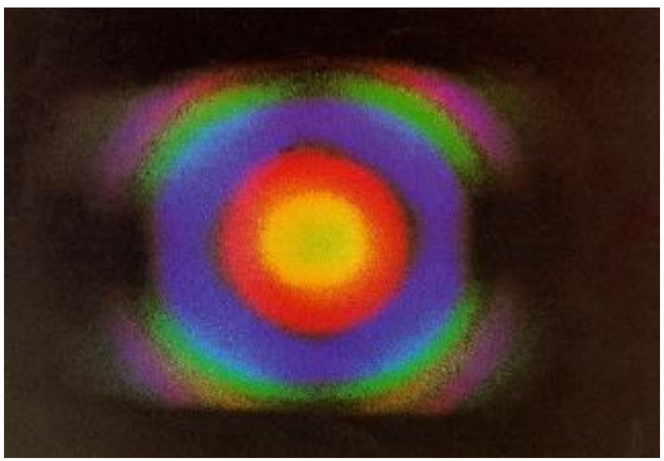
=> short wavelength λ requires high electron energy E_e

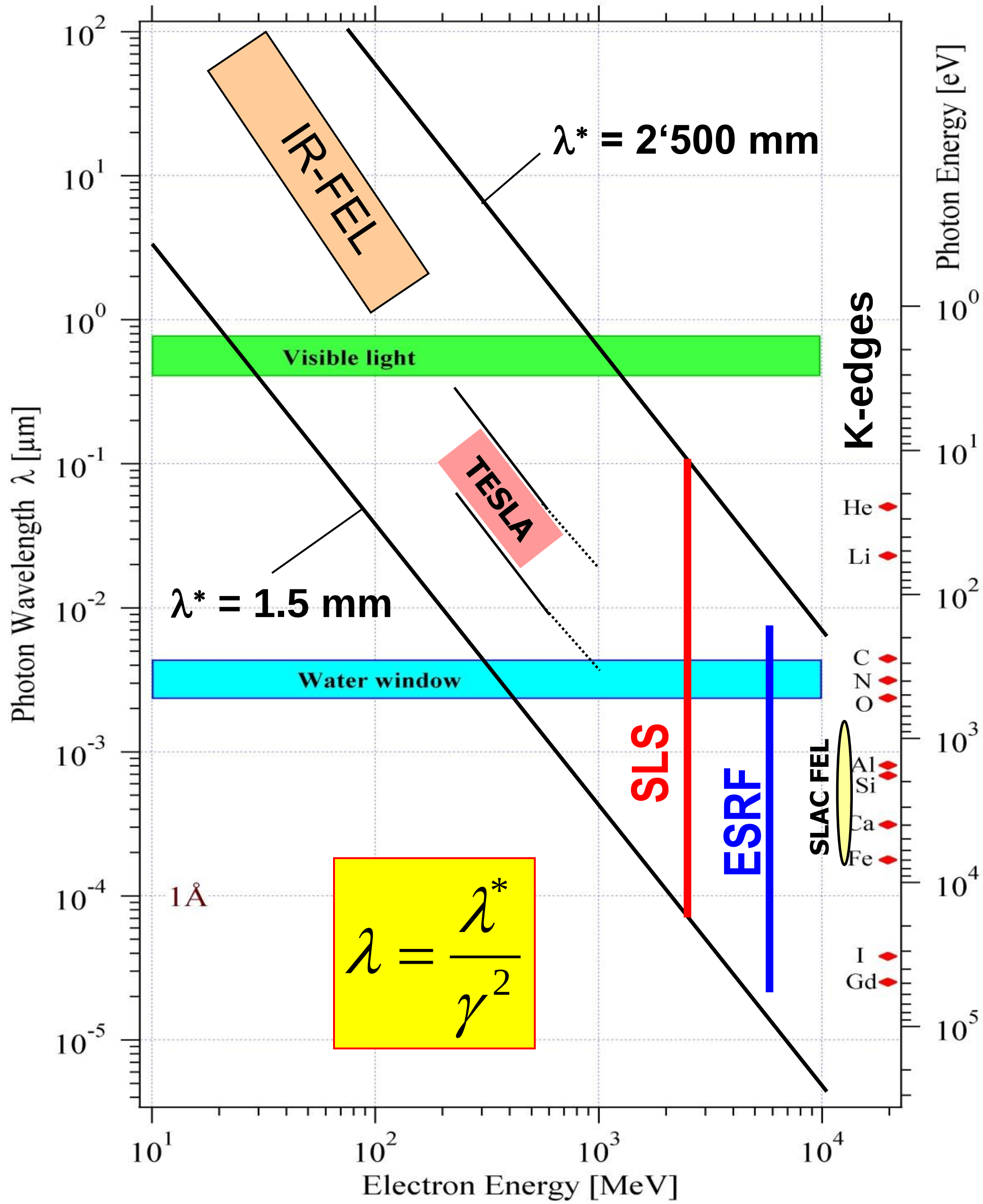
=> large storage ring

Undulator Radiation



$$\lambda^* = \frac{\lambda_u}{2n}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$





Undulator UE56

Permanent Magnets

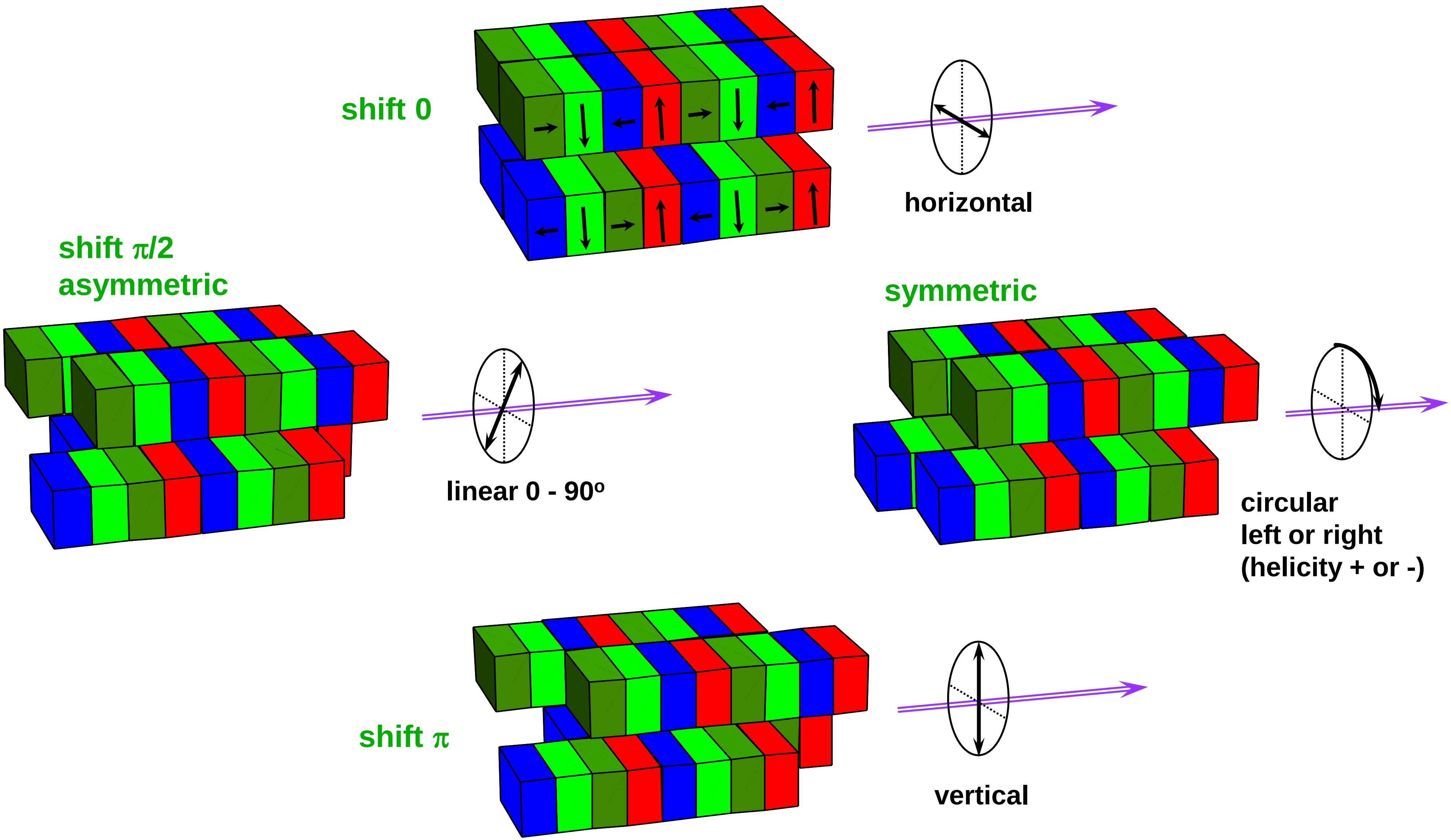
62 Periods à 56mm

helical Fields give

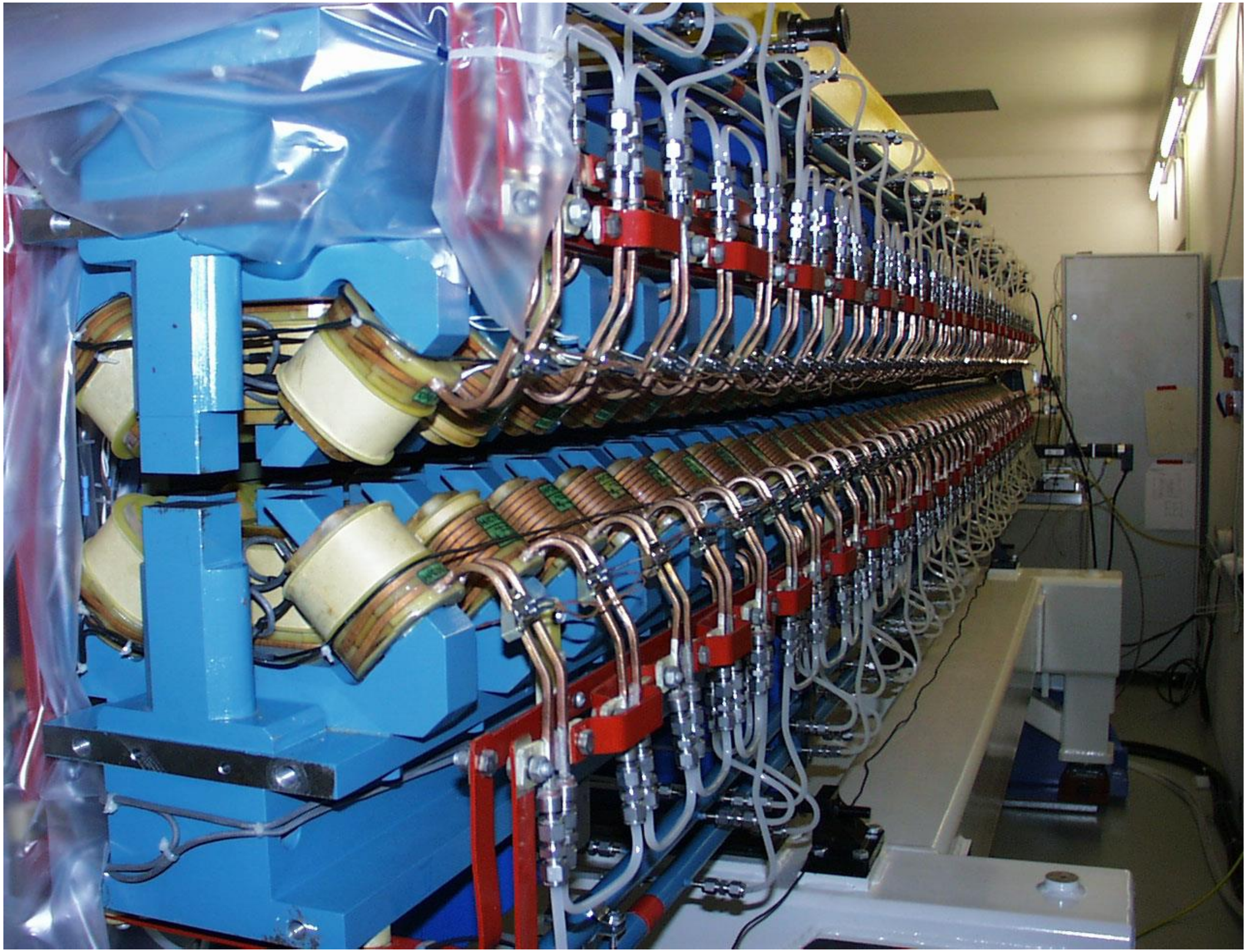
circular and linear

Polarisation

Elliptical undulator → circularly or linearly polarised light



Undulator UE212, 9m long



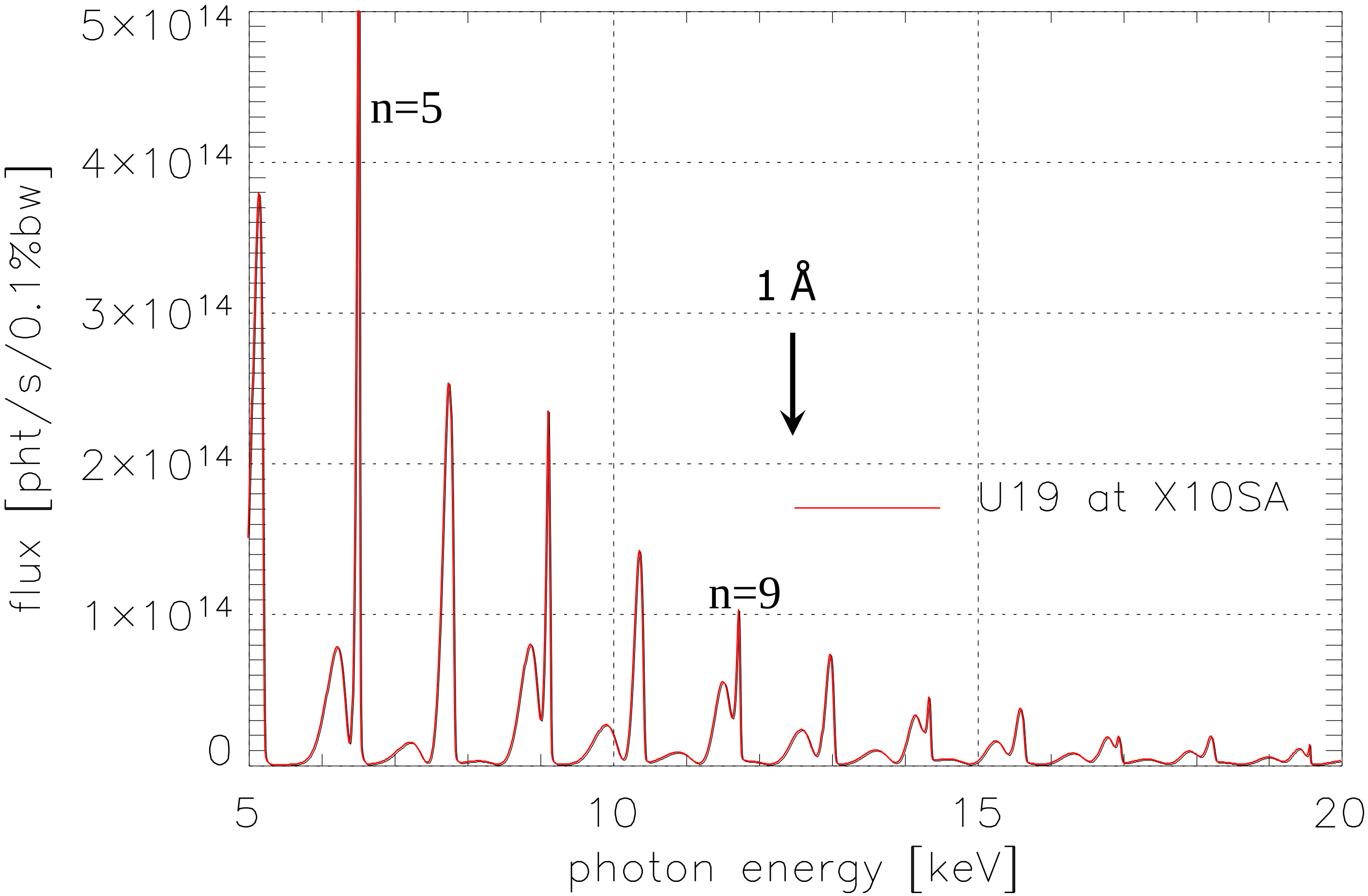
Electromagnets

2*21 Periods à 212mm

for low energy photons (10-80eV)

helical Fields give circular and linear Polarisation

Spectrum of Undulator U19



in-Vacuum Undulator

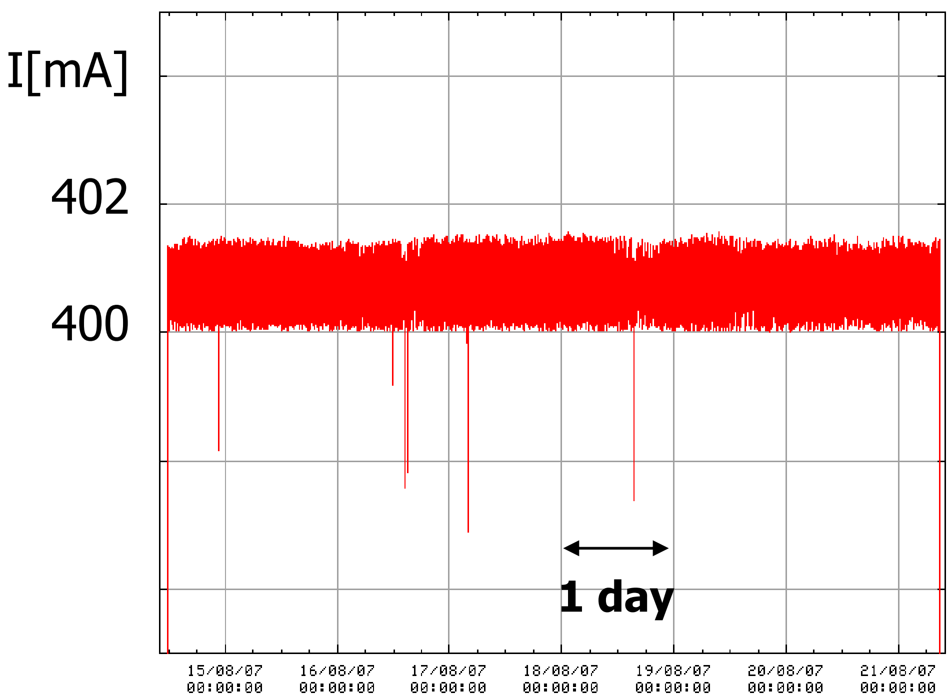
Protein Crystallography

(Clemens Schulze)

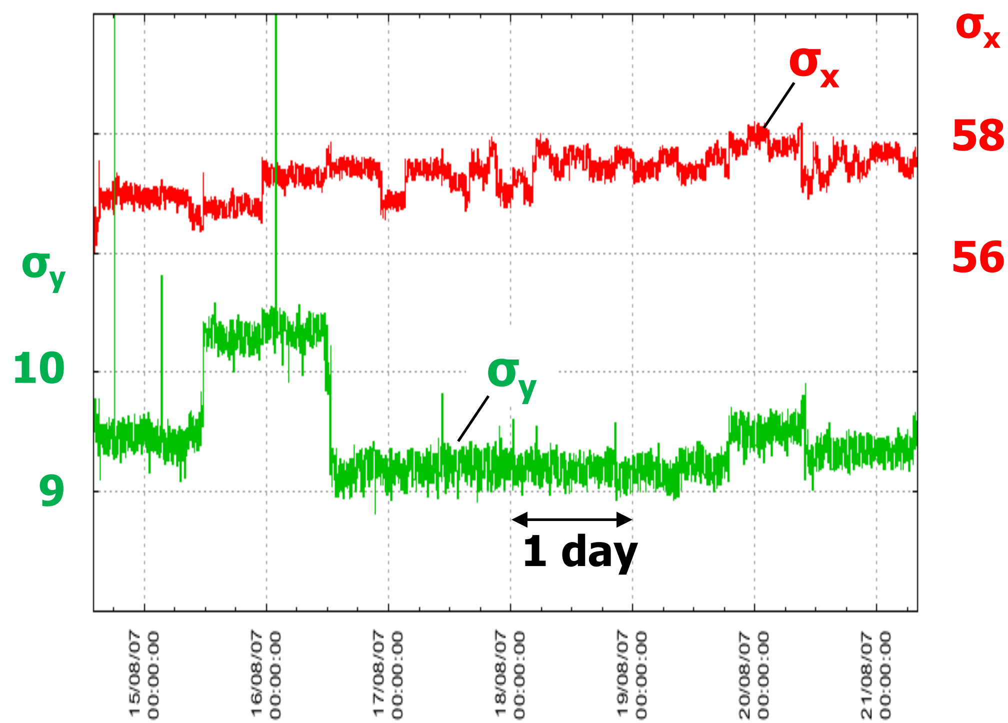
stable beams with top-up

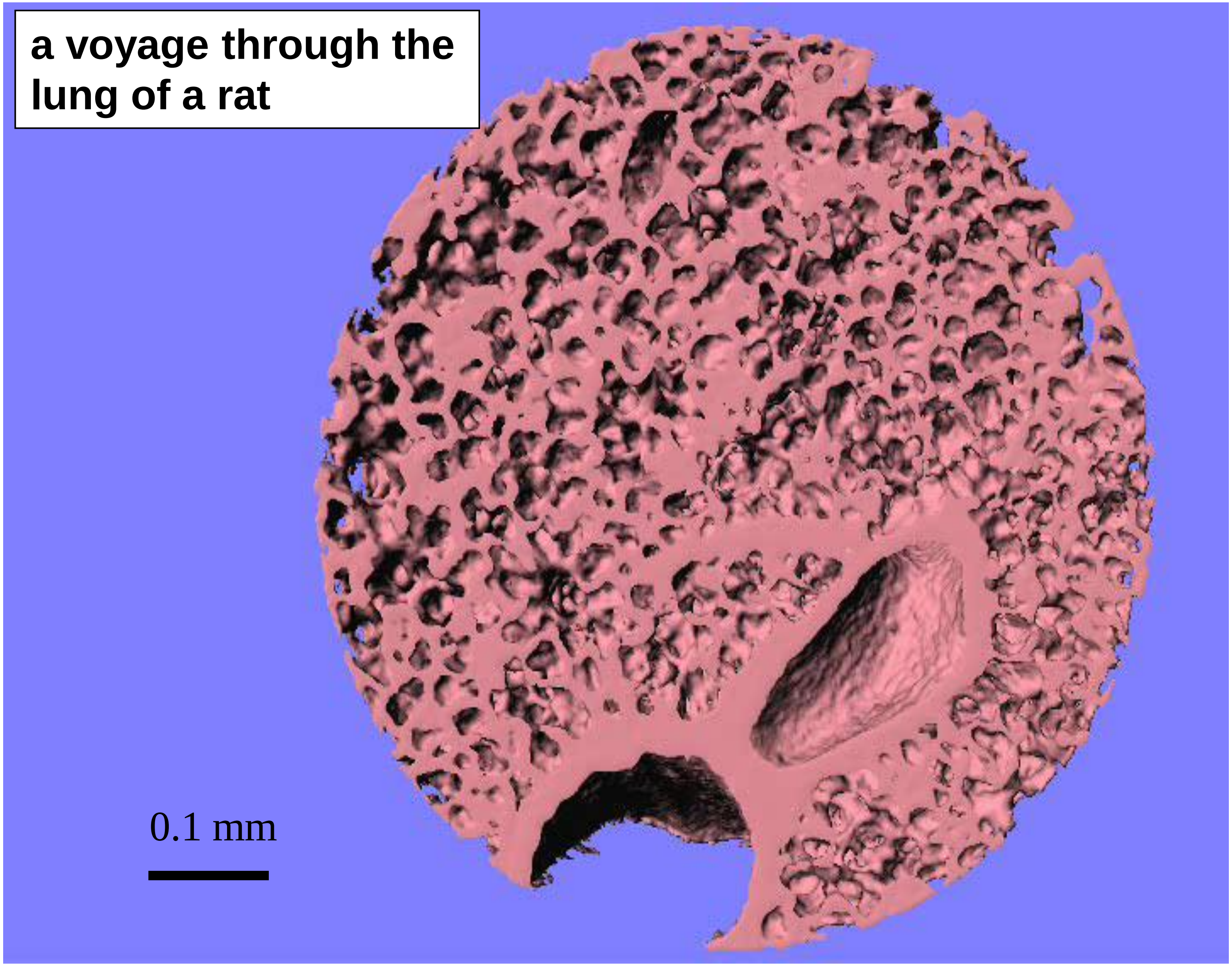
7 days in August 2007 , without interruptions!

top-up every 2.5 min.
Beam current 400-401.5 mA



Beam size σ_x , σ_y [μm]





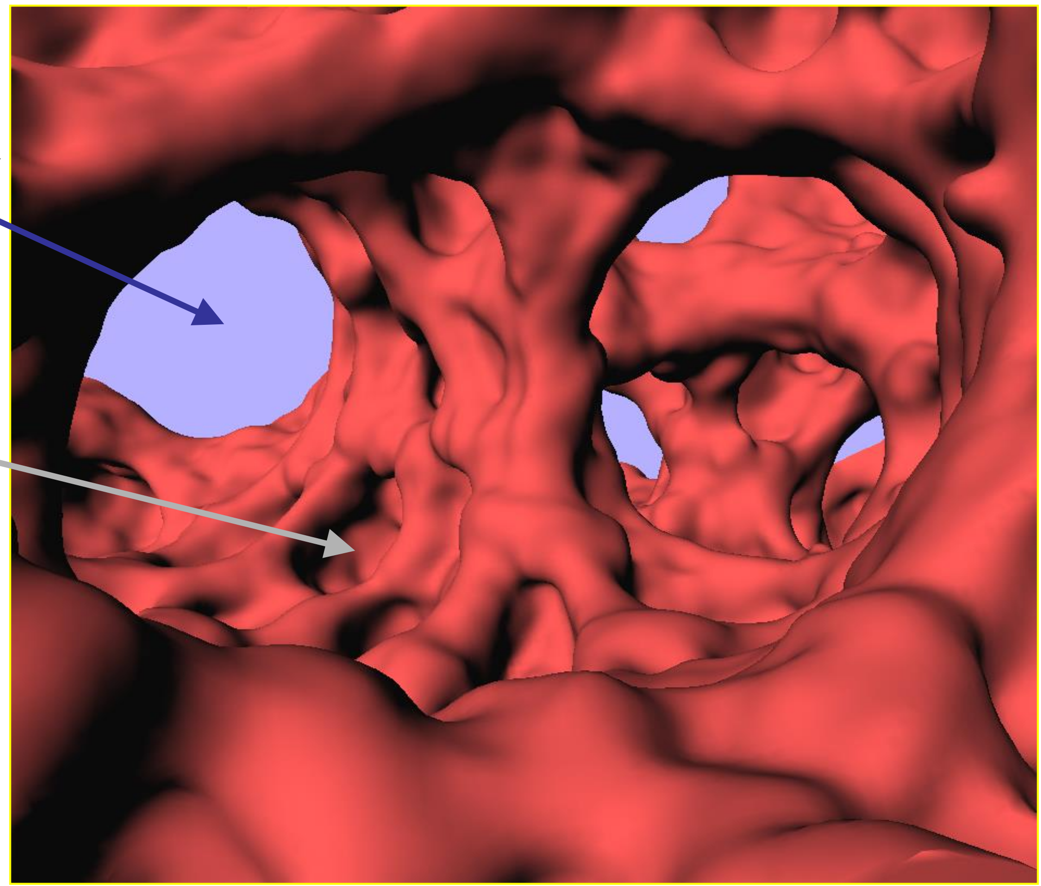
Prof. J. Schittny, University Bern

X-ray Tomography

Gas exchange region in the lung of a rat

60 μm daughter airway

25 μm pouches: alveoli of lung



Prof. Schnittny (Univ. Bern) et al
Tomogram taken at beamline XO4SA-MS, M. Stampanoni et al.

Micro-Tomography

Blood Vessels in the Brain of a Mouse (infected by Alzheimer)

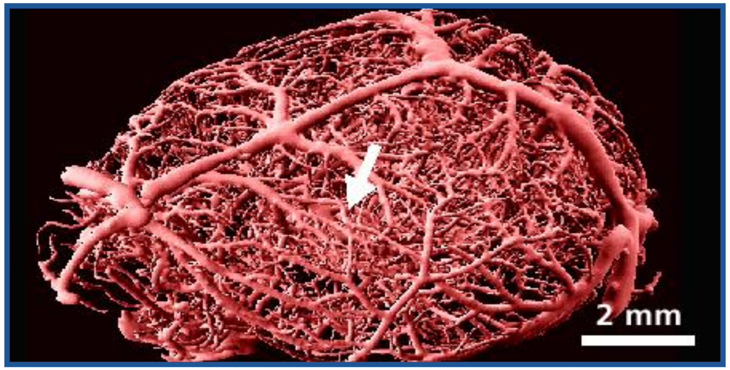
uni | eth | zürich

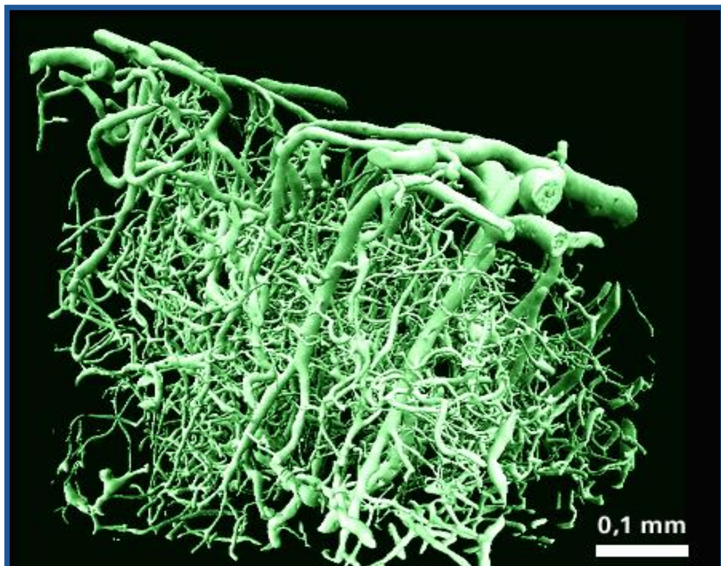
University of Zürich
Dept. of Zoology- Neurobiology

The Scripps Research Institute

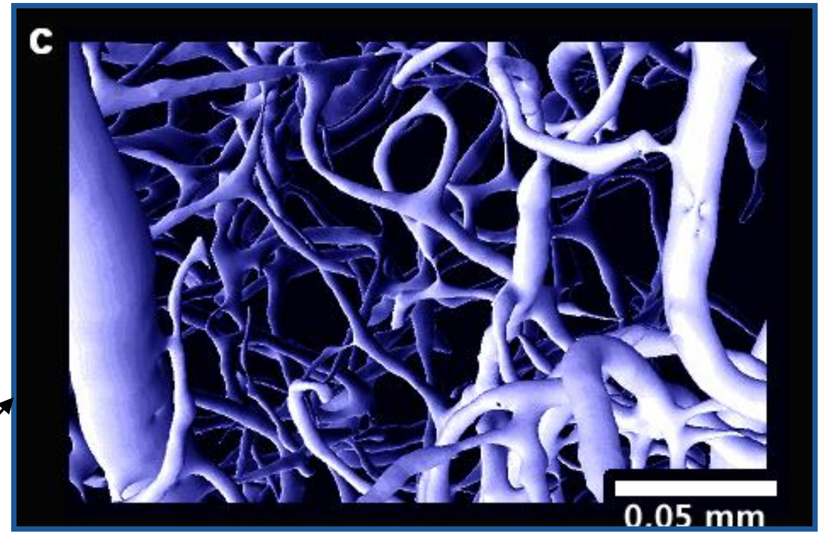
Novartis

full size





Details



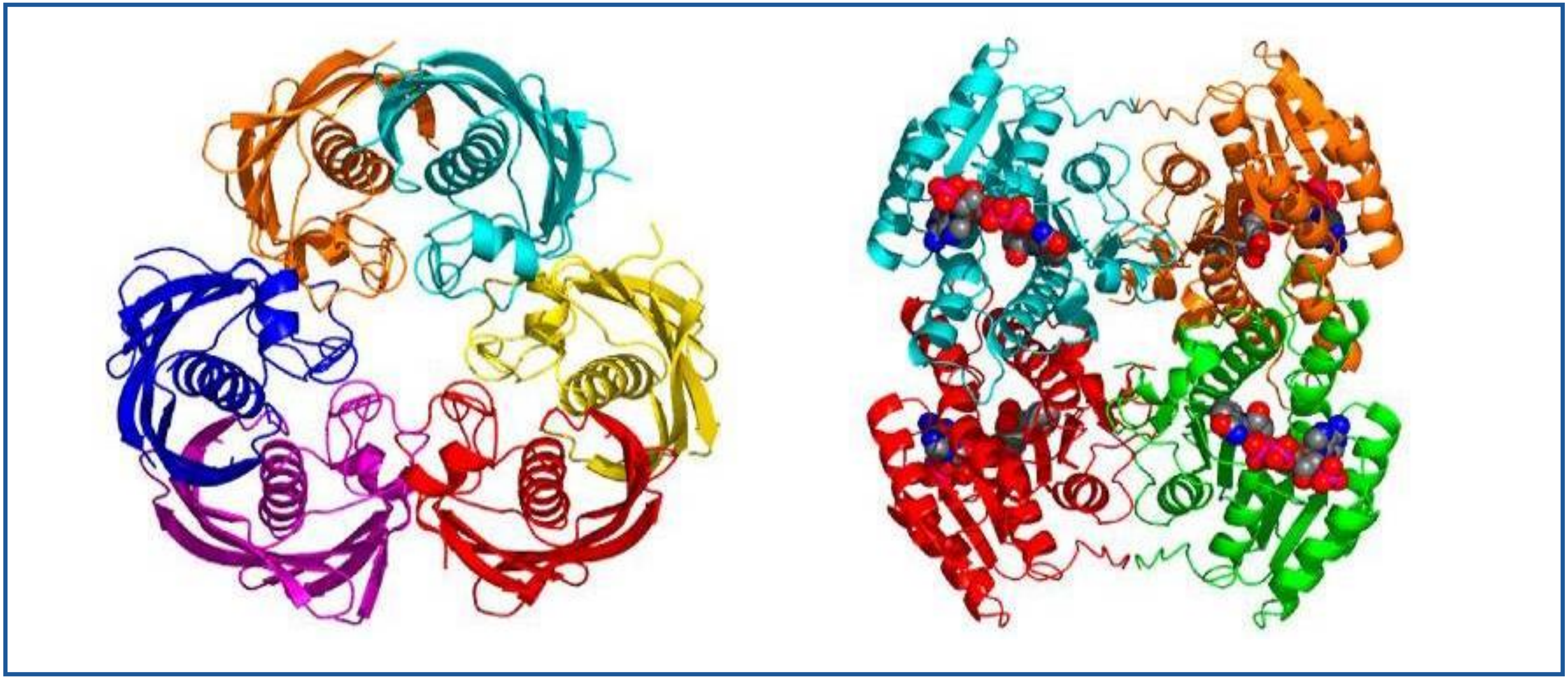
insufficient Blood Circulation

⇒ Deficency in Oxygen

⇒ Protein Deposits

⇒ Alzheimer

Protein Cristallography



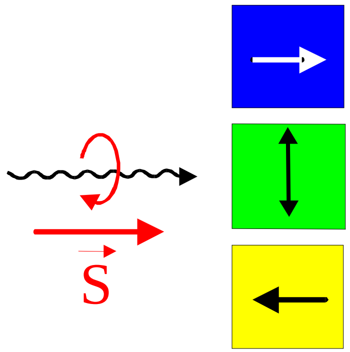
Structures of two important Enzymes of the Generator of Malarya

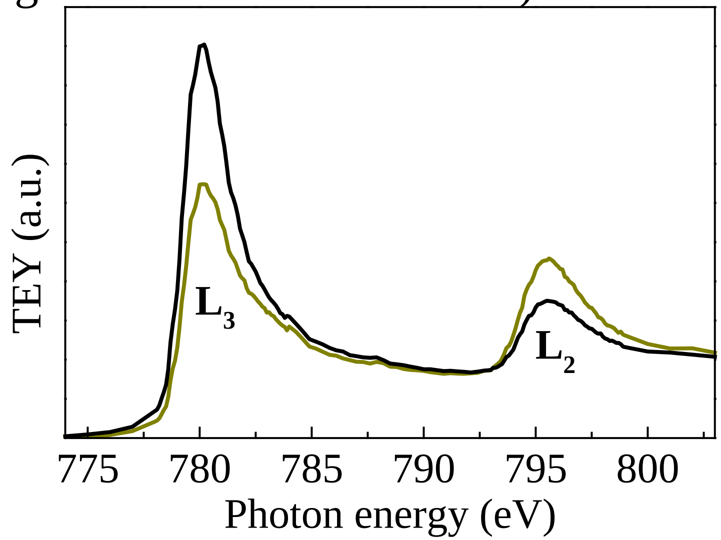
Growth of Bio Molecules to Crystals (size 5-50 μm)

=> Reconstruction with X-rays

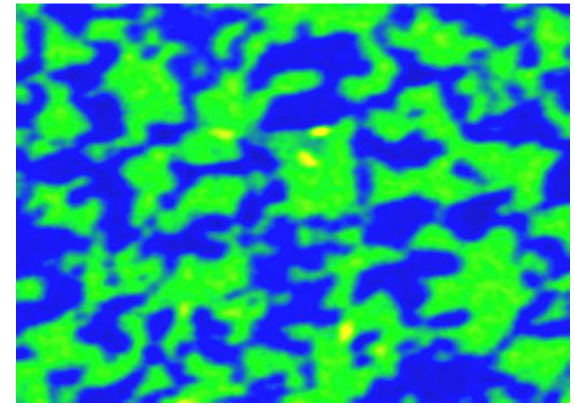
magnetic Microscopy

XMCD (**X**-ray **M**agnetic **C**ircular **D**ichroism)



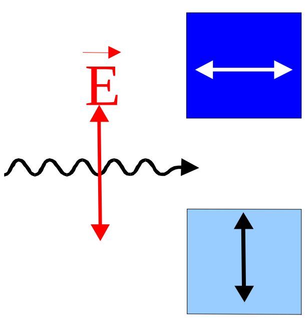


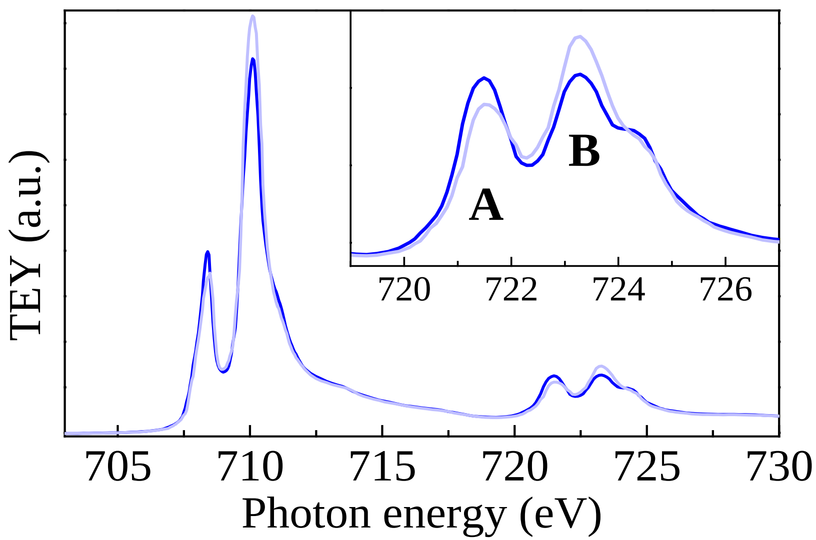
Co



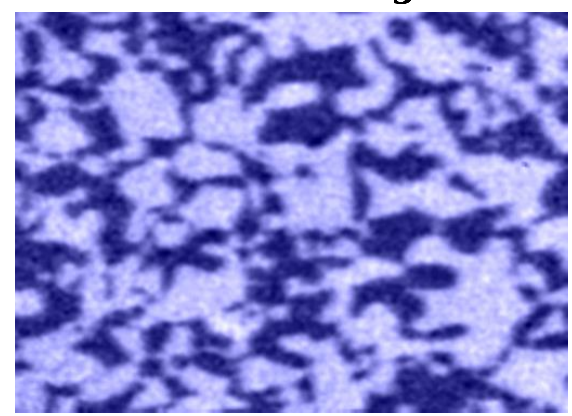
ferromagnetic

XMLD (**X**-ray **M**agnetic **L**inear **D**ichroism)





$LaFeO_3$



anti-ferromagnetic

Frithjof Nolting
PSI/Berkeley

Milestones for SLS

First Ideas	1991
„Giessbach-Meeting“ (Users support SLS)	Oct. 1994
ETH-council approves SLS	Sept. 1995
Parlament approves SLS	**18.June 1997**

Start of Building:	2.June 1998
Building finished:	1.July 1999
Beam in Linac:	23.March 2000
Beam in Booster:	8.Aug. 2000
Beam in Storage Ring	**13.Dec. 2000**
goal of 400 mA reached	5.June 2001
=> Begin Experiments:	2.Aug. 2001

Celebrating the success of SLS

Micha Dehler | Meinrad Eberle Director | Volker Schlott | Werner Joho | Albin Wrulich Project Leader

SLS control room

Andreas Lüdeke, Werner Joho, Michael Böge

SwissFEL Project

Combination of advantages of

Laser

- extremely short pulses
- extremely high intensity
- monochromatic light
- coherence

X-rays

- very short wavelenghts
  => details of very small structures
- transparency of materials
- adjustment of wavelength
  to specific elements

Free Electron Laser

excellent beamquality of electron gun

$\Rightarrow$ microbunches of electrons in undulator

$\Rightarrow$ extremely short and intense X-ray flashes

$\Rightarrow$ „film of dancing molecules"

- Neutrons
- Muons
- Synchrotron Light
- X-ray Flashes

=> this combination of probes for research in

Physics, Chemistry, Biology, Material Science

is worldwide unique !!

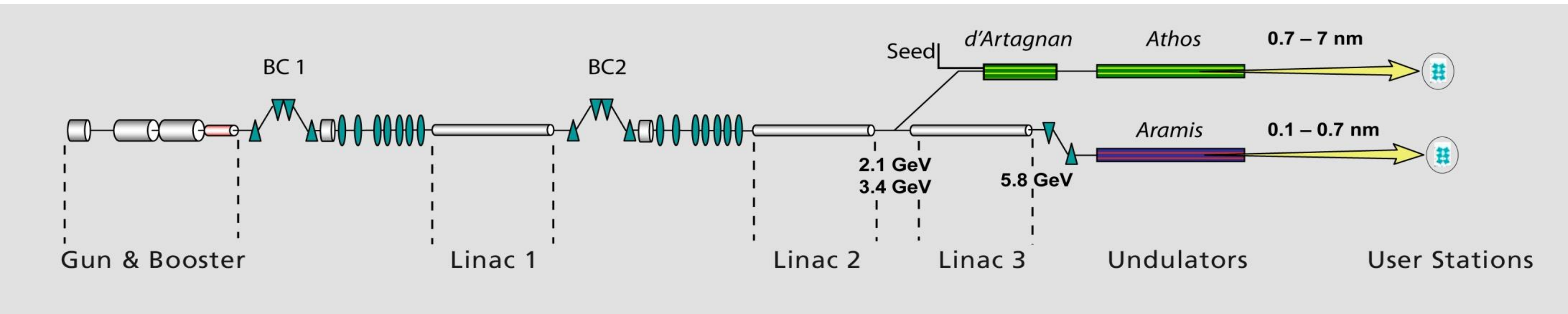
Layout of SwissFEL

Electron Injector

Linear-Accelerator

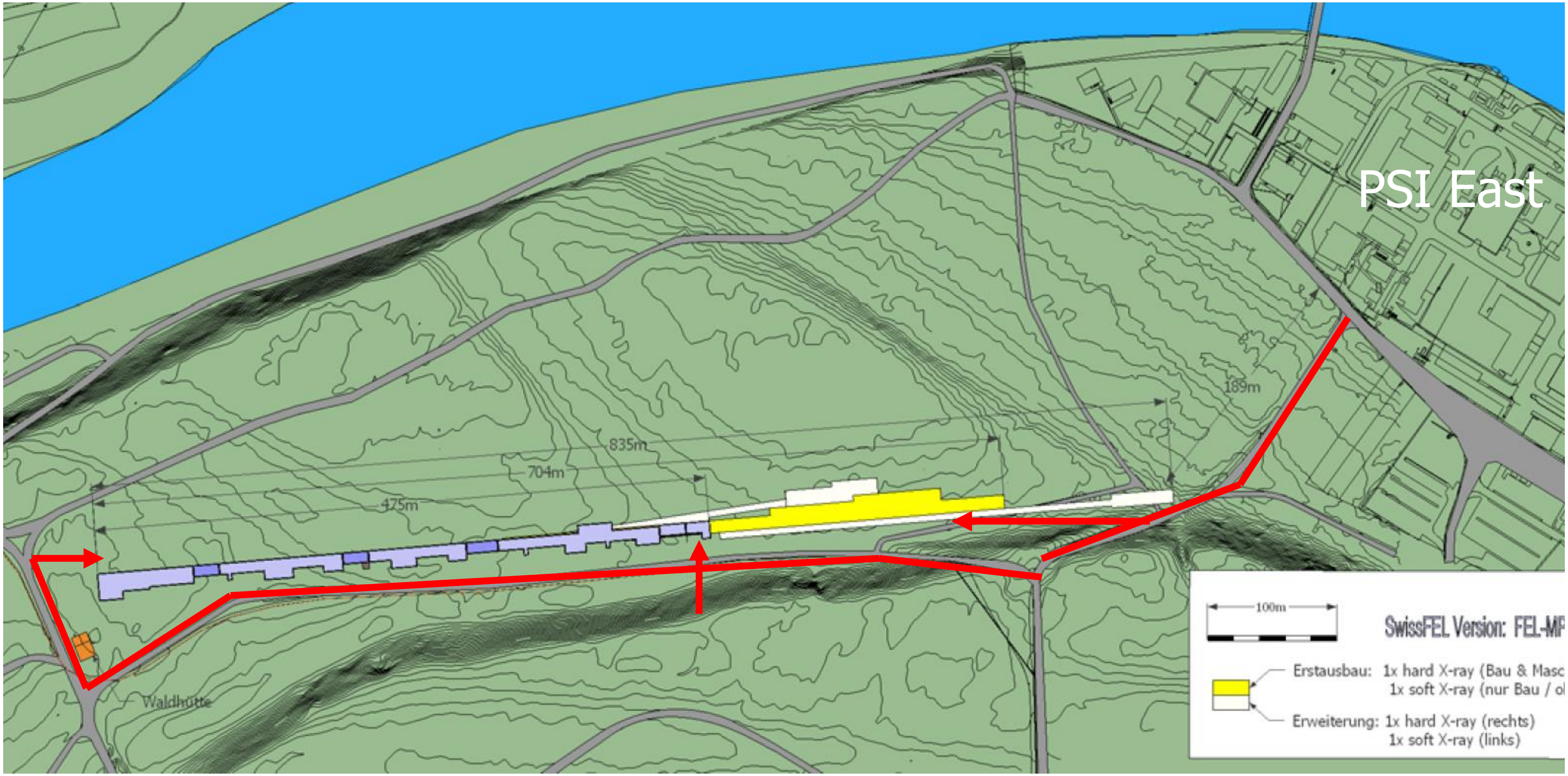
Free Electron Laser

Experiments



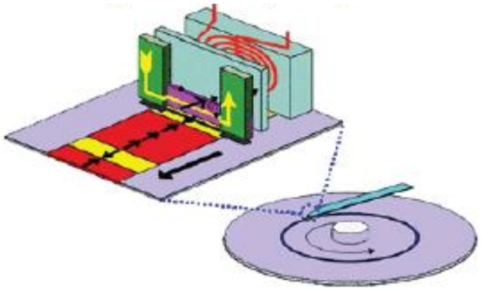
700 m

SwissFEL Würenlingen

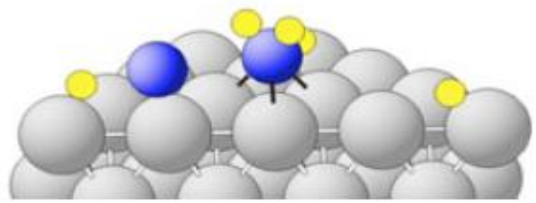


SwissFEL Science
(R.Abela)

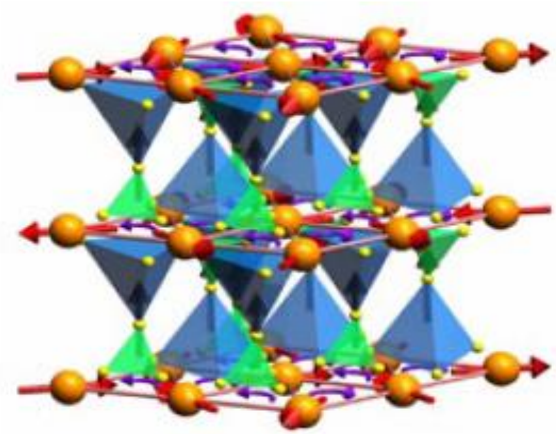
Magnetism:
materials and processes for
tomorrow's information technology



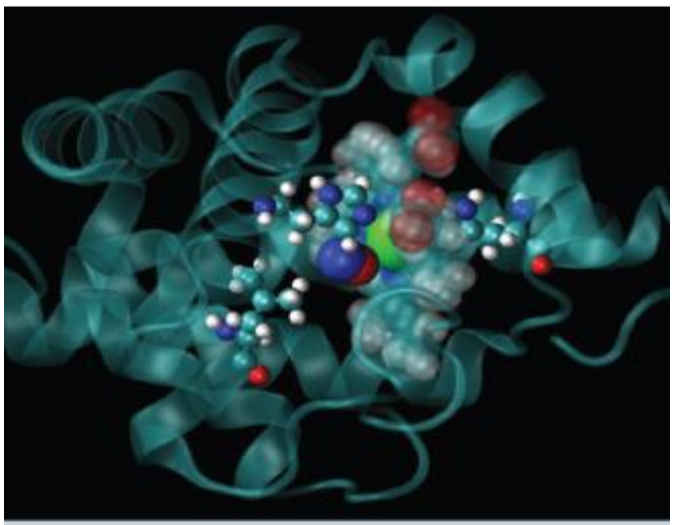
Catalysis and solution chemistry:
for a clean environment and
a sustainable energy supply



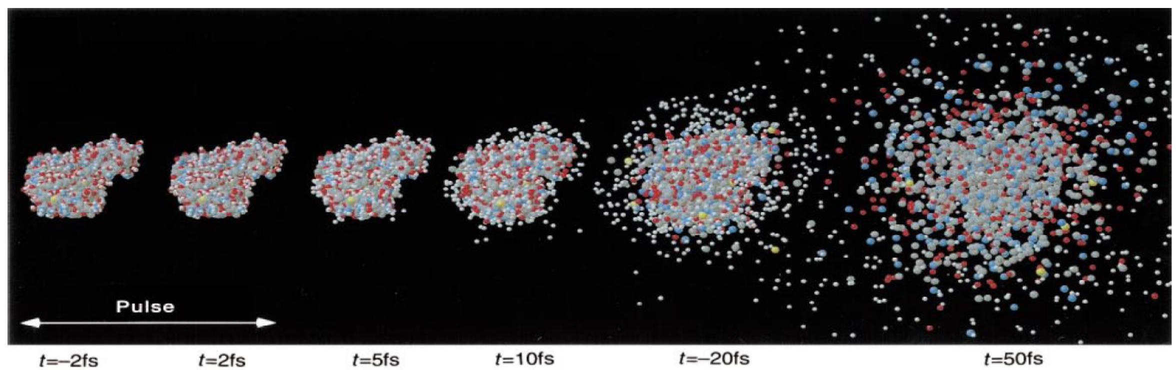
Correlated electrons:
the fascination of
new materials



Biochemistry:
shedding light on the processes of life



Coherent diffraction:
flash photography of matter



SwissFEL Inauguration 5.December 2016

C.Quitman A.Hürzeler B.Moor J.Staiblin
F.Schiesser U.Hofmann Joel Mesot

the PSI Director explains the SwissFEL to prominent guests

Space Charge Limits and Single Turn Extraction in the 590 MeV Ring Cyclotron

W.Joho

Paul Scherrer Institute

CH5232 Villigen

Switzerland

Introduction

- Concept of Ring Cyclotron with separate sectors by **Hans Willax** in 1962

- Early recognition of potential for „high currents" due to

  high voltage cavities, large radius and **strong vertical focusing**

⇒ goal of 100 μA for **meson factory**, considered "very ambitious" by experts

(at that time the record from synchro-cyclotrons was 0.1 μA !)

- critical point was **Injector**

  => Concept for Injector II (replacing Injector I) before ring cyclotron was commissioned !

- Today (2013) the record intensity is 2.4 mA, a **factor of 24 over its design goal !**

what are the key points for this success and

where is the limit to even higher currents?

Key points for PSI Ring Cyclotron

- 4 **high voltage** cavities (initially 500 kV, now up to 900 kV) give high current limit
- 650 kW of RF power can be coupled into each cavity (350 kW goes to the beam)
- **Q_r at extraction** (drops from 1.75 to 1.5) is ideal to increase the turn separation at extraction by a factor of ≈ 3 (from 6 to 17mm), using **eccentric injection**
- installation of a **flattop cavity** (at a later stage!) gives monoenergetic beam

=> single turn extraction with very low losses

- **„Panofsky“ quadrupole** at extraction avoids excessive radial beam blow up from fringe field in last sector magnet
- drift space between magnets allows easy construction of **straight septa**
- **low power consumption** of magnets due to narrow magnet gap

Key points for PSI Injector Cyclotrons

Philipps Injector

- **vertical collimators** in center of cyclotron give excellent beam quality

  => extraction efficiency jumped from 70% to 94% **(**100 **=> 200µA)**

Injector II

- space for new Injector II was **foreseen in initial layout**

  („provocation hole" in shielding wall !)
- large size of Injector II allows injection from **Cockkroft-Walton** at 870 keV
- large size gives **large turn separation** at extraction => very low losses
- **„spaghetti effect"** increases space charge limit by a factor of about 10 to ≈ **3 mA**

Current Limit

- **RF-System**: today 1.4 MW are delivered to the beam

  (100 kW are taken out again by the flattop system).

  => any further increase in current requires an upgrade of the RF system.

- **Activation of Cyclotron components**:

  Initially a loss of 5 µA at extraction was considered as acceptable !?

  Today the tolerance is about 0.5 µA in order to allow "hands-on" maintenance.

  => The losses at extraction determine the current limit

- **Transversal space charge forces**

  defocus the beam: The vertical tune is lowered and the beam size increases.

  For the Ring Cyclotron this effect becomes serious for currents above 10 mA

- **Longitudinal space charge forces**

  much more serious, because they increase the energy spread and thus

  the final beam size at extraction, increasing beam losses.

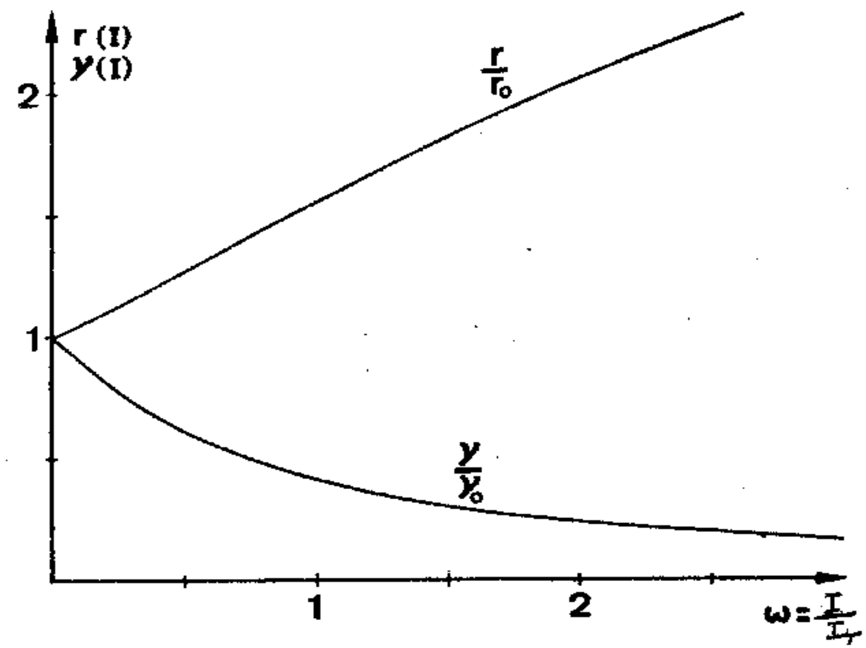
Model for Transversal Space Charge

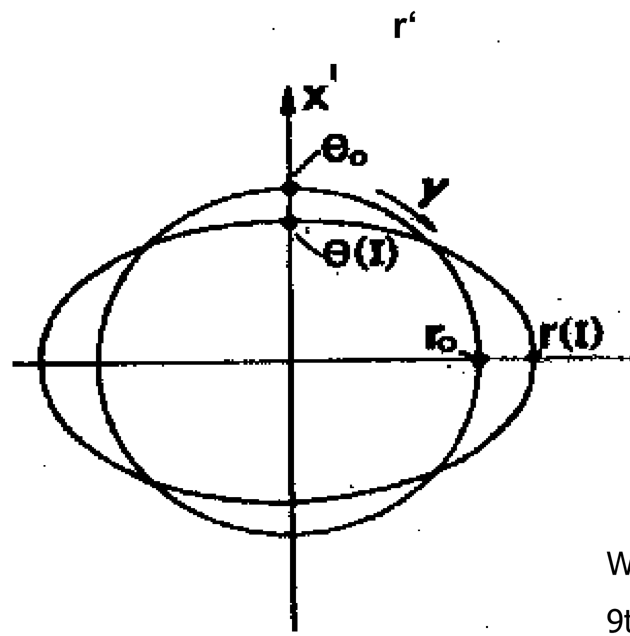
For a round beam the formula for the average tune $\nu(I)$ and beam radius $r(I)$ is given by :

$$\frac{\nu(I)}{\nu_0} = \sqrt{1+\omega^2} - \omega, \qquad \left[\frac{r(I)}{r_0}\right]^2 = \sqrt{1+\omega^2} + \omega, \qquad \omega \equiv \frac{I}{I_T}, \quad I \text{ is the average current,}$$

for a parabolic longitudinal charge distribution with phase width $\Delta\Phi$:

$$I_T = \frac{2}{3}\frac{\Delta\Phi}{2\pi}\frac{\varepsilon\,\nu_0}{R}\,\tilde{p}^3\, I_0, \qquad \varepsilon = \text{emittance}, \;\; \tilde{p} \equiv \beta\gamma, \;\; R = \text{orbit radius}, \;\; I_0 = \frac{938\,\text{MV}}{30\,\Omega} = 31\,\text{MA}$$





W.Joho,
9th Int. Cyclotron conference
CAEN (1981) p.337

Transversal Space Charge

At the injection energy of 72 MeV we have in the ring cyclotron:

$\tilde{p} = 0.4, \quad R = 2\,m, \quad \nu_0 \approx 1, \; \varepsilon \approx 2\,mm\,mrad, \; \Delta\Phi \approx 15^0, \; => I_T = 60\,mA$

This gives for $I \approx 3\,mA: \quad \omega = 0.05,$

and thus only mild changes in r and ν :

$r(3mA) \approx 1.025 r(0), \quad \nu(3mA) \approx 0.95 \nu(0)$

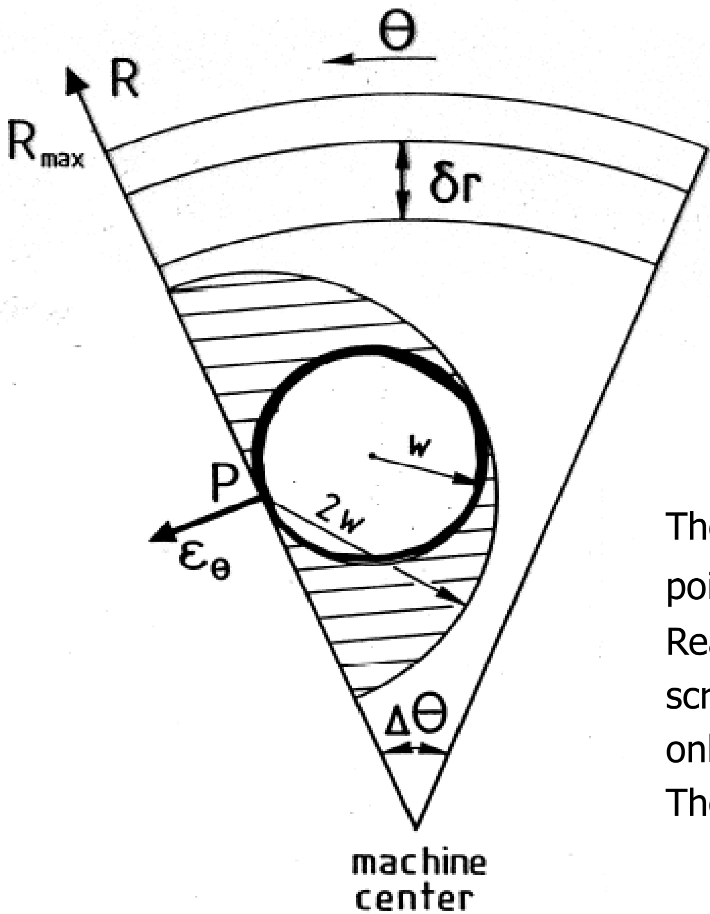
At an energy of 2 MeV we have in the injector II :

$\tilde{p} = 0.065, \quad R = 0.6\,m, \quad \nu_0 \approx 1.3, \; \varepsilon \approx 11\,mm\,mrad, \; \Delta\Phi \approx 9^0, \quad => I_T = 3\,mA$

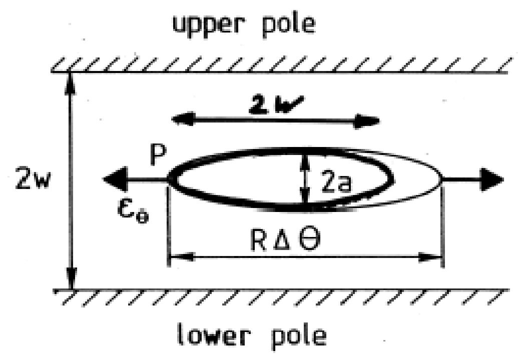
This gives for $I \approx 3\,mA: \quad \omega = 1,$ and thus substantial changes in r and ν :

$r(3mA) \approx 1.55 r(0), \quad \nu(3mA) \approx 0.41 \nu(0) \approx 0.5$

Space Charge Fields in Sector Model



top view



side view

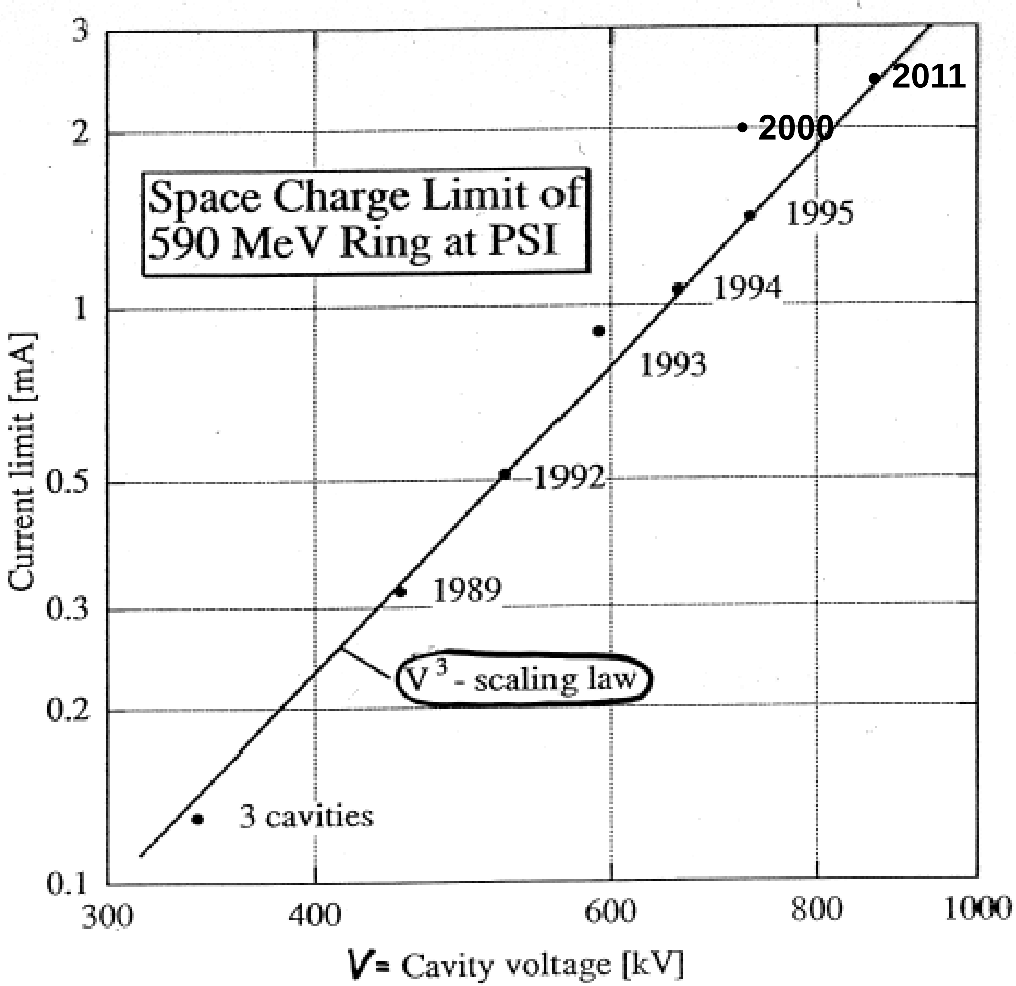
circulating protons fill a cake-like piece with azimuthal extension Δθ. Neighbouring orbits are assumed to overlap radially.

The azimuthal electric field at the edge of the „piece of cake" at point P is approximated by the calculable field of a **Disc** with radius w.
Reasoning: the charge of the protons outside of the half circle around P is screened by the upper and lower poles and protons in the hashed area give only a small contribution to the azimuthal field ϵ_θ.
The proton at P gains through ϵ_θ an additional energy/turn:

$$dE/dn = 2\pi R\, \epsilon_\theta$$

This simple model predicts, that the intensity limit from longitudinal space charge forces increases with $\mathbf{V^3}$!!
(V=cavity voltage/turn)

Longitudinal Space Charge



Longitudinal space charge forces increase the energy spread

=> higher extraction losses

=> limit on beam current

Remedy:

higher voltage V on the RF cavities

=> lower turn number **n** (V·n = const.)

current limit ~ $V^3 \sim 1/n^3$!

There are 3 effects,
each giving a factor V(~1/n):

1) beam charge density ~ **n**
2) total path length in the cyclotron ~ **n**
3) turn separation ~ **V**

W.Joho, 9th Int. Cyclotron conference
CAEN (1981) p.337

Longitudinal Space Charge in Cyclotrons

starting point: formula (11) in reference paper:

$\Delta E_{sc}(\text{lin}) = e\,\Delta U_{sc}(\text{lin}) =$ induced energy spread from linear space charge forces

$$(11)\quad \Delta U_{sc}(\text{lin}) = I_{\text{peak}}\, Z_I \,\frac{n^2}{\beta_f}$$

$I_{\text{peak}} =$ peak current

$\bar{I} = \frac{\Delta\Phi}{2\pi} I_{\text{peak}} =$ average current

$\Delta\Phi =$ average total phase width

$$Z_I = 2.8\,\text{k}\Omega = g_{1c}\frac{64\pi}{3} Z_0, \qquad g_{1c} \approx 1.4 = \text{formfactor}, \quad Z_0 = \frac{1}{4\pi\varepsilon_0 c} = 30\,\Omega$$

$n =$ number of turns

$E \equiv eU =$ kinetic energy, $\qquad \beta_f = v_f / c =$ final "velocity"

Current Limit in Cyclotrons

ΔE_{sc}(lin.) can be compensated with a tilted flattop voltage;

there remains a nonlinear part ΔE_{sc}(nonlin.) :

$$f_n \equiv \frac{\Delta E_{sc}(\text{nonlin.})}{\Delta E_{sc}(\text{lin.})} = \text{ fraction which cannot be compensated}$$

separated turns at extraction requires :

$$\Delta E_{sc}(\text{nonlin.}) < \mu_n \Delta E_n \,, \qquad \Delta E_n = \text{energy gain per turn}$$

$$\mu_n \approx 1/3 \text{ for centered beam, } \quad \mu_n \approx 1 \text{ for an eccentric beam}$$

=> we obtain from this simple model the following current limit :

$$I_{max} = \frac{\mu_n}{f_n} \frac{(U_f - U_i)}{Z_I} \frac{\beta_f}{n^3} \frac{\Delta\Phi}{2\pi}$$

Current Limit in 590 MeV Ring Cyclotron

$$I_{max} = \frac{\mu_n}{f_n} \frac{(U_f - U_i)}{Z_I} \frac{\beta_f}{n^3} \frac{\Delta\Phi}{2\pi} = \text{current limit from longitudinal space charge}$$

$$U_i = 72\ \text{MV}, \quad U_f = 590\ \text{MV}, \quad \beta_f = 0.8$$

$$n = 188\ \text{turns} \ \ (\Delta E_n \approx 3\ \text{MeV}) \ , \ \Delta\Phi \approx 12^0$$

$$f_n \approx 1/4 \ \ (\text{rough estimate!})$$

$$\mu_n \approx 1 \ \ \text{for eccentric injection} \ \ (\approx 1/3\ \text{for centered beam!?})$$

=> $I_{max} \approx 3\,\text{mA}$

This estimate is remarkably close to the present limit of 2.4 mA (2011), given the crude assumptions in this sector model:

- non relativistic case (at high energies: the charge density $\rho \propto \gamma^3$, M.Gordon)
- no turn structure, no radial cut of charge sheet at injection and extraction
- uncertainties in the parameter f_n and μ_n

Current Limit in 72 MeV Injector II

$$I_L = \frac{\mu_n}{f_n} \frac{(U_f - U_i)}{Z_I} \frac{\beta_f}{n^3} \frac{\Delta\Phi}{2\pi} = \text{current limit from long. space charge}$$

$$U_f = 72\,\text{MV} \ , \ \beta_f = 0.37$$

$$n = 85 \quad (\Delta E_n \approx 0.75\,\text{MeV}) \ , \ \Delta\Phi \approx 6^0$$

$$f_n \approx 1/4 \ \text{(rough estimate only!)}$$

$$\mu_n \approx 1/3 \ \text{for centered beam}$$

$I_L \approx 0.3\,\text{mA}$ (present record = 2.7 mA !)

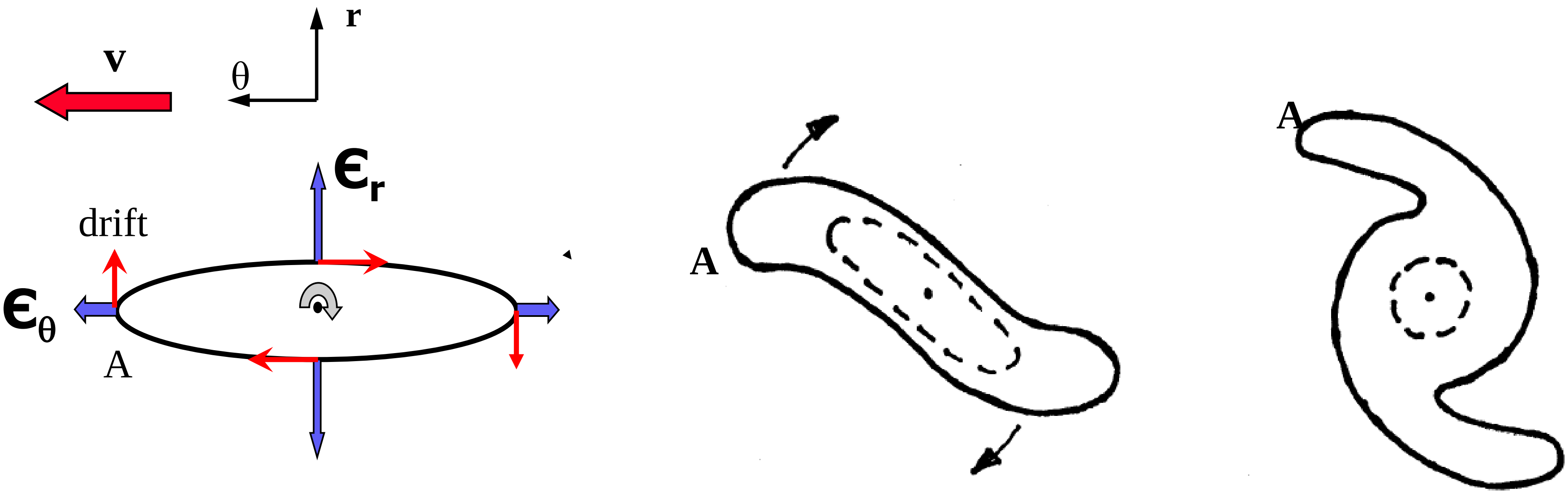
=> sector model fails due to phase mixing

(space charge forces produce spherical bunch, "spaghetti effect")

=> this lowers energy spread from longitudinal space charge

=> much higher current limit !

Longitudinal Space Charge in a Cyclotron Bunch



Particle at position A:

=> gains additional energy from space charge forces

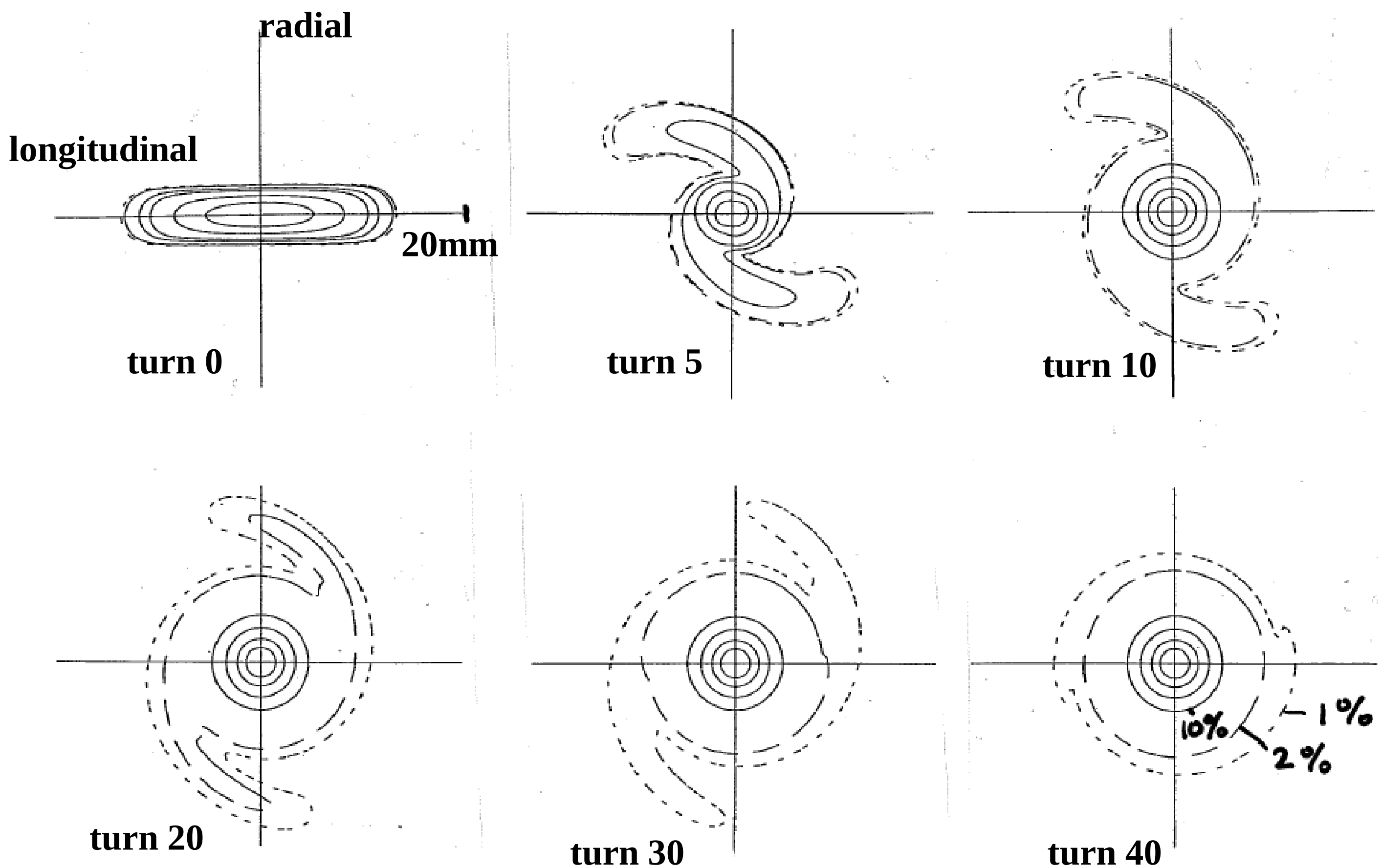
=> moves to higher radius due to isochronous condition

=> rotation of the bunch

=> nonlinearities produce spiral shaped halos

=> production of a **rotating sphere** (mixes phases)

Longitudinal Space Charge in Injector II Cyclotron



Simulation of a 1mA beam, circulating in Injector II at 3 MeV for 40 turns without acceleration.

The core stabilizes faster than the halos (calculations by Stefan Adam)

Aristocracy ⇔ Democracy

Synchrotron

Linac

democratic:

a particle oscillates between head and tail

(phase focusing)

Cyclotron

aristocratic :

a particle „born ahead“ stays ahead !

(isochronism)

but **at high intensity**

a cyclotron becomes **democratic** !!

space charge mixes phases („spaghetti effect“)

=> higher current limit

Prediction of Current Limits in the PSI Cyclotrons

Predictions from 1978

(when I_{max} was 100 µA)

W.Joho, 8. Int. Cyclotron Conference

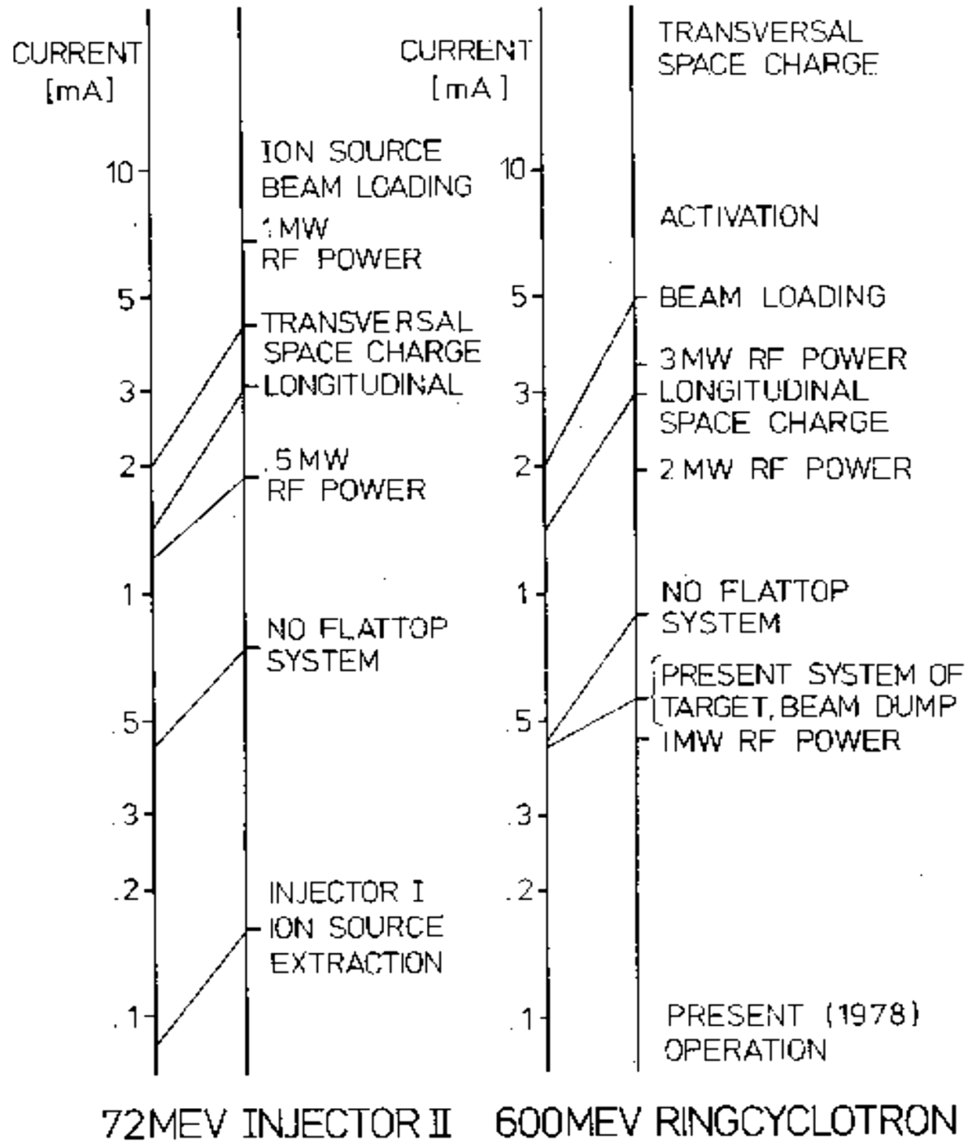
Indiana 1978 , p.1950

many limits are still valid.

exception: even without flattop system

2.7 mA are possible in Injector II

due to „spaghetti effect" !



Model of the last turns in the 590 MeV Ring Cyclotron

- the turn separation is proportional to the orbit radius **R** and the cavity voltage **V**

  => concept of a large ring cyclotron with many high voltage cavities

- Flattop cavity gives mono-energetic beam

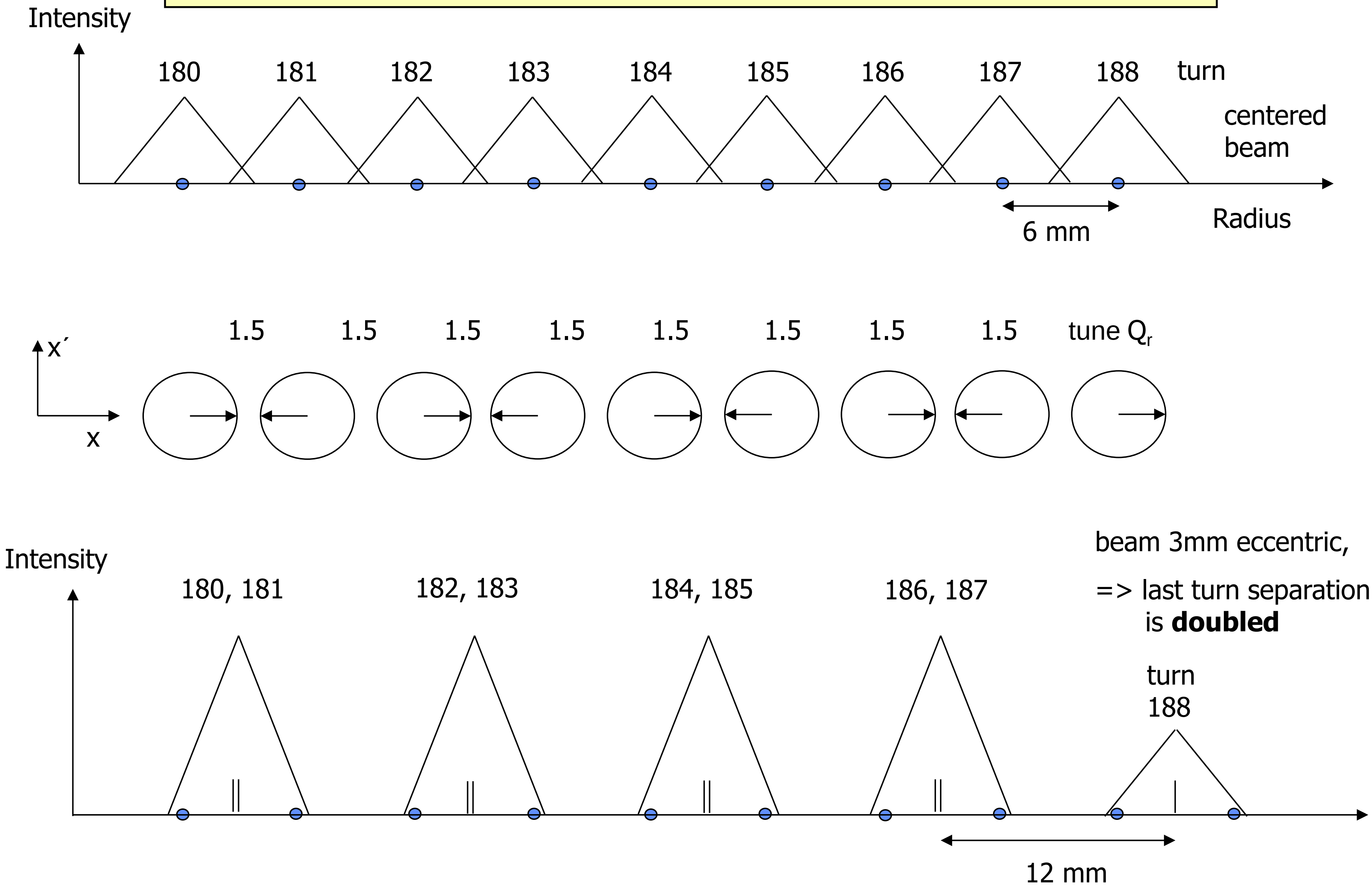
  => leads to single turn extraction

  => an eccentrically injected beam is still eccentric at extraction.

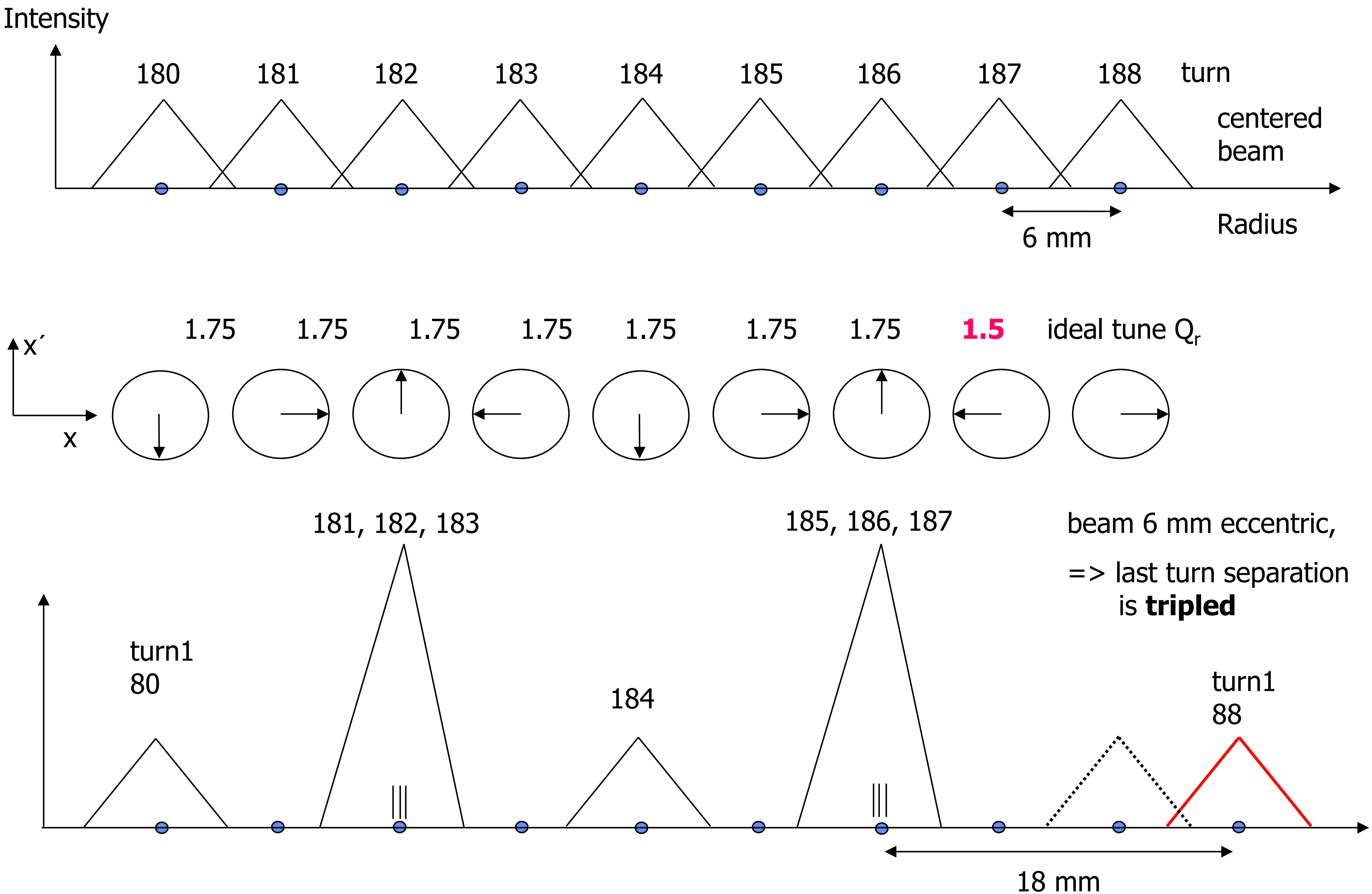
  => This can be used to increase the radial separation between the last two turns.

- In our simple model we assume an average turn separation of 6mm at extraction (energy gain 3 MeV/turn)

the last turns in the Ring Cyclotron, model with half integer tune



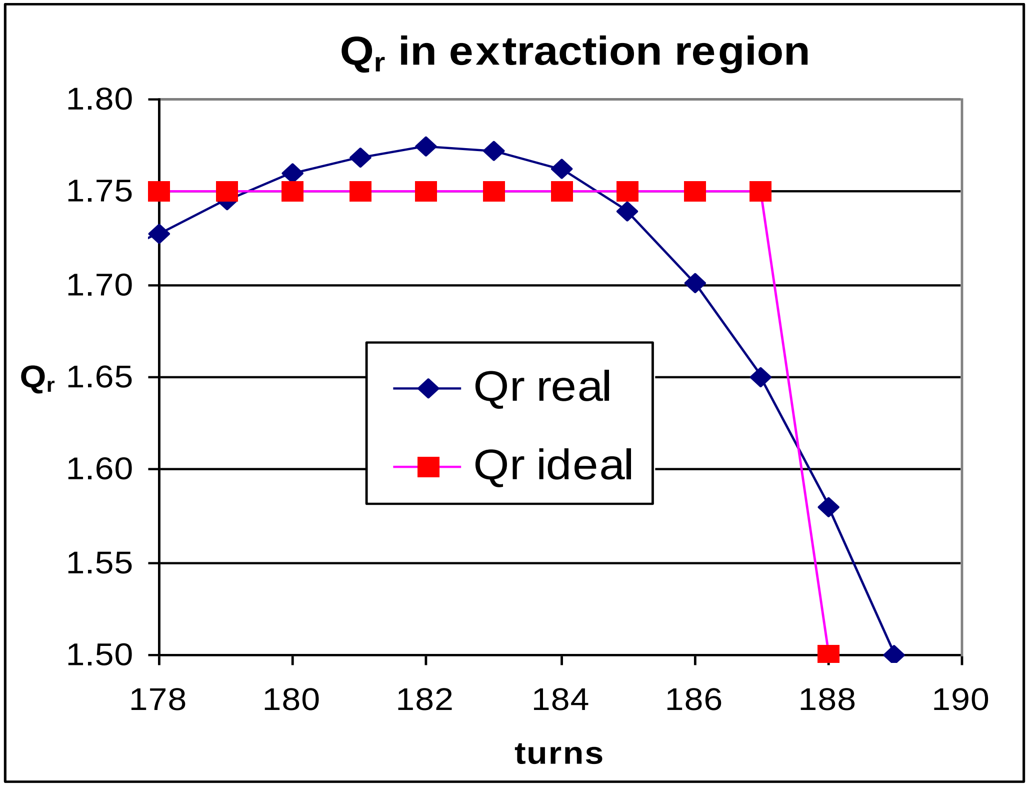
the last turns in the Ring Cyclotron, model with ideal tune



beam 6 mm eccentric,

=> last turn separation is **tripled**

Tune Qr in Extraction Region

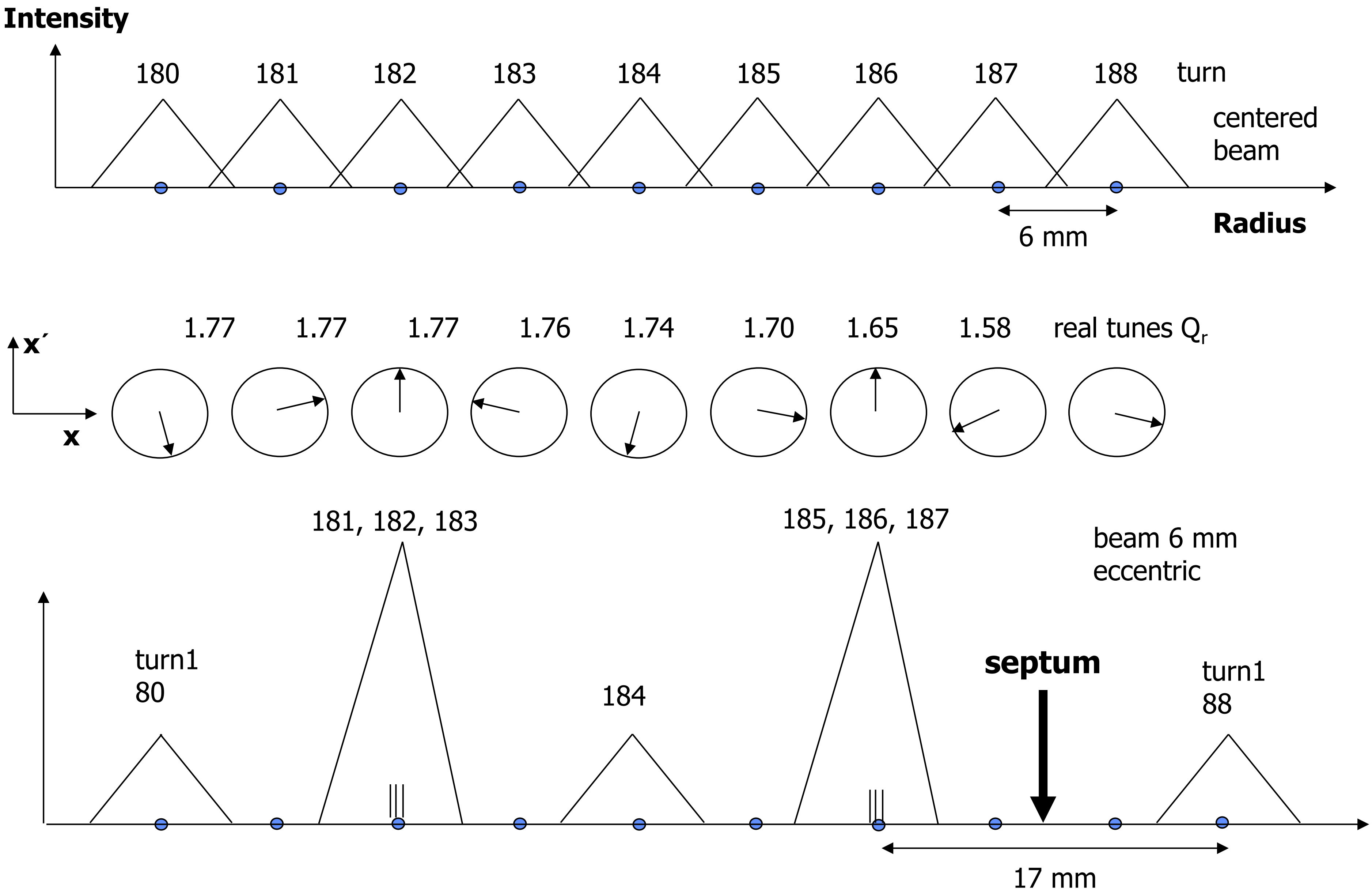


In the **ideal case** a tune of 1.75 puts 3 turns together, while with a fast drop to 1.5 the last turn is pushed away from the previous 3 turns.

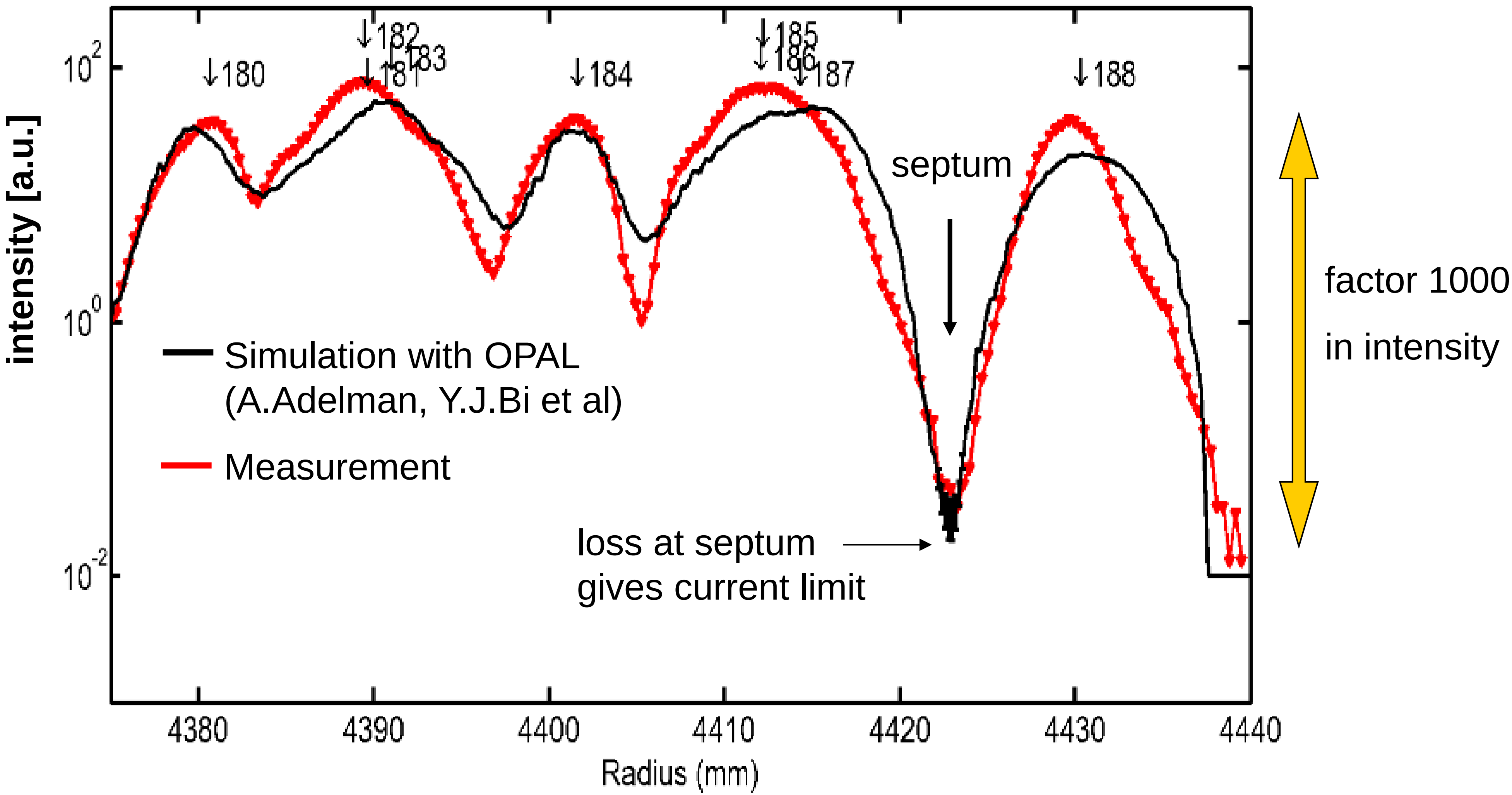
In the fringe field region of the PSI ring cyclotron the **real tune** is close to the ideal one **(just by pure luck!),** giving an increase of the last turn separation from 6 to 17mm, using eccentric injection. The drop of Qr in the fringe field helps to increase the turn separation even for a centered beam ($dR \sim 1/Qr^2$)

To compensate the horizontal defocusing of the fringe field on the extracted beam, a focusing quad in front of the last sector magnet is vital (proposed by George Vecsay).

the last turns in the Ring Cyclotron, model with real tune Q_r

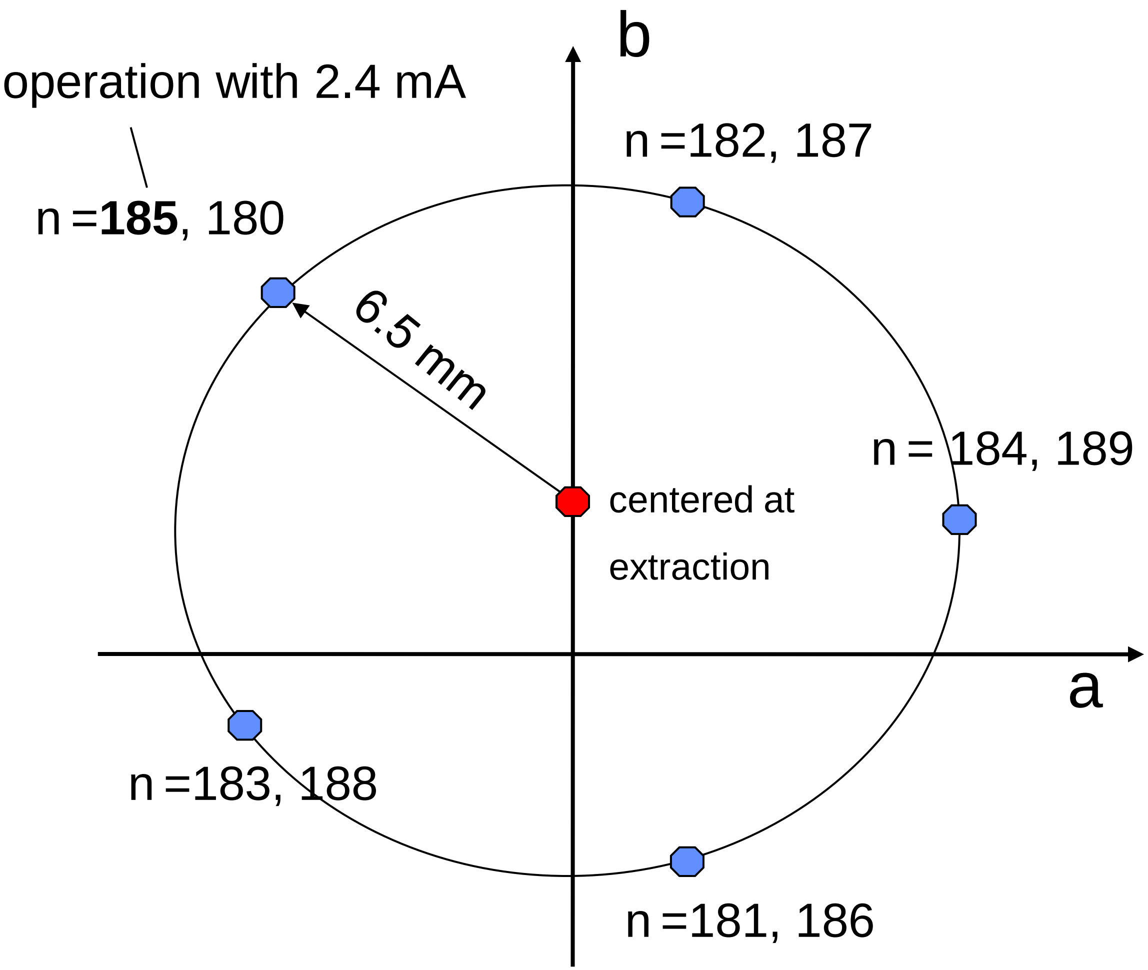


590 MeV Ring Cyclotron
last 9 of 188 turns for a 2 mA beam



Eccentric Injection

for maximum turn separation at extraction septum



horizontal oscillation:

$x = a \cos[(Qr - 1)\, 2\pi\, n] +$
$\quad b \sin[(Qr - 1)\, 2\pi\, n]$

n= total turnnumber

Start at probe RRI2 ($\vartheta = 172^0$)

average tune from injection to extraction: Qr(av.) ≈ 1.4 => same eccentricity, modulo 5 turns (5*1.4 = 7 oscillations)

maximum turn separation at Extraction Septum

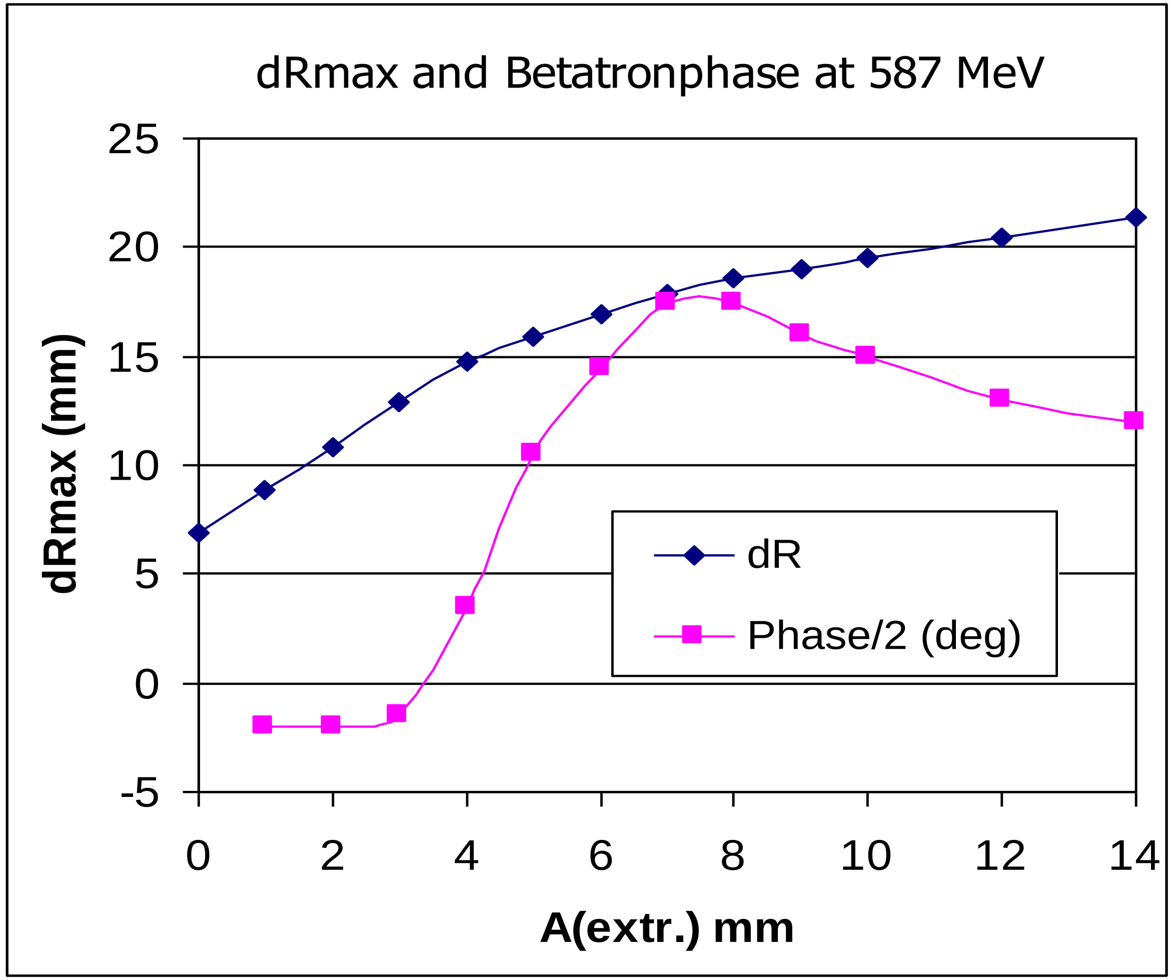
dRmax = max. separation between last turn and previous turns as a function of the eccentricity amplitude A at extraction. At injection this amplitude is about a factor 1.5 higher (effect of adiabatic damping).

dRmax starts to level off at an amplitude of 7mm, where the second last turn is now at a lower radius than the previous turns (turn crossing).

During 2011 with operation at 2.2 mA an amplitude of about 6.5 mm was used to obtain extraction losses of less than 0.01%.

Using much higher amplitudes leads to vertical losses due to the coupling resonance Qr = 2 Qz.

(This plot was obtained in collaboration with Herbert Müller).



Reduction of Extraction losses

Cavity Voltage [kV]	Beam	Flattop Cavity	Losses [%]	Losses [µA]	Imax [µA]
500	Orig. Design	no	5	**5**	100
450	centered	no	1.2	0.5	40
450	eccentric	no	0.25	0.5	200
450	eccentric	yes	0.1	0.5	500
850	eccentric	no	0.06	0.5	800
850	eccentric	yes	0.02	0.5	**2’400**

Loss Reduction by	Factor	
Beam Quality	~ 3	
eccentric Injection	~ 5	
Flattop Cavity	~ 3	
Cavity Voltage	~ 5	(≈ V^3 law)
total	**250**	

professional career of Werner Joho

1958 – 1962 physics student at ETH Zurich

1971 PHD in physics at ETH Zurich (beam extraction from ring cyclotron)

1962 – 1990 Cyclotron group ETH => SIN/PSI , leader Beam Dynamics

1990 – 2003 Synchrotron Light Source (SLS) , Project leader Booster

1981-1989 Organising Committee for the International Cyclotron Conferences

1988-2000 Program and Scientific Advisory Committee for the European Particle Accelerator Conferences (EPAC)

> 2003 Consulting (Barcelona, Taiwan, Beijing, Vancouver, PSI)
tour guide at PSI

external stays:

1963 CERN , Geneva, computer codes for cyclotron orbits

1964 Michigan State University, graduate studies

1971 – 1973 TRIUMF Vancouver, Canada, Injection Line
lectures on thermodynamics at University of BC

1990 Berkeley, California, Advanced Light Source ALS

some personal References

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More talks by the author are found in www.google.ch with "Werner Joho PSI"

More information on the PSI Accelerator Facilities can be found in: www.psi.ch and in

"The Swiss Institute for Nuclear Research SIN" by Andreas Pritzker, Munda Verlag 2013