Accelerator driven Muon and Neutron Sources

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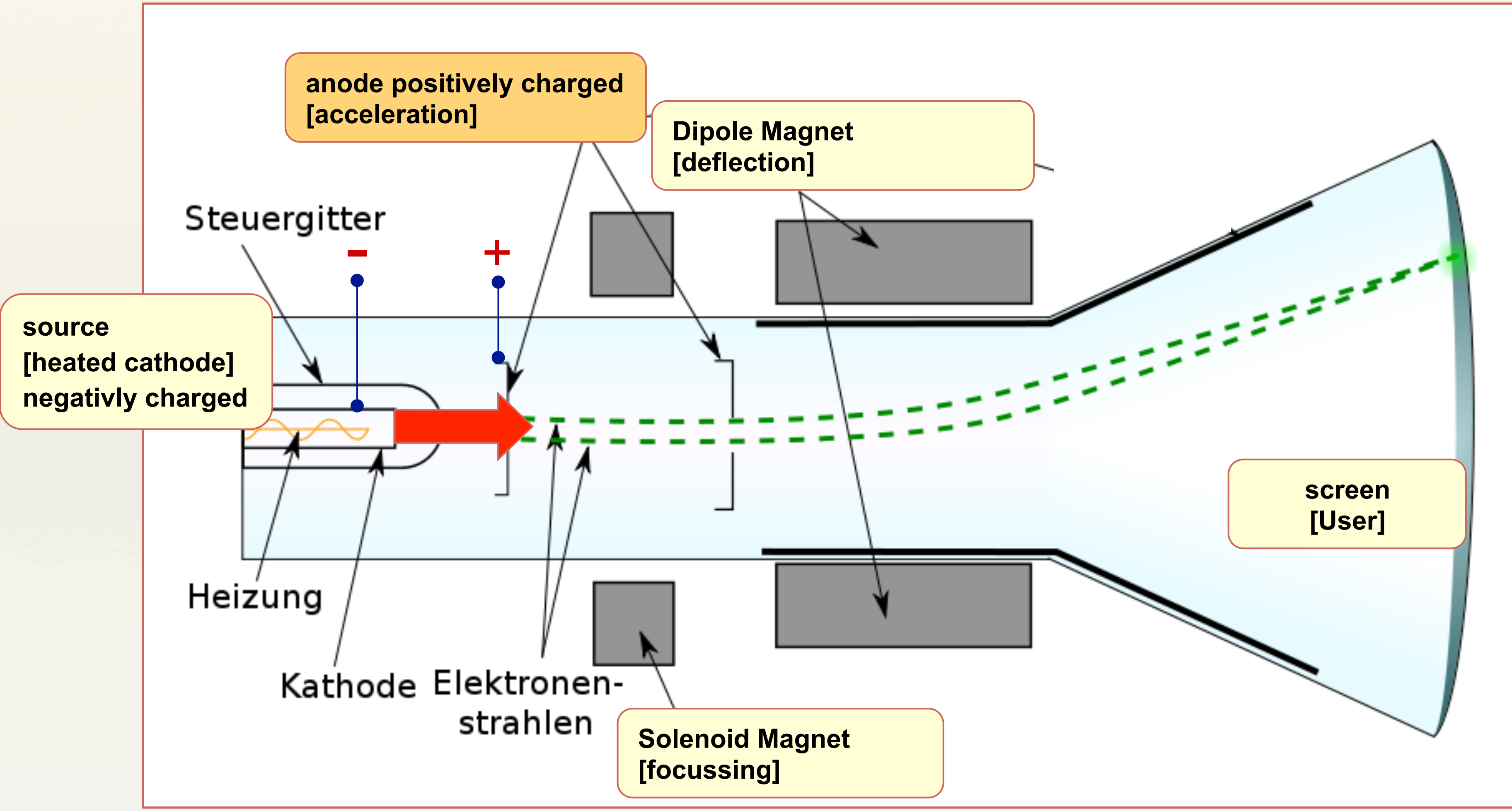
Zuoz, Switzerland, August 2015

PAUL SCHERRER INSTITUT
PSI

Outline

- Accelerator Concepts
  - history of accelerators
  - relativity, e vs. p, magnets, resonators, cyclotron
- Production of secondary radiation with accelerators
  - Muon production
  - Neutron production
- The PSI High Intensity Proton Accelerator
- The European Spallation Source
- Summary.

Intro: television tube involves all essential features of an accelerator



typical numbers: U = 20 kV → E_k = e×U = 20 keV → v = 0.27×c

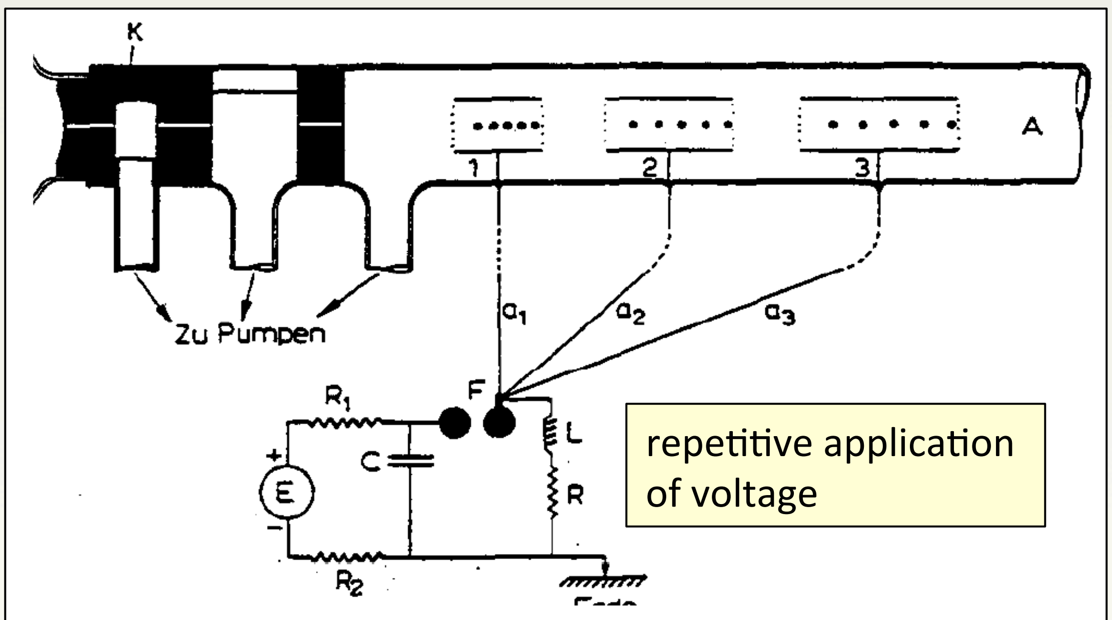
→ electrons reach 27% of speed of light!

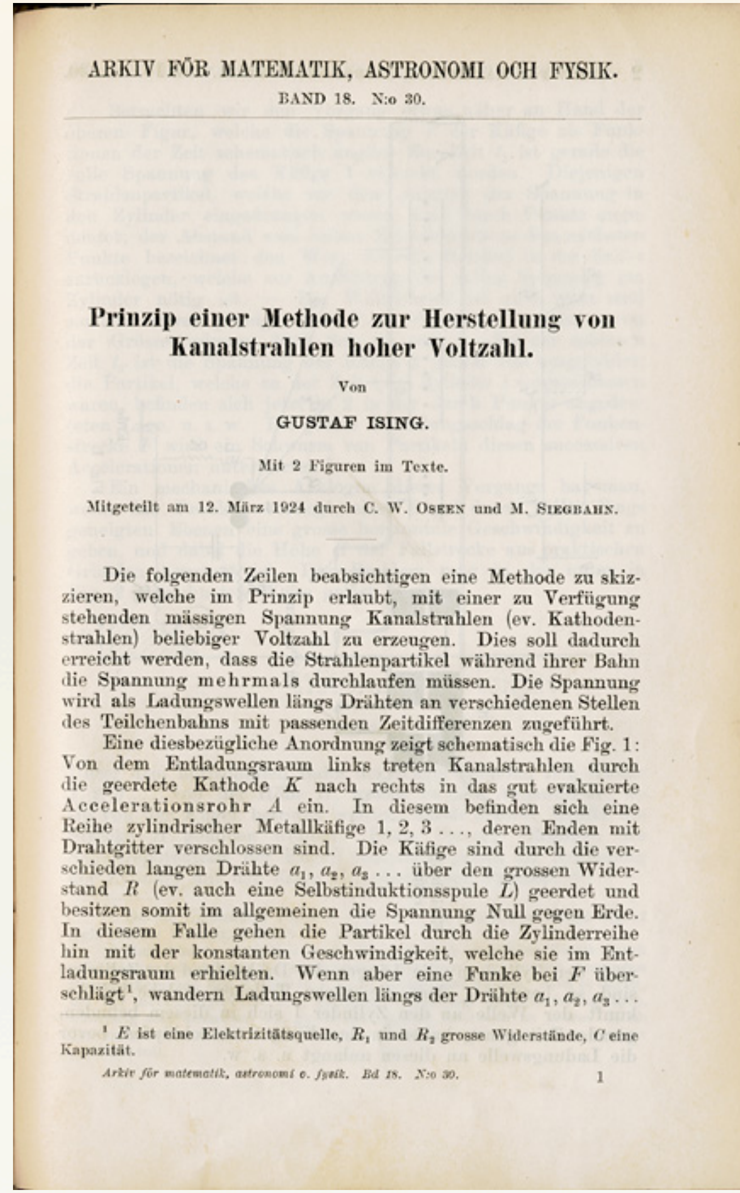
first proposal for a linear accelerator

- <u>1924:</u> Gustav Ising

*19 February 1883 in Finja, Sweden, † 5 February 1960 in Danderyd, Sweden), Prof. at the technical university Stockholm,

- **this marked 90 years of particle accelerators in 2014 (!)**





ARKIV FÖR MATEMATIK, ASTRONOMI OCH FYSIK.
BAND 18. N:o 30.

Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

Von

GUSTAF ISING.

Mit 2 Figuren im Texte.

Mitgeteilt am 12. März 1924 durch C. W. Oseen und M. Siegbahn.

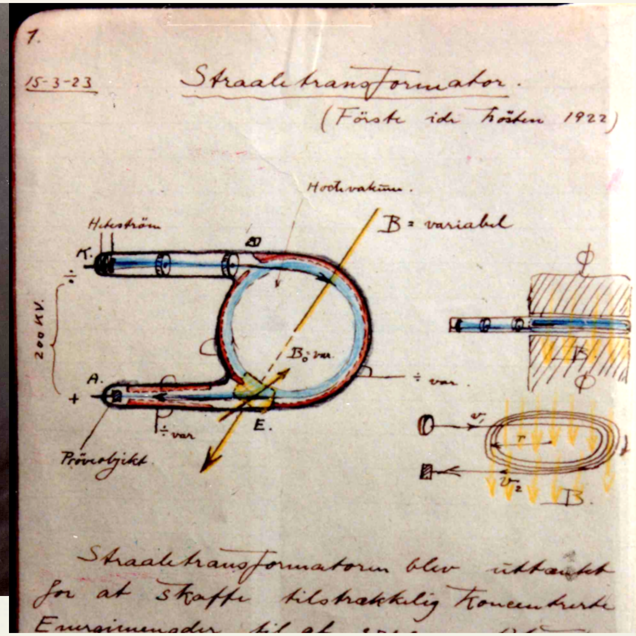
Die folgenden Zeilen beabsichtigen eine Methode zu skizzieren, welche im Prinzip erlaubt, mit einer zu Verfügung stehenden mässigen Spannung Kanalstrahlen (ev. Kathodenstrahlen) beliebiger Voltzahl zu erzeugen. Dies soll dadurch erreicht werden, dass die Strahlenpartikel während ihrer Bahn die Spannung mehrmals durchlaufen müssen. Die Spannung wird als Ladungswellen längs Drähten an verschiedenen Stellen des Teilchenbahns mit passenden Zeitdifferenzen zugeführt.

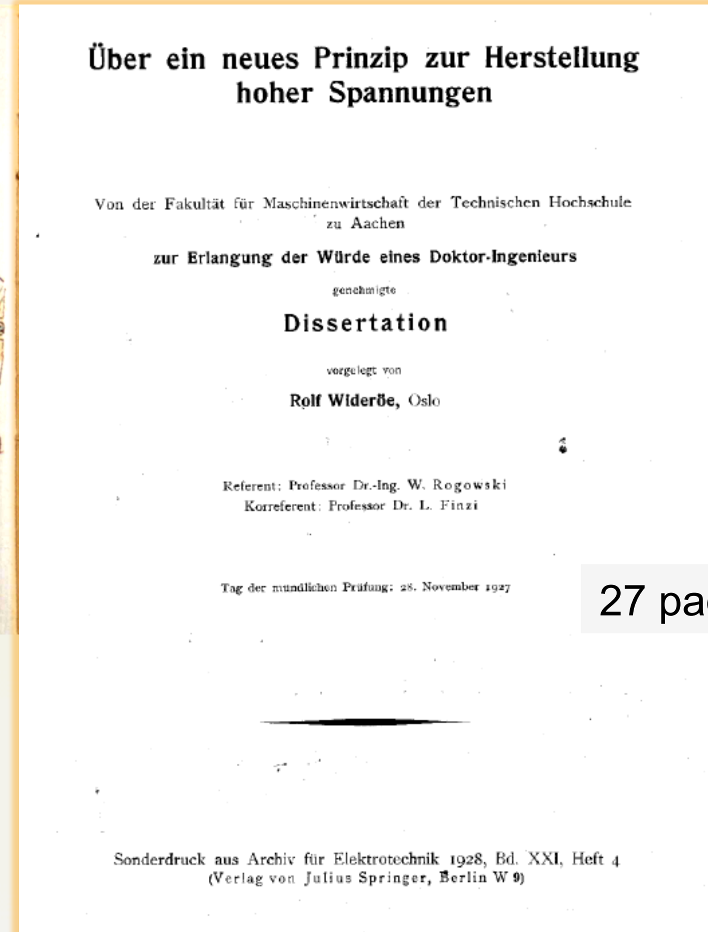
Eine diesbezügliche Anordnung zeigt schematisch die Fig. 1: Von dem Entladungsraum links treten Kanalstrahlen durch die geerdete Kathode K nach rechts in das gut evakuierte Accelerationsrohr A ein. In diesem befinden sich eine Reihe zylindrischer Metallkäfige 1, 2, 3 ..., deren Enden mit Drahtgitter verschlossen sind. Die Käfige sind durch die verschieden langen Drähte $a_1, a_2, a_3 \ldots$ über den grossen Widerstand R (ev. auch eine Selbstinduktionsspule L) geerdet und besitzen somit im allgemeinen die Spannung Null gegen Erde. In diesem Falle gehen die Partikel durch die Zylinderreihe hin mit der konstanten Geschwindigkeit, welche sie im Entladungsraum erhielten. Wenn aber eine Funke bei F überschlägt[1], wandern Ladungswellen längs der Drähte $a_1, a_2, a_3 \ldots$

[1] E ist eine Elektrizitätsquelle, R_1 und R_2 grosse Widerstände, C eine Kapazität.

Arkiv för matematik, astronomi o. fysik. Bd 18. N:o 30. 1

Wideröe's PhD in 1927, Univ. Aachen





Über ein neues Prinzip zur Herstellung hoher Spannungen

Von der Fakultät für Maschinenwirtschaft der Technischen Hochschule zu Aachen

zur Erlangung der Würde eines Doktor-Ingenieurs

genehmigte

Dissertation

vorgelegt von

Rolf Wideröe, Oslo

Referent: Professor Dr.-Ing. W. Rogowski
Korreferent: Professor Dr. L. Finzi

Tag der mündlichen Prüfung: 28. November 1927

Sonderdruck aus Archiv für Elektrotechnik 1928, Bd. XXI, Heft 4
(Verlag von Julius Springer, Berlin W 9)

27 pages (!)

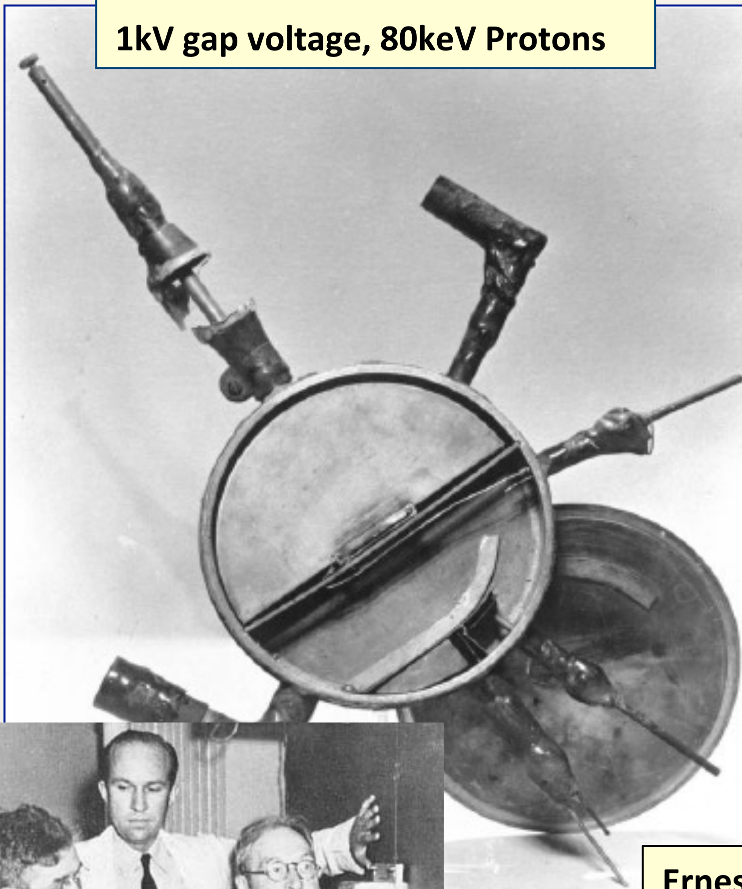
«Strahlentransformator» = Betatron

- 1944: 15MeV Betatron in Hamburg
- from 1946 BBC, Baden; 78 Betatrons produced
- 1953 teaches at ETH/CH
- †1996 in Nussbaumen/CH

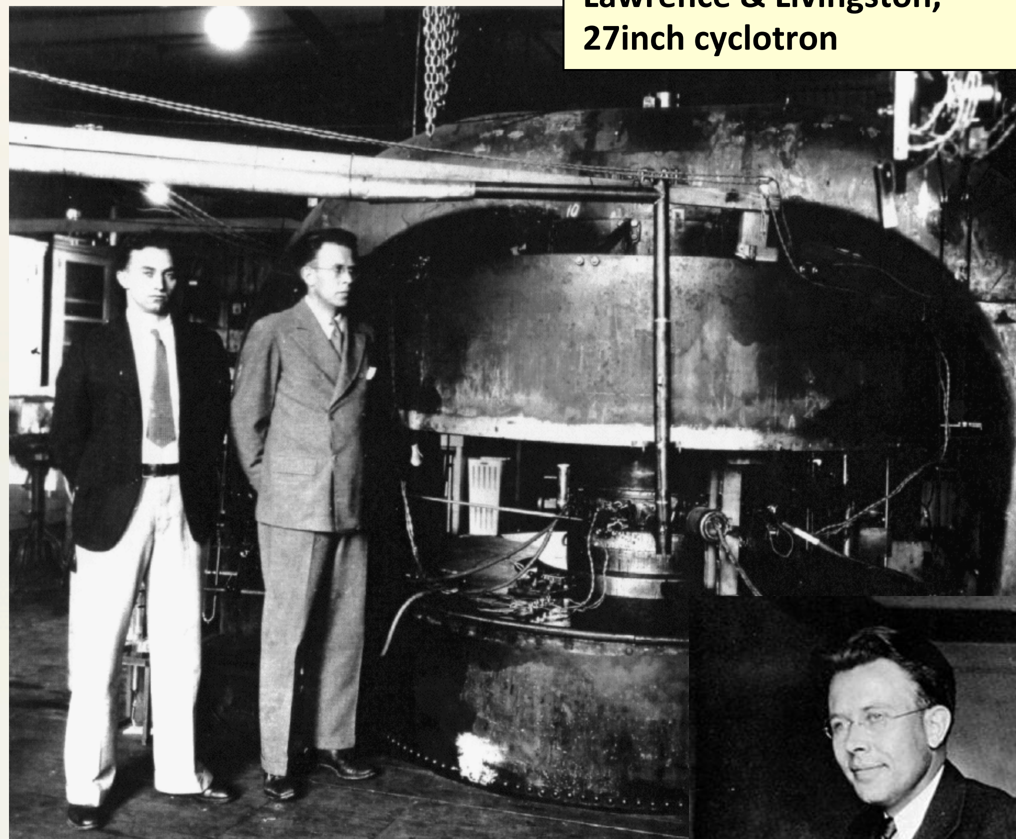
history of cyclotron

first cyclotron: 1931, Berkeley

1kV gap voltage, 80keV Protons

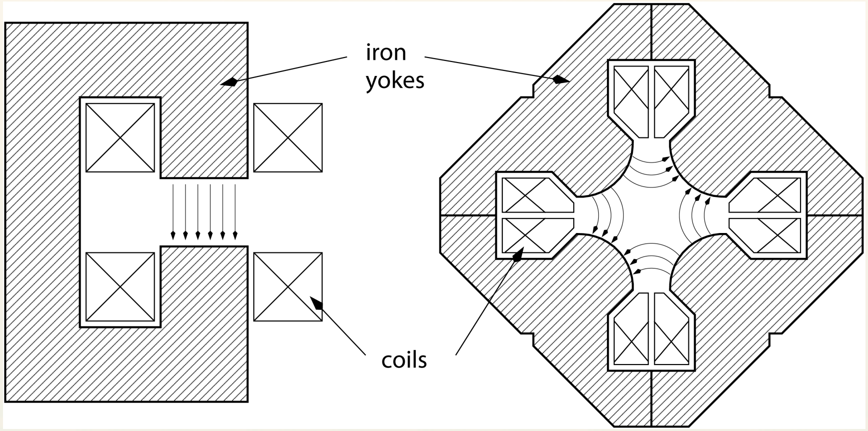


Lawrence & Livingston, 27inch cyclotron



Ernest Lawrence, Nobel Prize 1939
"for the invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements"

John Lawrence (center), 1940'ies
first medical application: treatment of cancer with neutrons using the 60inch Zyklotron



next: accelerator concepts and building blocks

- acceleration, velocity, relativity and all that …
- magnets and accelerating structures
- cyclotrons and linacs
- applications of accelerators

velocity/energy of particles and comparison with real world examples

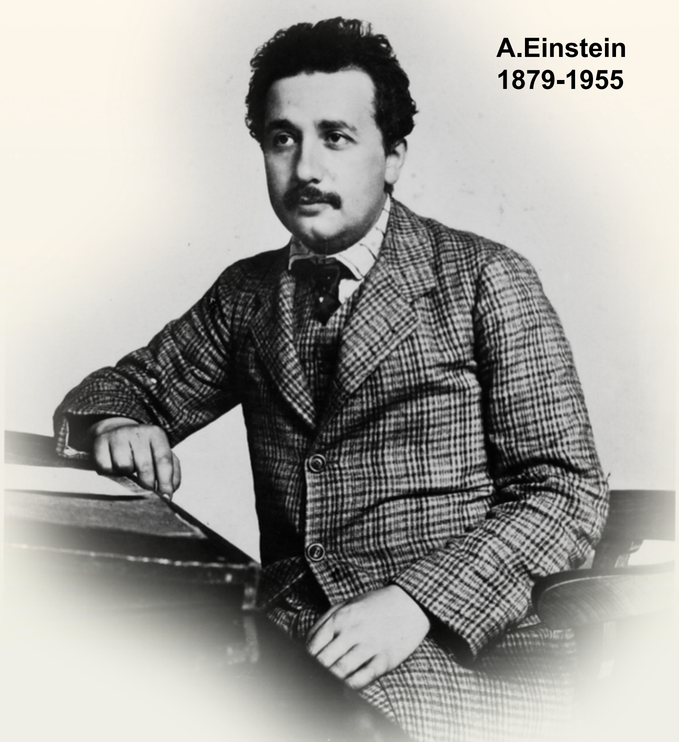
macroscopic example	velocity	energy
100kg fall from 1m height	0.0045 km/s	1 kJ
bullet from rifle (4g)	0.8 km/s	1.3 kJ
same bullet at 1. cosmic velocity (earth escape)	11,2 km/s	?

in the accelerator	velocity	energy
proton passes voltage of 10V	?	10eV = 1.6×10^{-18}J
1 second HIPA beam: 2.2mA protons, 590MeV	0.8×c	1.3 MJ
LHC beam: 3×10^{14}p = 0.5ng hydrogen, 7‘000GeV	0.999999991×c	?

sufficient to bring 1t of water to boiling

…but only once per day, thus LHC average power ca. 10..20kW

relativistic particles



energy-momentum relation:

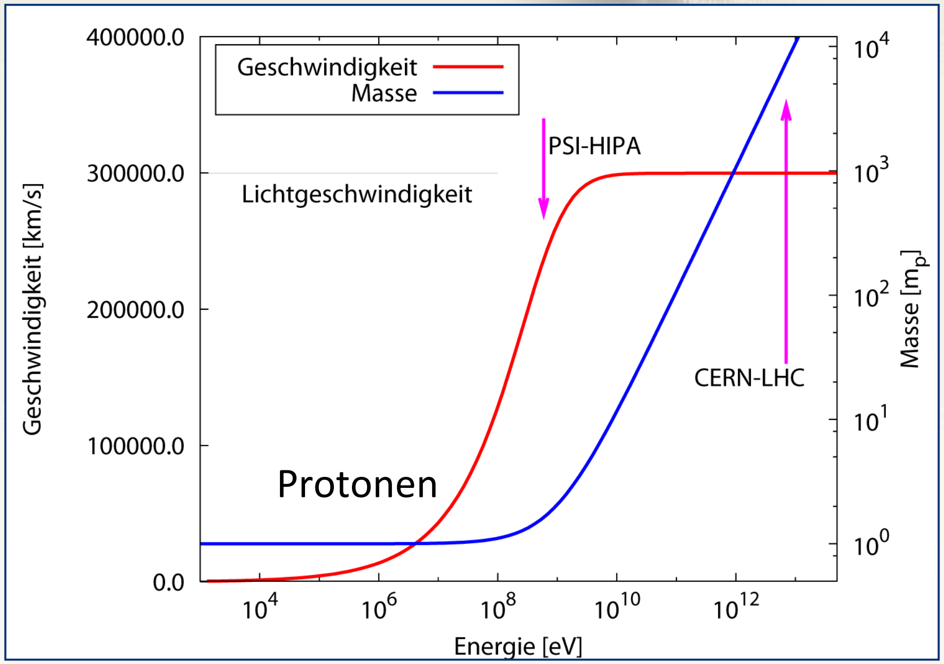
$$E = \sqrt{m_0^2 c^4 + c^2 p^2}$$

$$c^2 \vec{p} = E \vec{v}$$

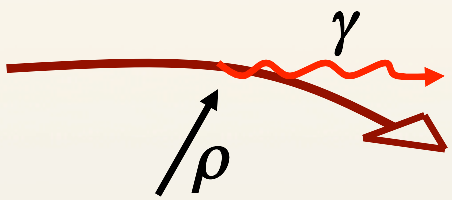
$$v = c\sqrt{1 - m_0^2 c^4 / E^2}$$

$$\vec{p} = m_0 \frac{E}{m_0 c^2} \vec{v}$$

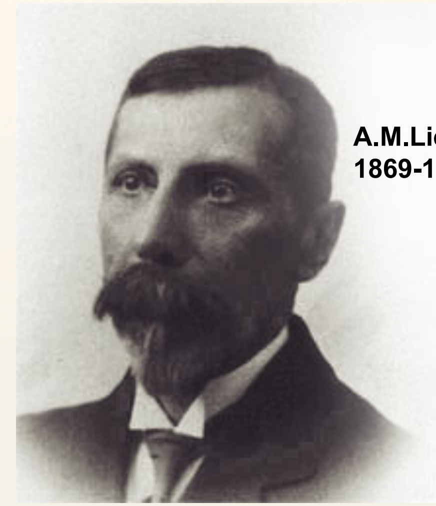
accelerated particles cannot be faster than *c*, instead we observe an increase of the effective mass
LHC: **E=7 TeV**, $m_{eff} \approx 7400 \times m_0$ **[Protons]**



electrons vs. protons



accelerated particles send out radiation in forward direction



A.M.Lienard
1869-1958

$$P_\gamma = \frac{e^2 c}{6\pi\varepsilon_0} \times \frac{E^4}{E_0^4 \rho^2}$$

particle energy

radiated power

rest energy (mass)

bending radius

$$E_c[\mathrm{keV}] = 2.2 \frac{E^3[\mathrm{GeV}]}{\rho^2[m]}$$

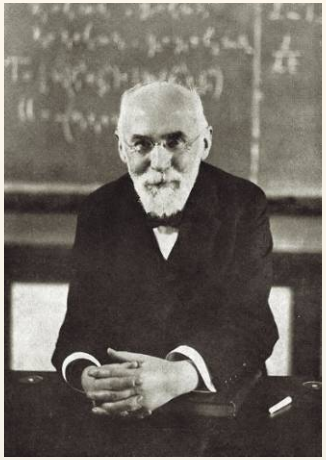
energy of radiation

► radiated power $\propto E_0^{-4}$!
i.e. electrons radiate **10^{13}** times stronger than protons → strong implications

► electrons: typically energy of radiation is in the X-ray area with many applications [synchrotron radiation sources]

Lorentz-force

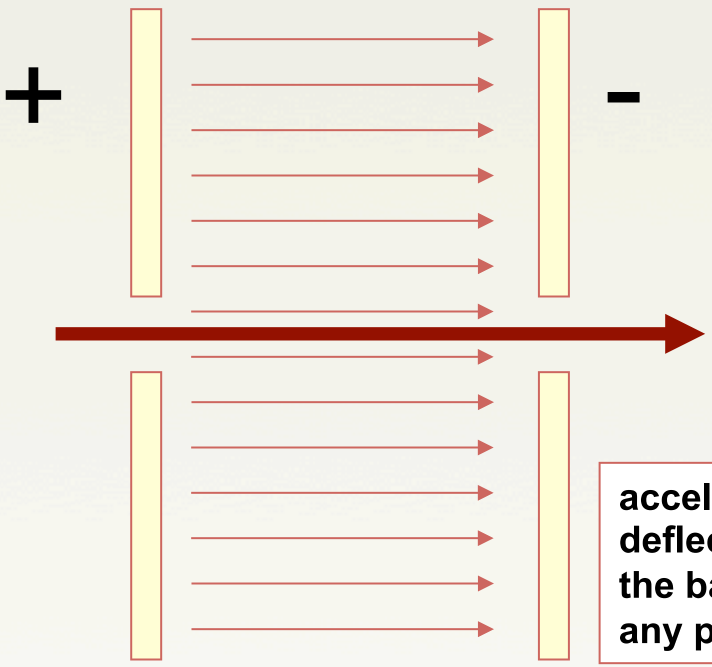
H.A.Lorentz
1853-1928



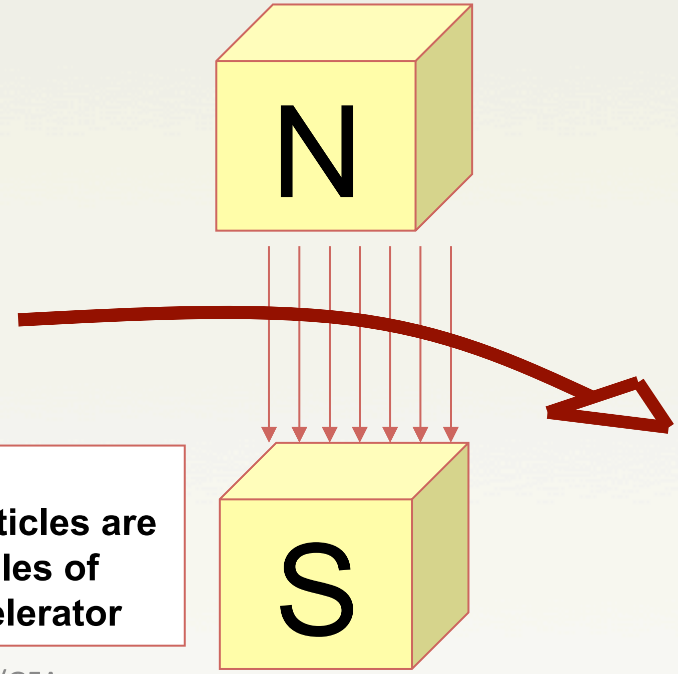
$$\vec{F} = e\vec{E} + e\vec{v} \times \vec{B}$$

electric field: energy gain; $\Delta E_k = eU$

magnetic field: bending force; $\Delta E_k = 0$, $B\rho = p/e$

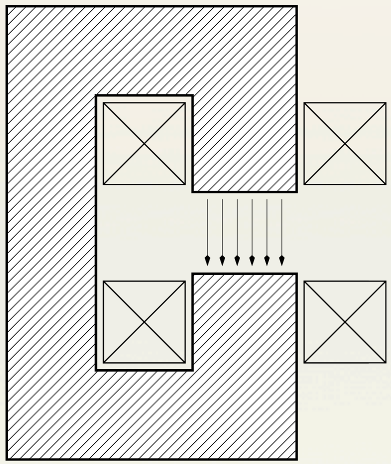


acceleration and deflection of particles are the basic principles of any particle accelerator



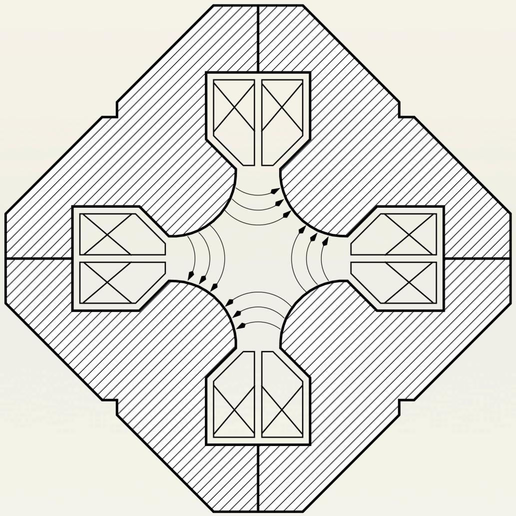
magnets in an accelerator

Dipol
[bending, constant $B=b_0$]



$$d^2x/ds^2 = \pm 1/\rho$$

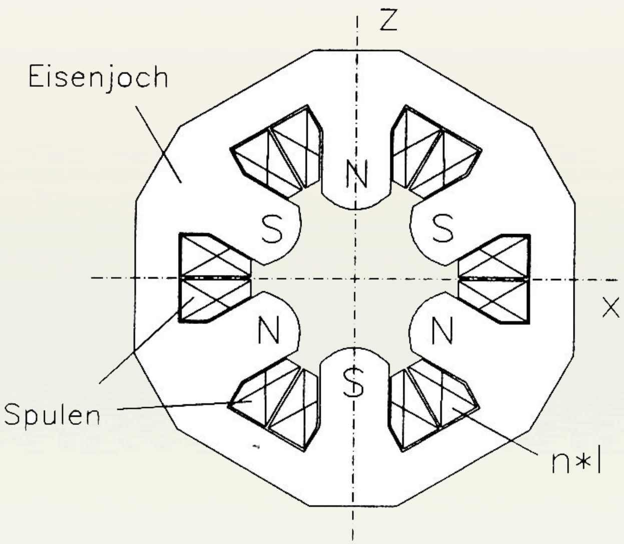
Quadrupol
[focusing, $B=b_1 \cdot x$]



$$d^2x/ds^2 = \pm K \cdot x$$

"position dependent dipol"

Sextupol
[chromatic correction, $B=b_2 \cdot x^2$]



$$d^2x/ds^2 = \pm K' \cdot x^2$$

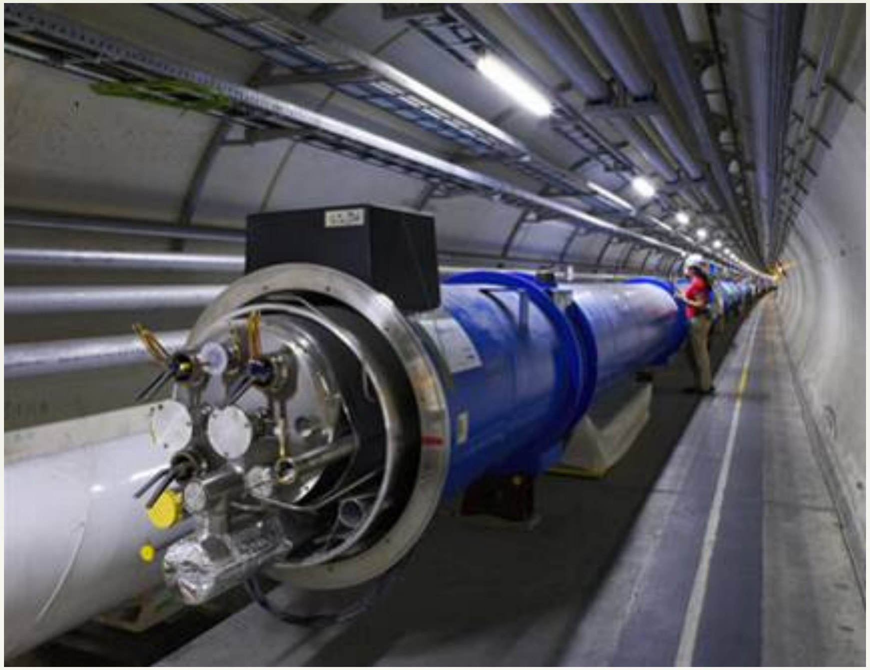
"position dependent quadrupol"

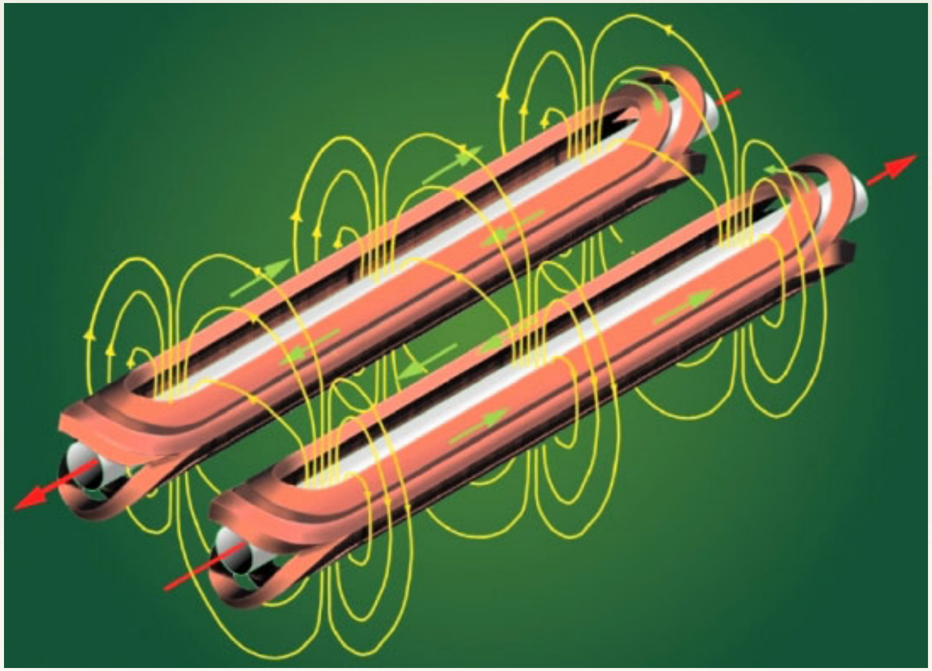
numerical example dipole field:
PSI-HIPA, iron dipol: 2Tesla, E_k=590MeV, ρ=2m

LHC superconducting dipole

[today the forefront of accelerator magnets]

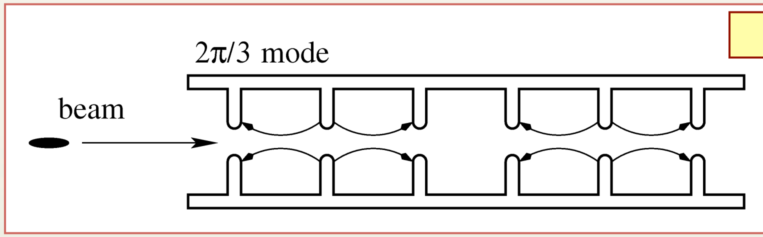
- 1232 magnets, 2 magnets integrated per cryostate
- B = 8.33 Tesla @ 7 TeV $\rightarrow$ ρ = 2800m
- temperature: 1.9 K, + several correction coils





Resonators for Linacs

coupled resonators or “Disk loaded Waveguide”
= LINAC Struktur



numeric example of SRF:

quality factor $Q_0 = 2 \cdot 10^{10}$ @ 1.3 GHz

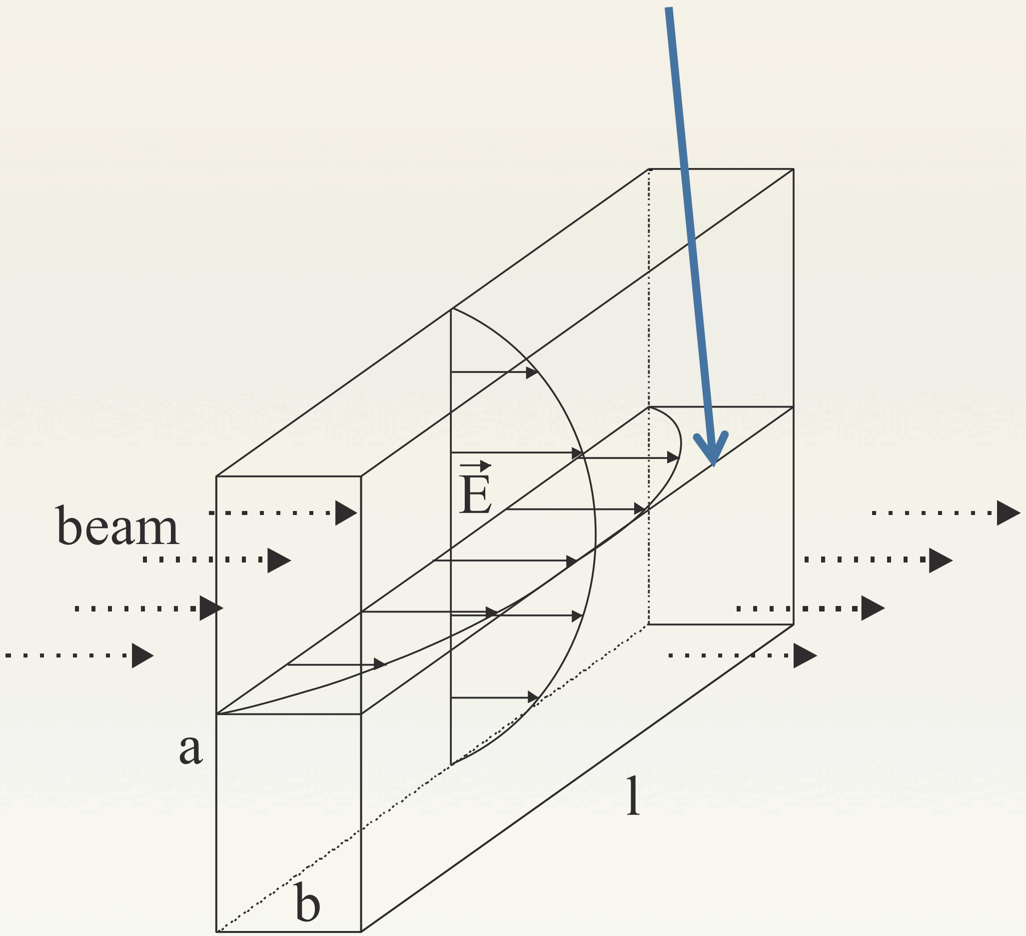
corresponds to one year church bell @ 500Hz!

- **NLC / Stanford Structure**
- **Parameter:**
- Length: $l = 60$ cm
- Frequency: (X-Band) $f = 11.424$GHz
- max. gradient: $G = 75$ MV/m (!)
- Pulse length: $\tau \approx 500$ns

superconducting resonator:
Niobium (2.5mm), f = 1.3GHz, $G \approx 25..30$MV/m, T = 1.8K
minimal losses; extremely high quality factor

modern resonators for cyclotrons

… are box-resonators, single cells, huge …
typ.: f = 50…100MHz, beam passes through slit in center plane



PSI example:
resonator for Injector II cyclotron

The Classical Cyclotron

two capacitive electrodes „Dees“, two gaps per turn

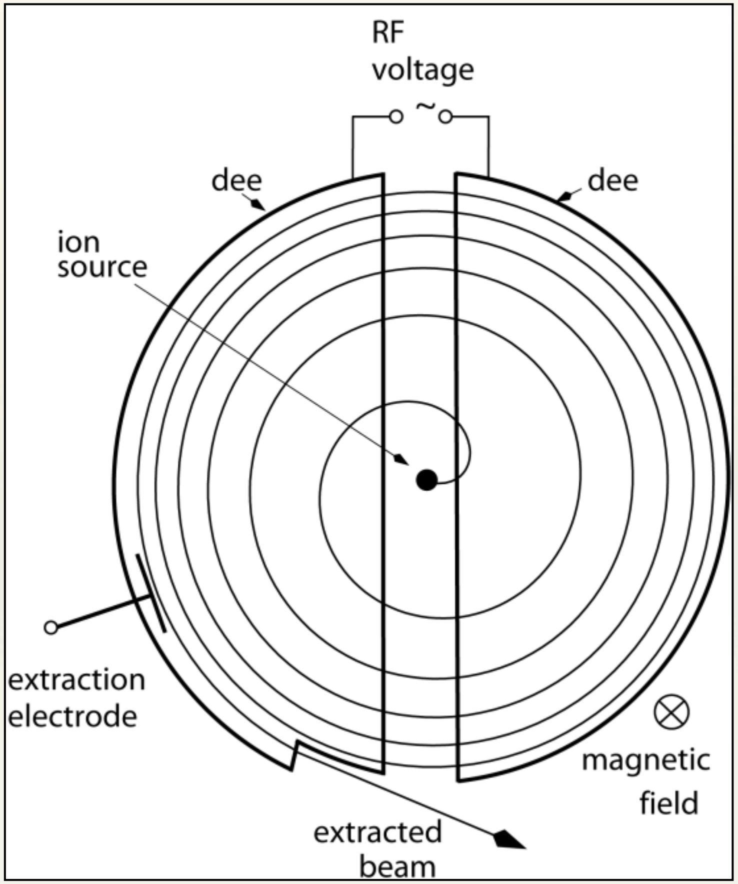
internal ion source

homogenous B field

constant revolution time

(for low energy, $\gamma \approx 1$)

$$\omega_c = \frac{eB_z}{\gamma m}$$



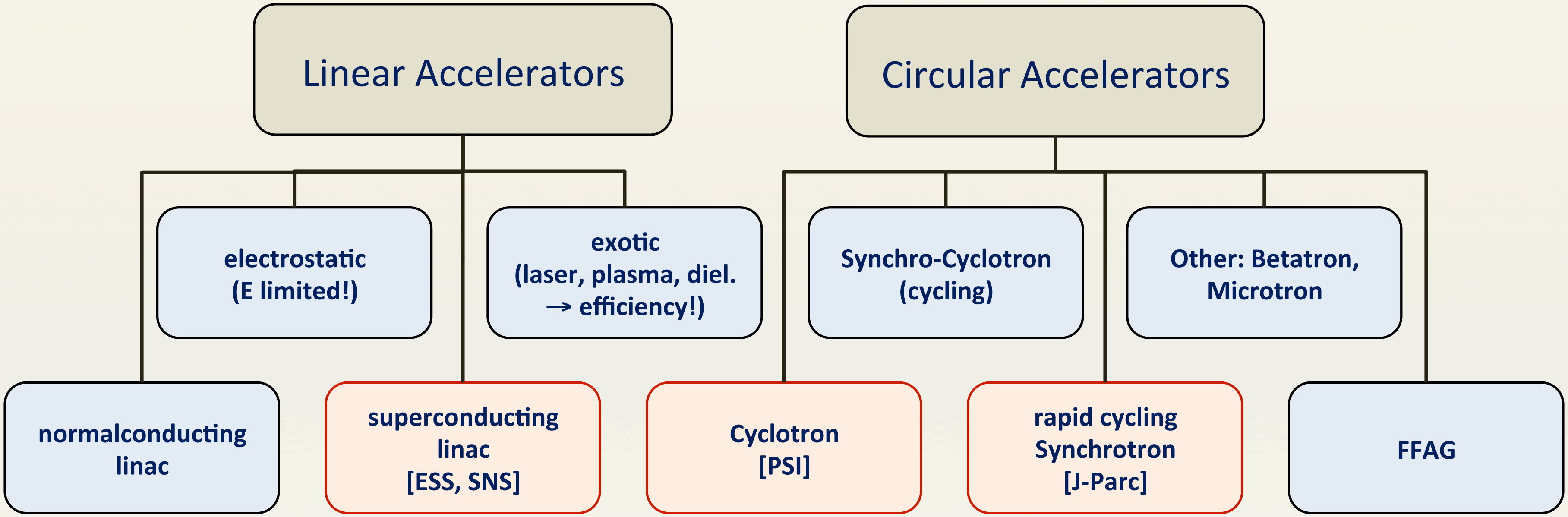
powerful concept:

➔ **simplicity, compactness**

➔ **continuous injection/extraction**

➔ **multiple usage of accelerating voltage**

High Intensity protons – suited concepts?



normalconducting linac
- pulsed
- CW: very low gradient

superconducting linac
- CW possible
- cooling power!
- cost!

Cyclotron
- CW possible
- beam dynamics!
- extraction!

rapid cycling Synchrotron
- pulsed
- power limited (1MW?)

FFAG
- compact
- cycling / CW questionable
- no demonstrator

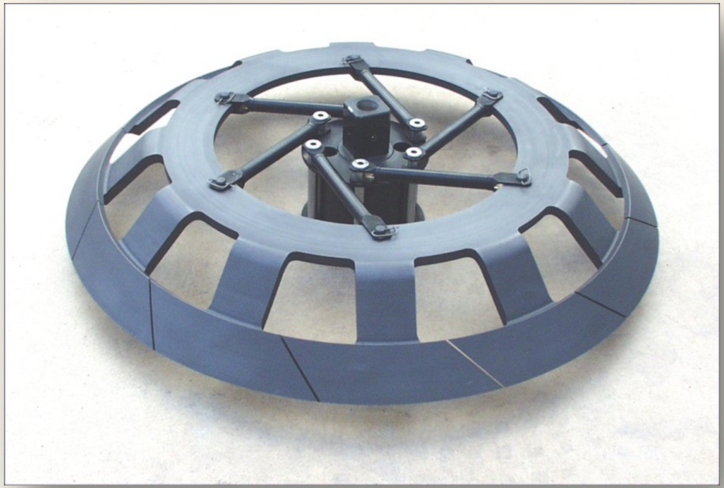
Applications of 30.000 Operating Accelerators

topic	example
radiotherapy: ions and X-rays	PROSCAN, MedAustron, HIT, SCRIPPS, HIMAC …VARIAN…
ion implanters, surface and bulk modification	semiconductor industry
industrial processing, isotope production, security	medical, food sterilisation, container imaging …
synchrotron light sources, FEL	SLS, SPRING-8, ESRF, SwissFEL, LCLS …
neutron sources	SINQ, SNS, ISIS, ESS
low and medium energy accelerators for research; nuclear physics	HIPA, TRIUMF, GSI, J-PARC, GANIL, RIKEN-Nishina …
high energy particle physics facilities	CERN (LHC), KEK, Fermilab, J-PARC

concrete ↕ **abstract**

90% by the number (radiotherapy; ion implanters; industrial processing)

majority of cost (synchrotron light sources through high energy particle physics)

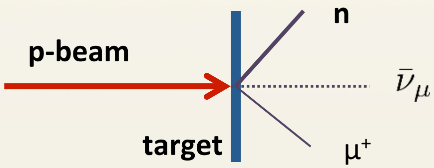


next: generation of secondary radiation

- concept of primary and secondary beams
- muons
- neutrons
- [ultracold neutrons]

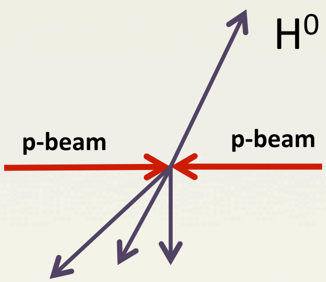
most accelerators are used to generate secondary radiation

targets are used to generate **neutrons, muons or neutrinos** from proton beams



neutrons, muons, neutrinos…

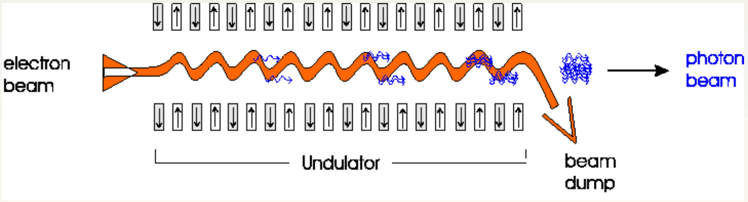
even the generation of **Higgs particles** in LHC is secondary radiation



collisions: exotic particles

magnets and undulators are used to generate **X-rays** from electron beams

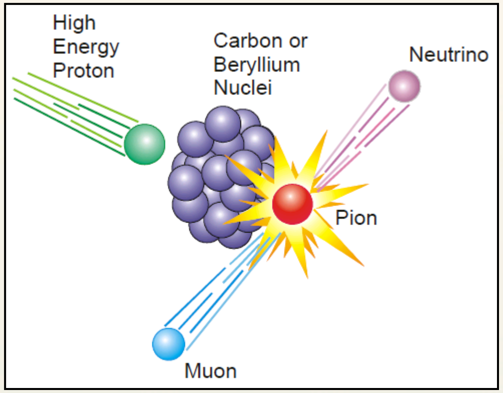
X-rays



secondary radiation for the actual application

facility	primary beam	secondary beam	application
SLS	e, 2.4GeV	X-rays	structure of matter
SwissFEL	e, 5.8GeV	X-rays, coherent	structure of matter
SPRING-8 (JP)	e, 8GeV	X-rays, 300keV, range: 300eV..2.9GeV	structure of matter
PSI-HIPA	p, 590MeV	n, μ	structure of matter, particle physics
J-PARC	p, 3GeV, 30GeV	n, μ, ν	particle-, nuclear-, applied physics
LHC	p+p, 2×7TeV	H^0, exotic particles	particle physics
Muon collider (proposed)	$\mu^+\mu^-$, 62.5GeV	H^0 factory	particle physics

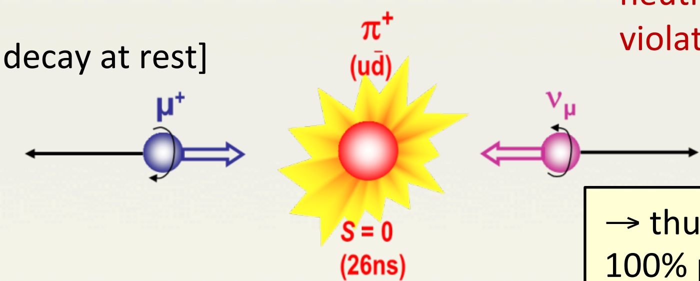
Production of Muons



1) high energy p hits nucleus and produces pion (u+d quark);
lifetime π^+: 26ns

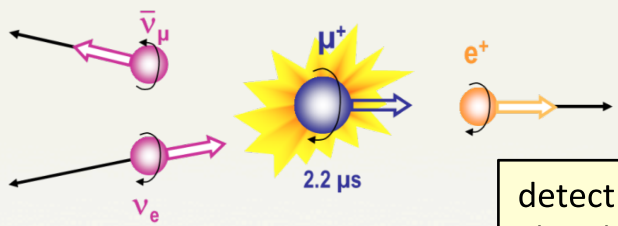
2) the Pion (spin 0) decays into a neutrino and the desired Muon, both Spin ½
[surface Muons = decay at rest]

only left handed neutrinos exist = violation of parity



→ thus Muons 100% polarized, spin antiparallel

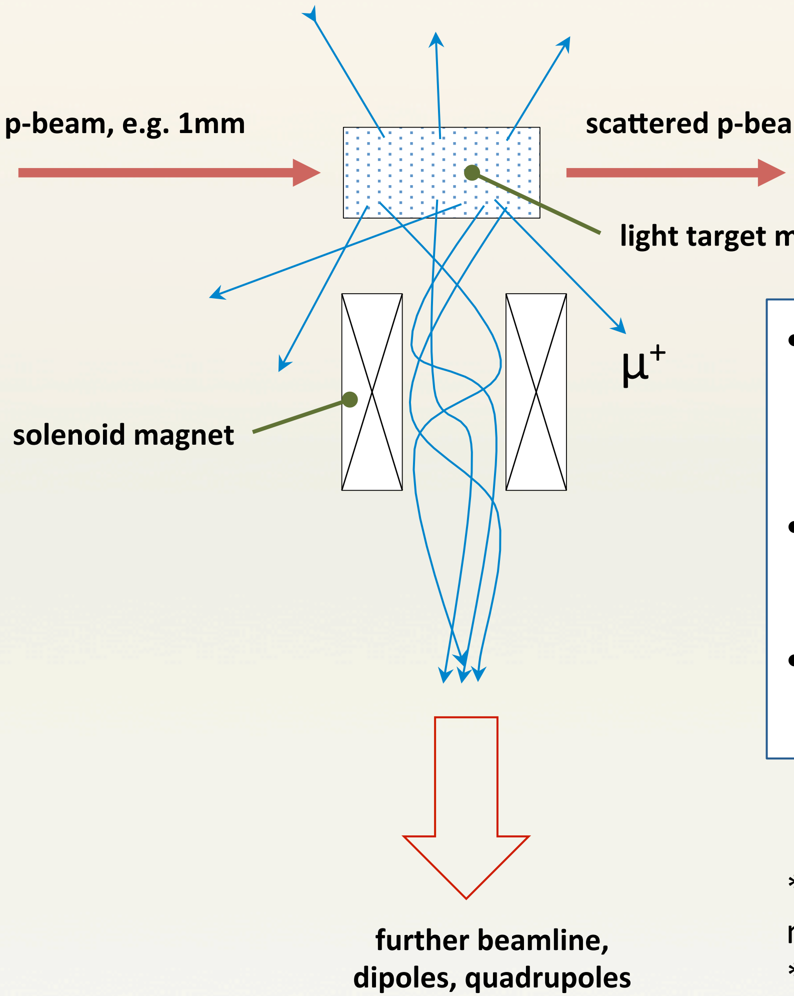
3) the Muon (now bound in test sample) decays after few µs into neutrinos and a positron



Muon properties
m_0 = 105,7MeV ≈ 200m_e
τ = 2,2 µs
spin = 1/2

detect positron → gives information on structure/magnetic properties of material

Concept of Muon Capture

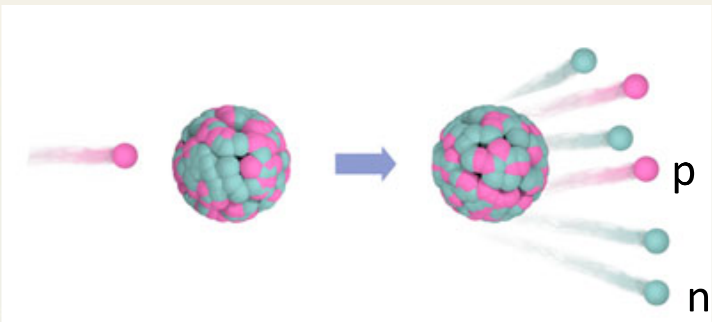


- p-beam produces pions, those stop in target material and decay to Muons with 100% polarization and E_k = 4.1MeV
- Muons are emitted close to surface, but under all angles [large emittance]
- use solenoid to focus this huge beam and capture as many as possible

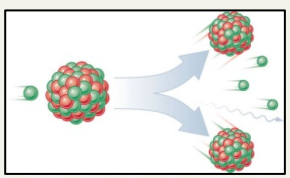
* other schemes involve decay of Pions in flight (higher muon energy)
** if spent p beam is not used further one can use heavy target materials
*** some schemes foresee Muon cooling (scattering and re-acceleration)

Production of Neutrons

we use spallation in a lead (heavy) target …



… compare fission as in a reactor



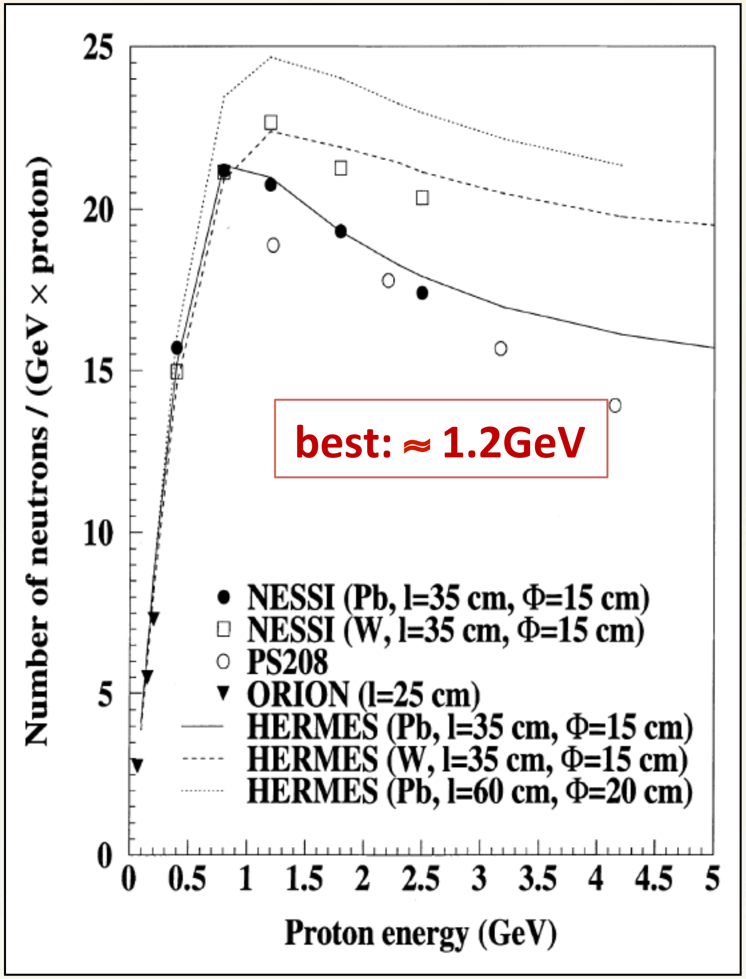
the neutron:
m_n = 939,6 MeV
(m_p = 938,3 MeV)
τ = 880,0(9) s
spin = ½

evaporated: 2 MeV
thermal: 100 meV
cold: 2 meV (~1Å)
ultracold: 200neV

moderation of the neutrons to the desired energy sprectrum is important

optimum p-energy for neutron production?

basic aspects of energy choice:

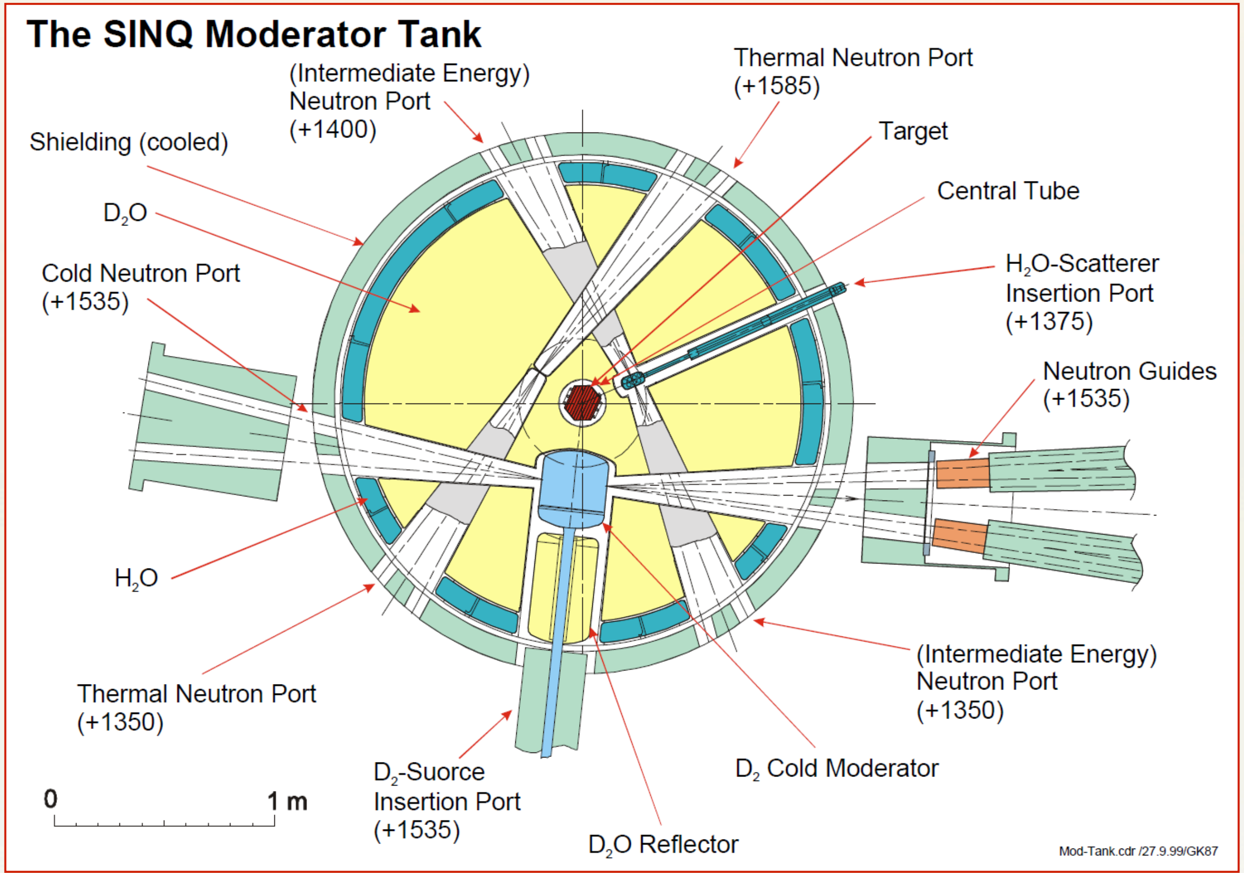


A. Letourneau et al. / Nucl. Instr. and Meth. in Phys. Res. B 170 (2000) 299±322

other practical aspects of energy choice:

- LINACS: may be easier to achieve high power at higher energy, since throughput per RF-coupler is lower if Linac is longer
- CYCLOTRONS: need radius increase per turn for extraction; 1GeV seems feasible; 0.8GeV much better
- TARGET: geometrical aspects!; density, stopping power and dE/dV?; n-distribution around target?

Example of a Target / Moderator Assembly

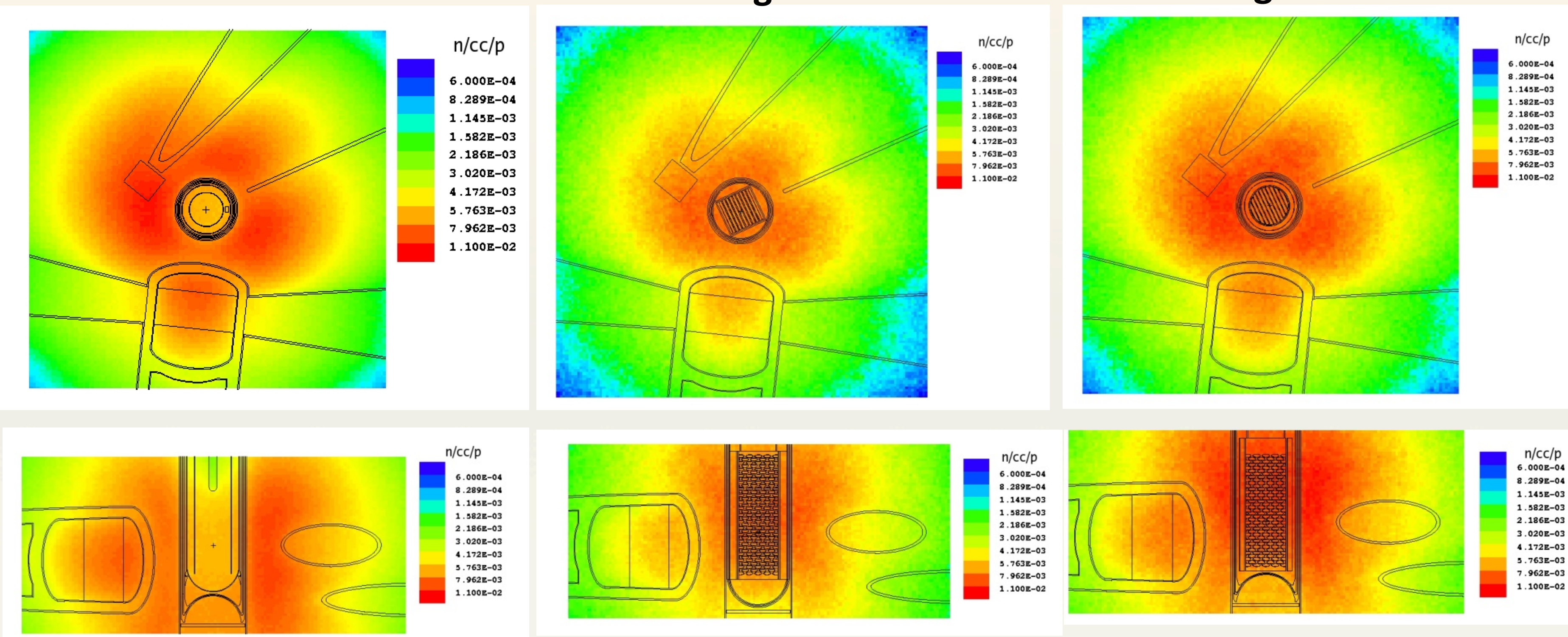


neutrons emitted from the target are moderated in D_2O* and then extracted using beam ports and neutron guides**

*factor 1000 lower absorption than water
** low loss guides are important; is a science by itself

Neutronic Simulations

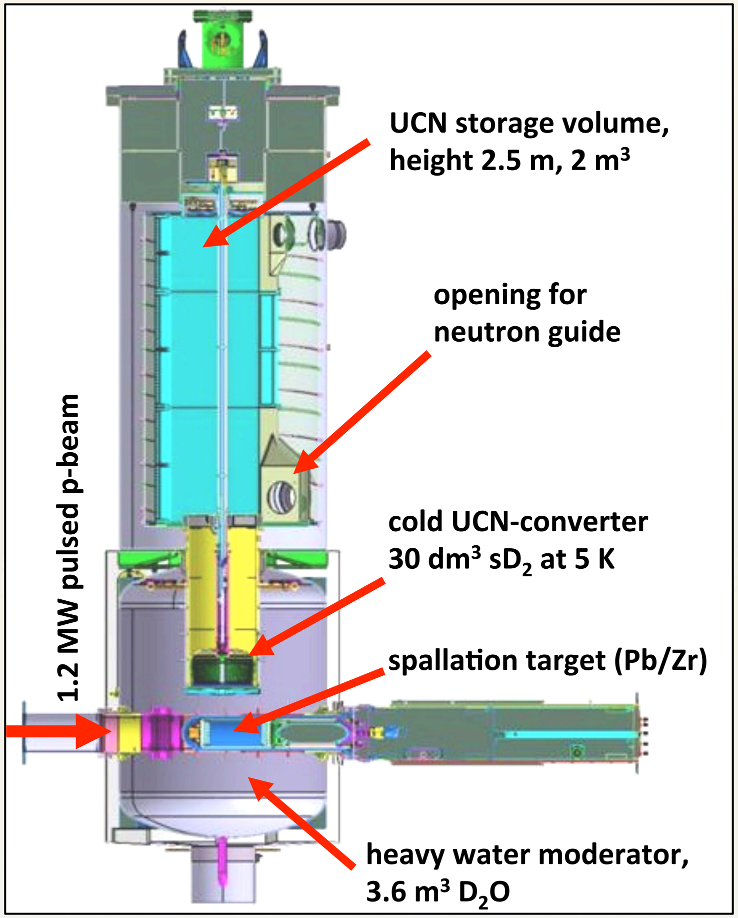
MEGAPIE | **MARK III Target 7** | **MARK IV Target 8**



- Simulated flux maps (MCNPX) of MEGAPIE, Target 7 (MARK III) and a MARK IV target
- Simulated differences to Target 6 are: MEGAPIE (~1.80), Target 7 (1.20), Target 8 (~ 1.60).

[M.Wohlmuther]

Ultracold Neutrons



UCN Tank:

height = 6.5 m
diameter = 1.7 m
mass = 3.3 to

same production mechanism as with thermal neutrons, but moderate to lower temperatures

in PSI case use frozen deuterium moderator at 5K

UCN can be stored in a bottle and a continuous stream of UCN is extracted through an opening

200neV neutrons reach 2m height due to gravity when emitted upwards

applications are fundamental measurements like electric dipole moment or lifetime

next: review of PSI HIPA accelerator

Ring cyclotron
the many components of HIPA
Mu production, SINQ target station

Overview PSI Facility

Injector II Cyclotron 72 MeV

Cockcroft Walton

Ring Cyclotron 590 MeV

2.2 mA /1.3 MW

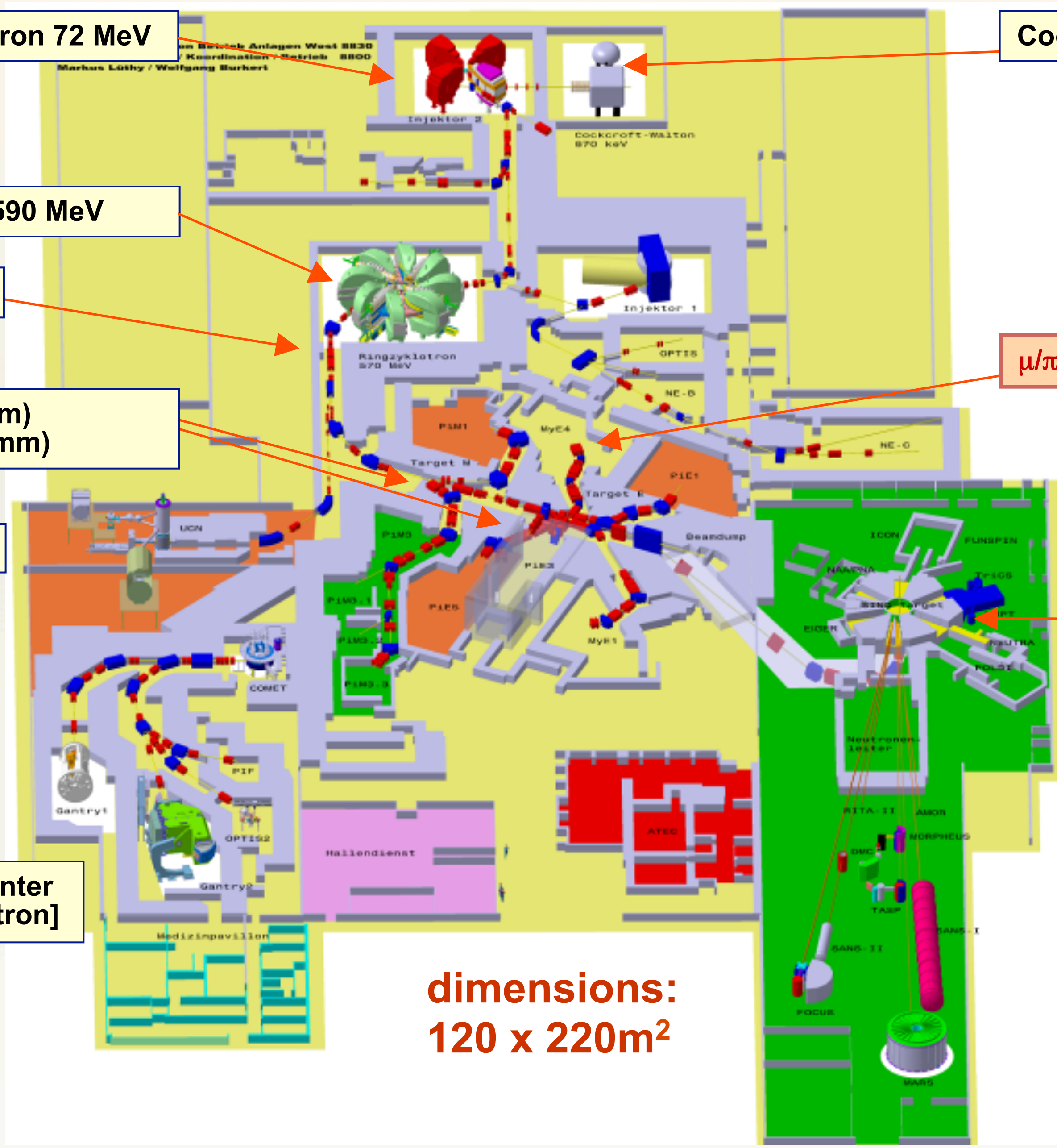
μ/π secondary beamlines

target M (d = 5mm)
target E (d = 40mm)

1.5 mA /0.9 MW
CW operation

UCN source

SINQ
spallation source



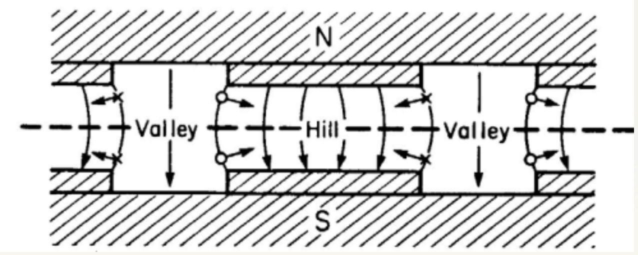
proton therapie center
[250MeV sc. cyclotron]

dimensions:
120 x 220m^2

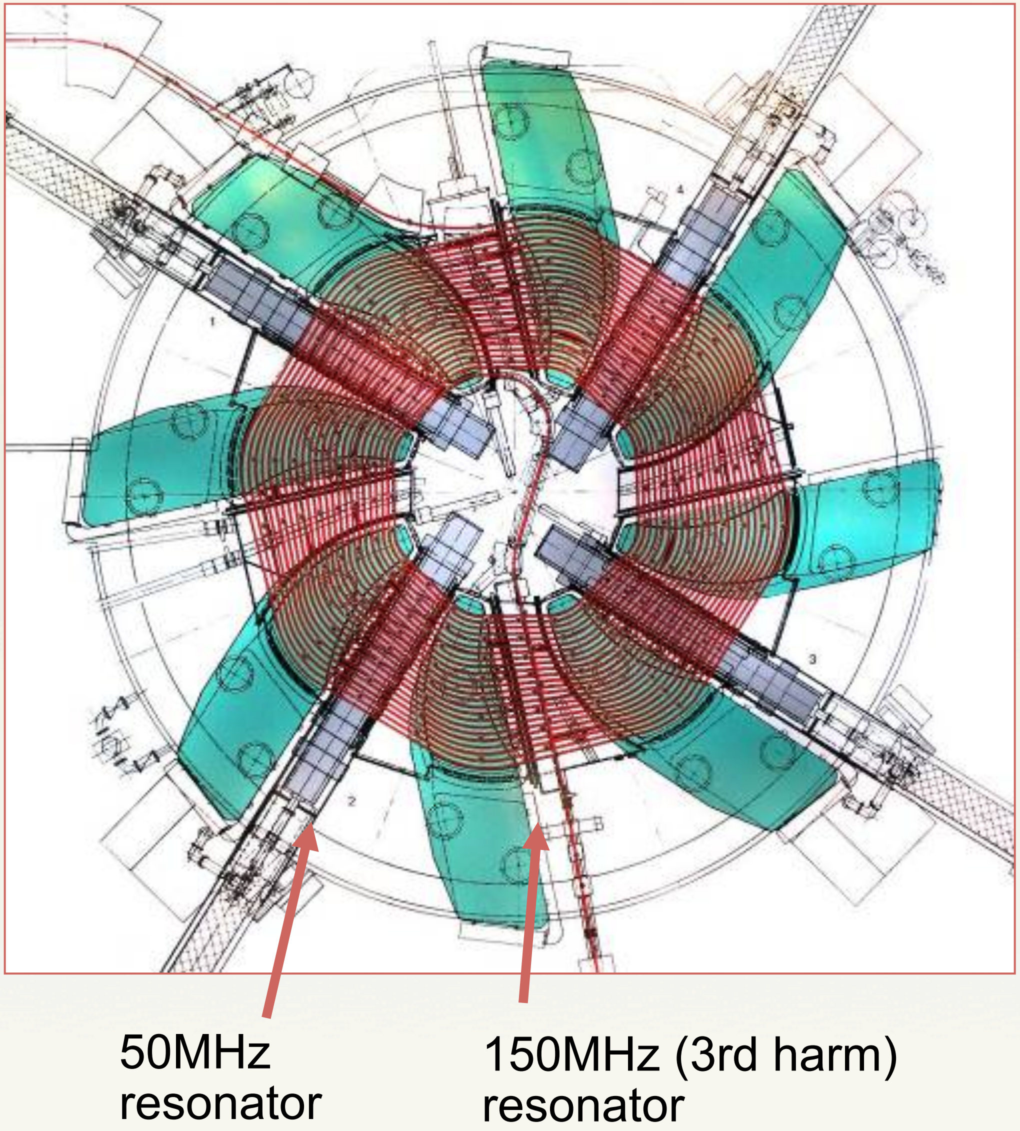
SINQ
instruments

PSI Ring - a separated sector cyclotron

- **edge+sector focusing**,
i.e. spiral magnet boundaries (angle ξ), azimuthally varying B-field (flutter F)
$Q_y^2 \approx - R/B\ dB/dR + F\ (1+2\cdot\tan^2(\xi))$
- **modular layout** (spiral shaped sector magnets, box resonators)
- **electrostatic elements** for extraction / external injection
- strength: **CW acceleration**; high **extraction efficiency** possible: 99.98% = 1 - $\mathbf{2\cdot10^{-4}}$
- relatively high energy efficiency of RF system: **32% from Grid to beam**

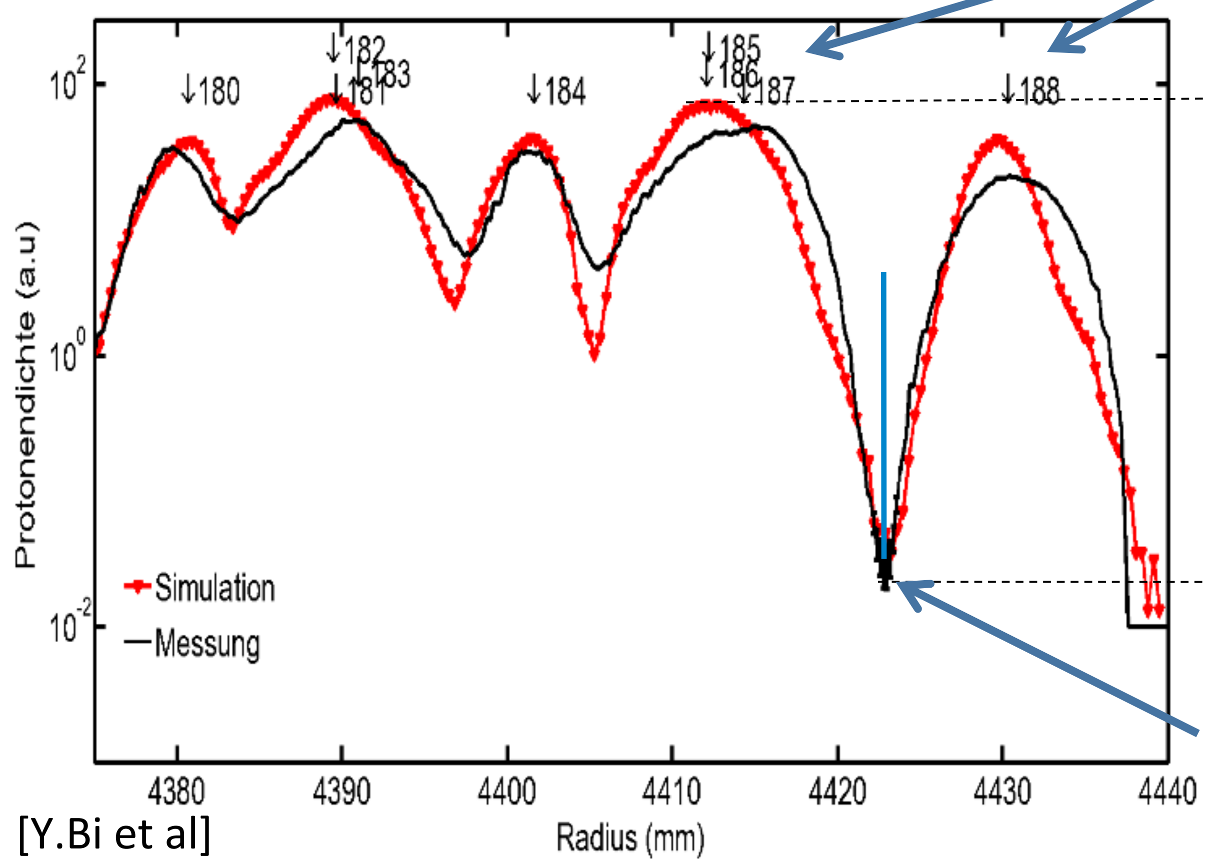


[illustration of focusing at edges]



extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement



[Y.Bi et al]

turn numbers

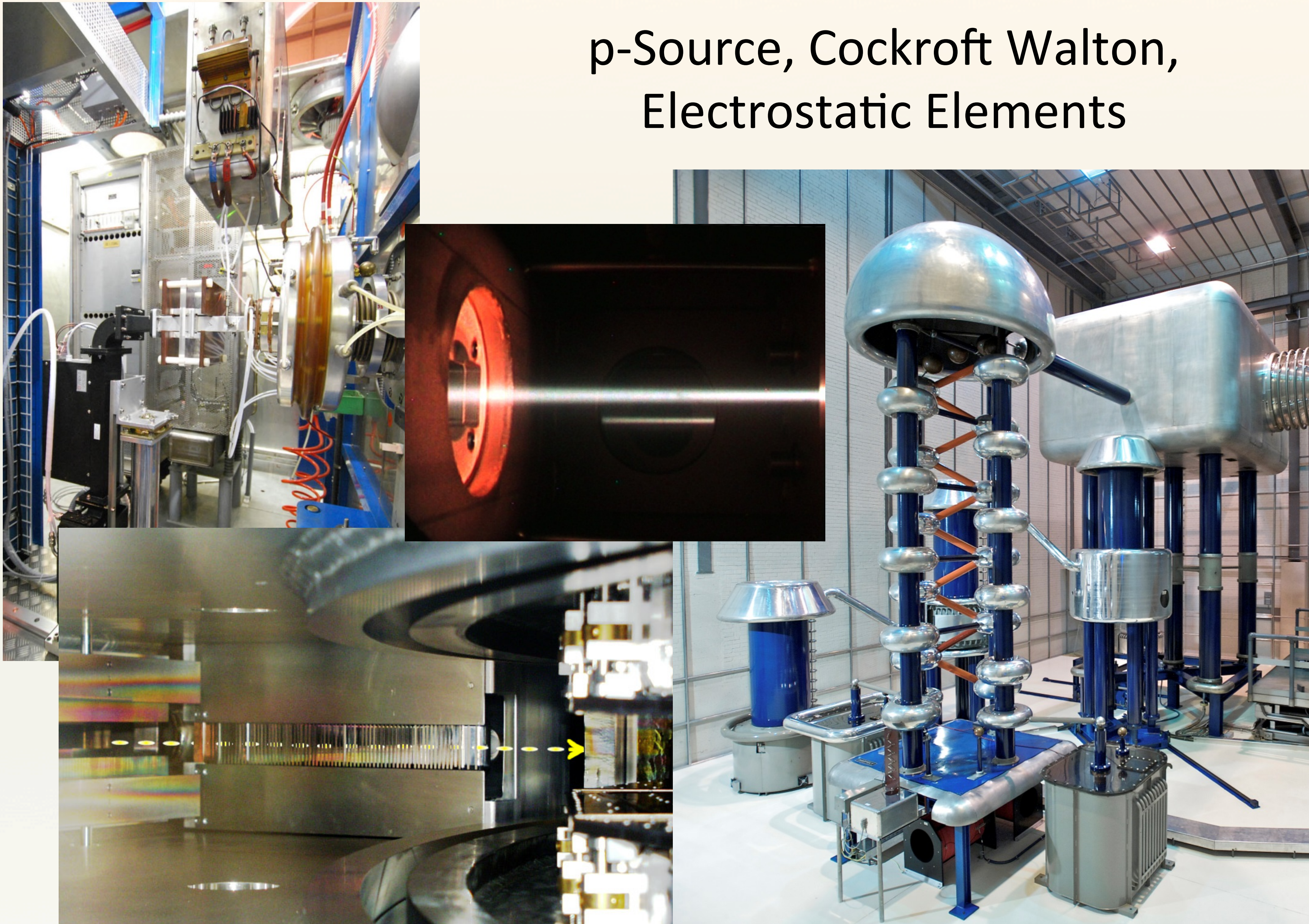
from simulation

dynamic range:
factor 2.000 in
particle density

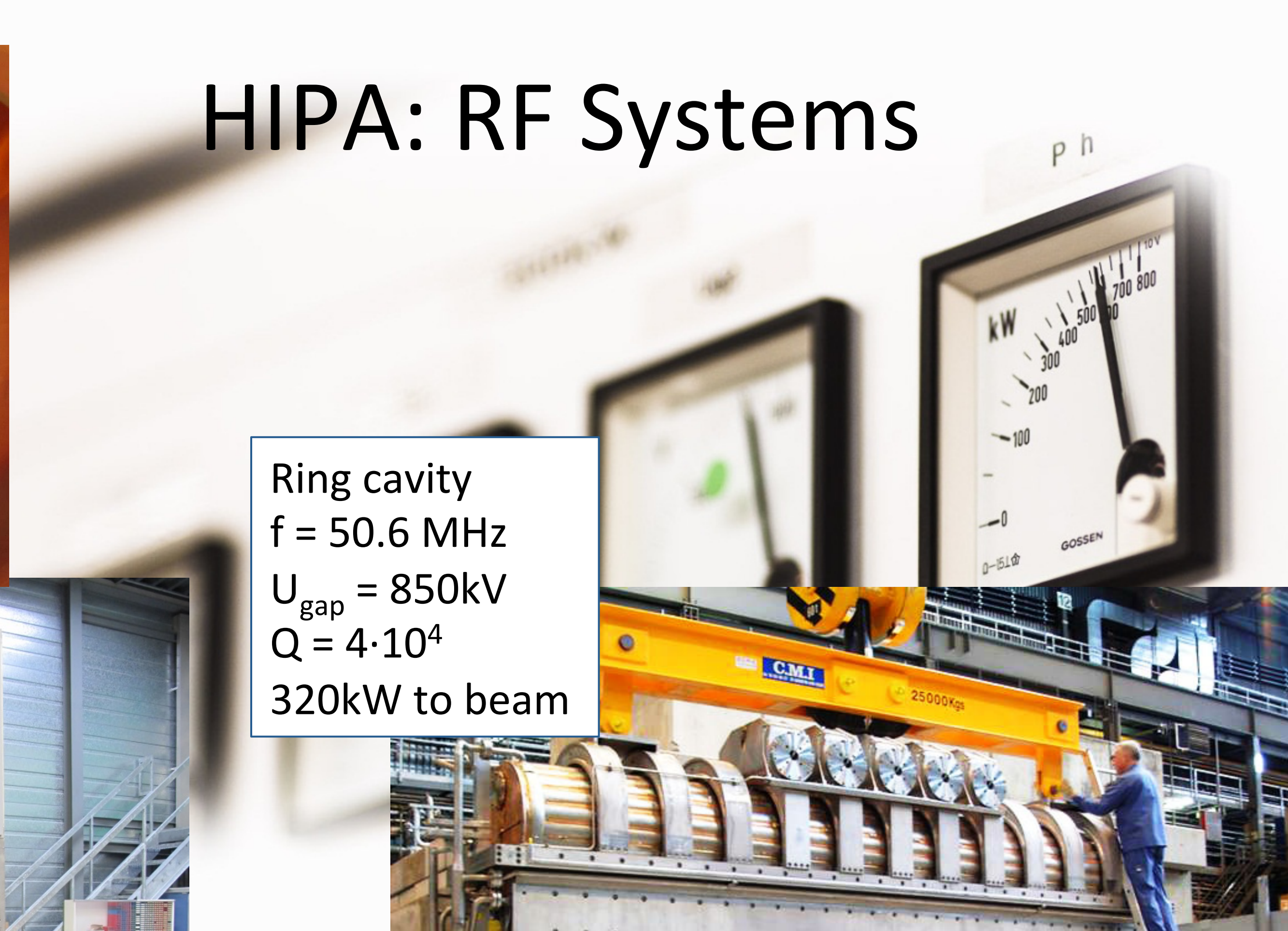
position of extraction septum

d=50μm

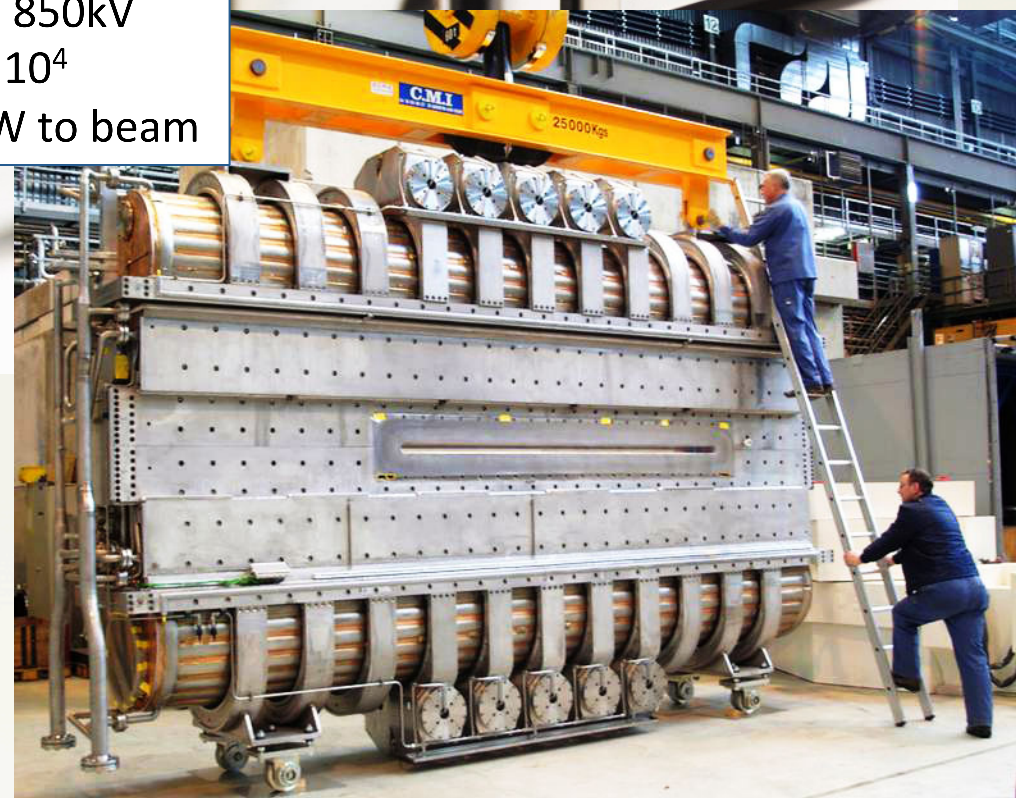
p-Source, Cockroft Walton, Electrostatic Elements



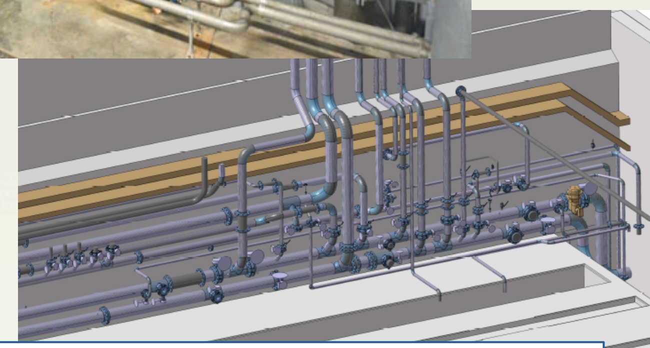
HIPA: RF Systems



Ring cavity
f = 50.6 MHz
U_{gap} = 850kV
Q = $4 \cdot 10^4$
320kW to beam



HIPA:Power Supplies, Electrical circuits & cooling



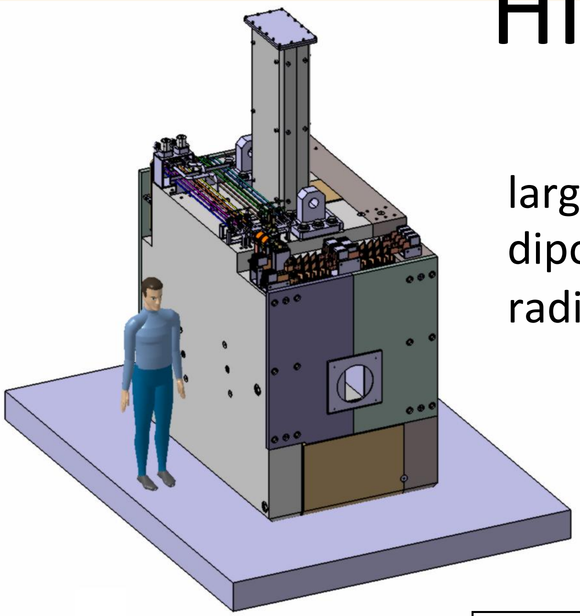
magnet circuits:

54 dipoles
210 quadrupoles
91 steering magnets
15 sextupole + solenoid
67 cyclo. trim+main coils
<u>437 total</u>

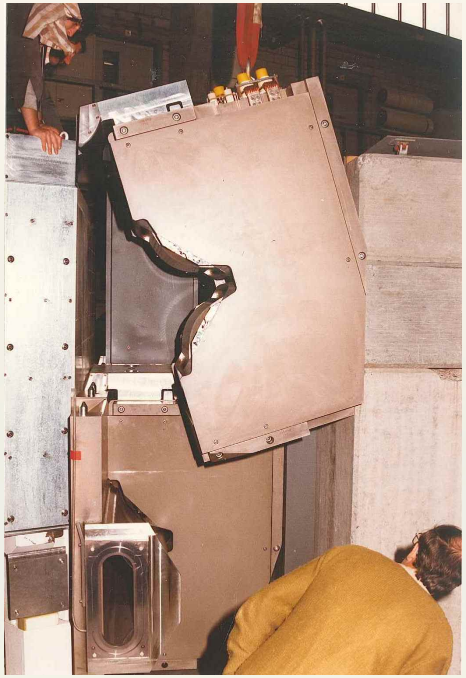
cooling circuits:

19 general circuits
6 tertiary circuits
36 MW installed cooling capacity
198m3 total water volume

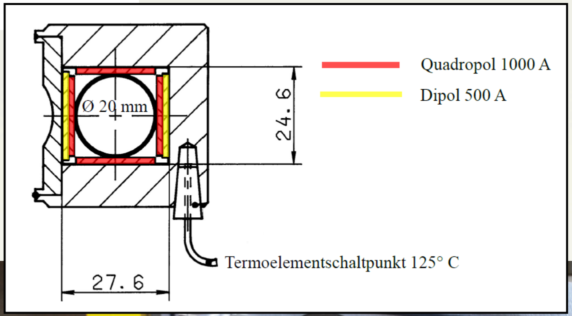
HIPA: Magnets (special examples)

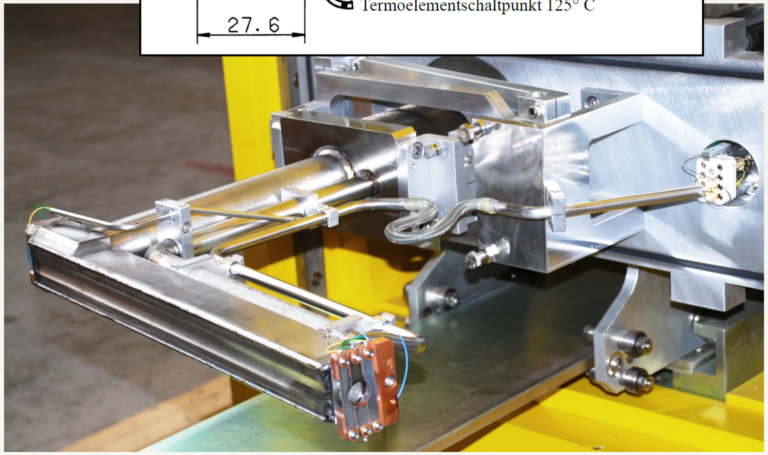


large aperture dipole magnet, radiation hard

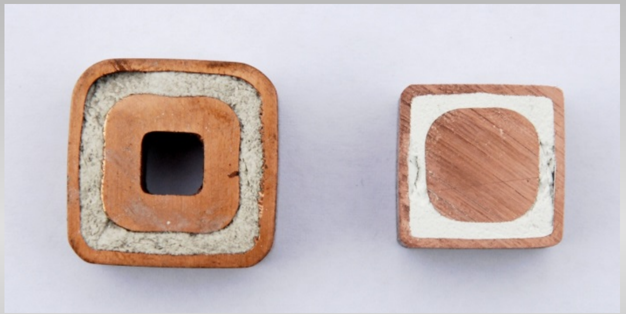


Half-Quadrupole for Muons





Panofsky type Septum magnet in Ring, He-gas-cooled

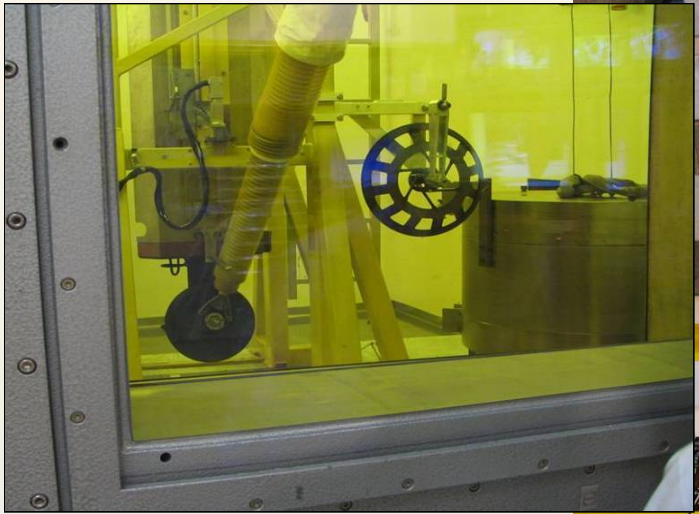


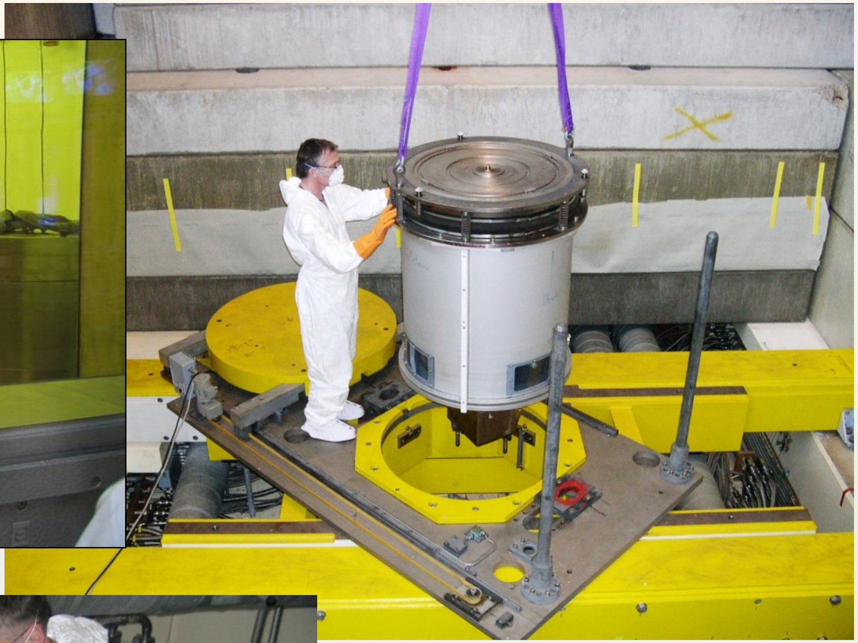
mineral insulated cable (MgO)

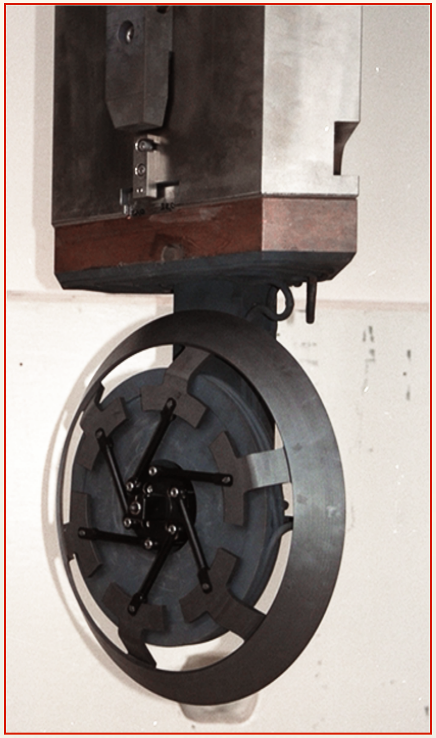
HIPA: Services, Shielding and Beamlines

- totally ~**10.000** shielding blocks, all in CATIA CAD system
- in sum **32.000** tons of weight
- iron is **20%** fraction by the number
- **14** different **standardized shapes**

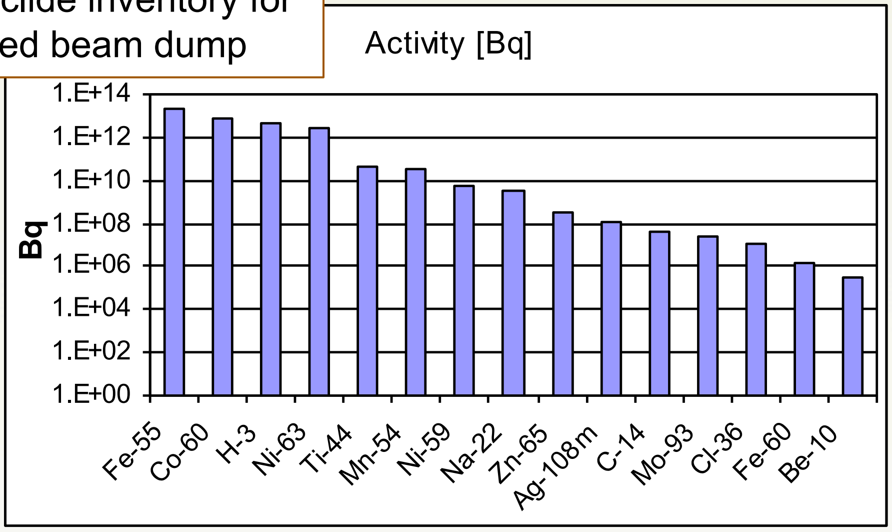
HIPA: Targets and Disposal



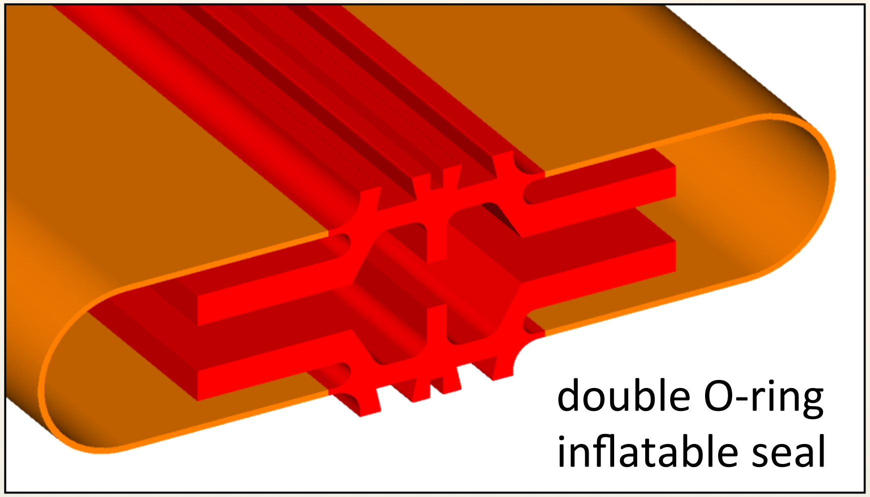




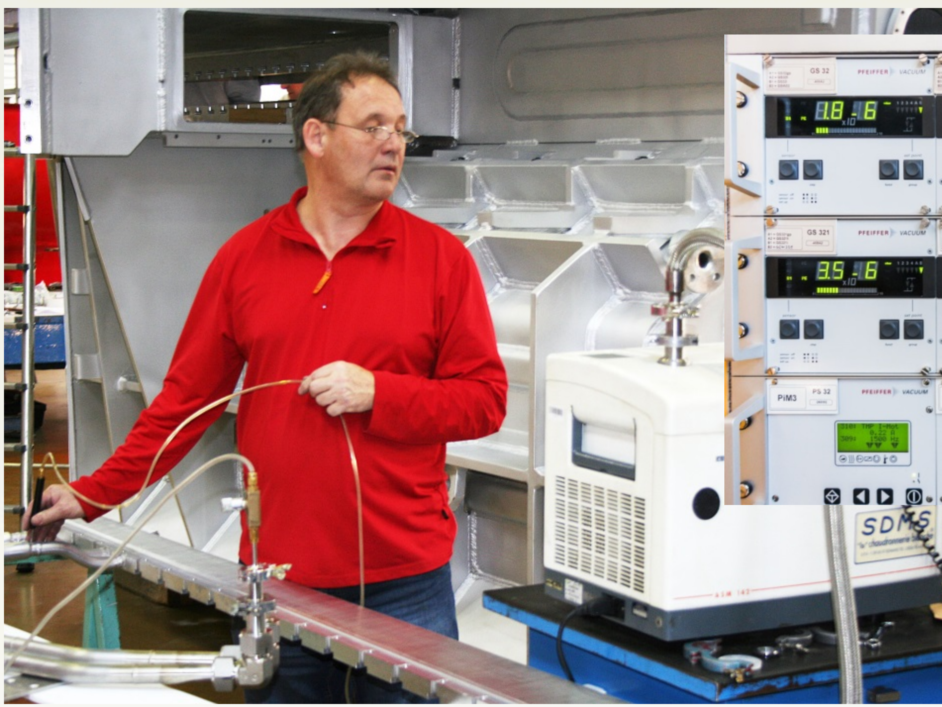
example: predicted nuclide inventory for used beam dump

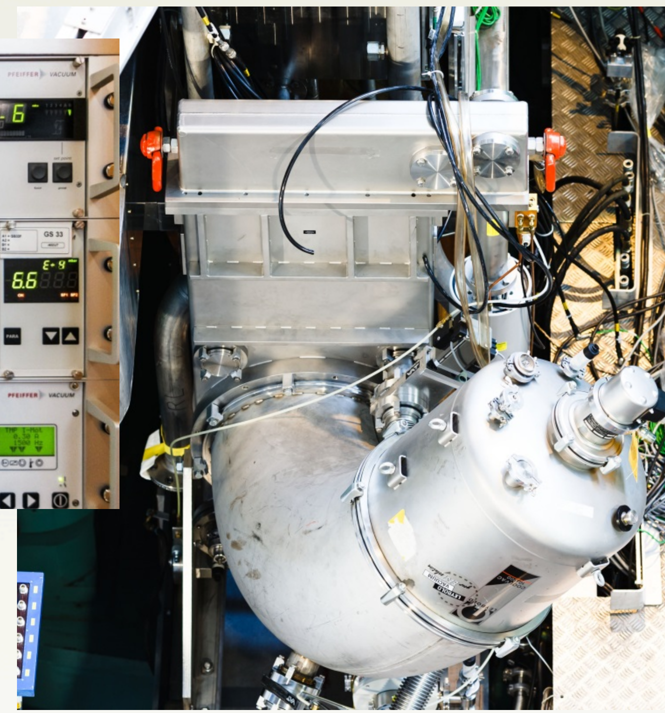


HIPA: Vacuum

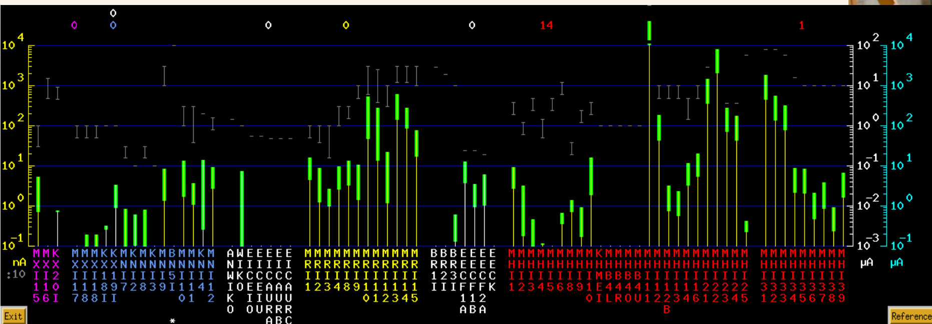


cryo pumps	10
turbo pumps	65
total pumping speed	74.500 l/s
evacuated volume accelerator	97m^3
pirani gauges	135
penning gauges	139

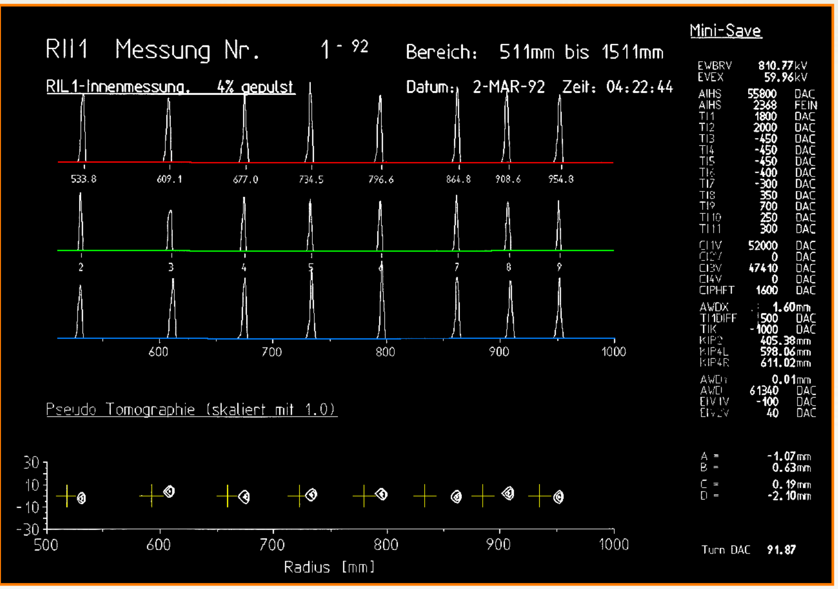




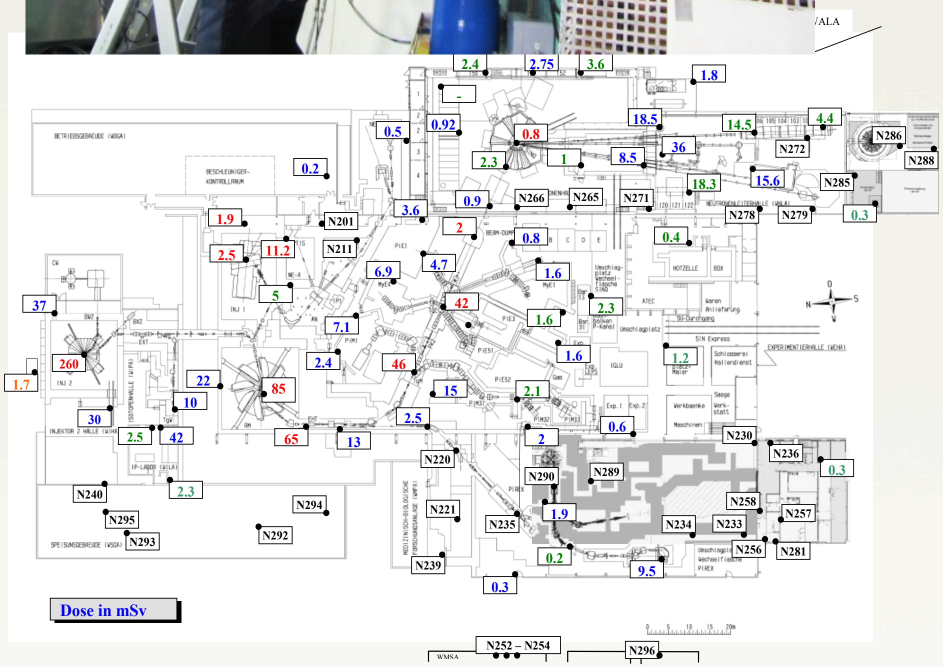
Operation, Controls & Diagnostics



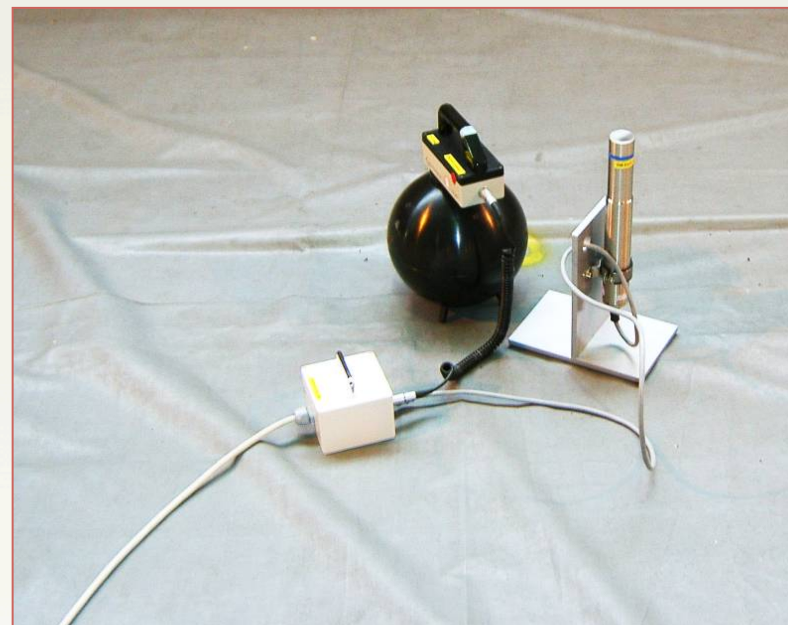
- 3 operators on shift for all PSI accelerators
- ~ 70k control channels for HIPA



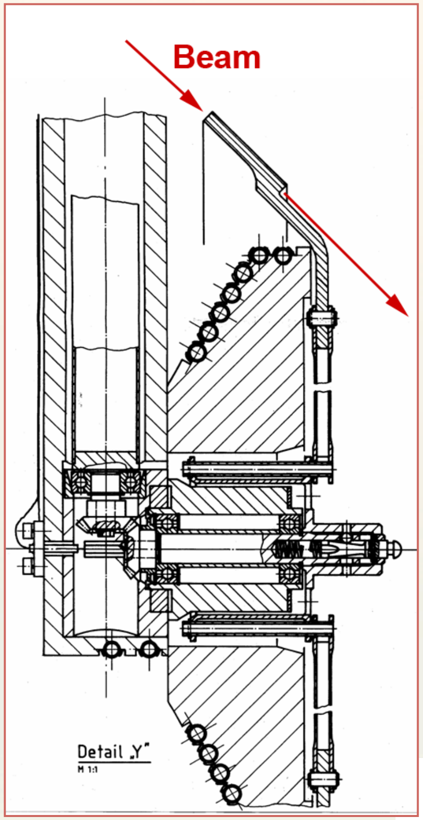
HIPA: Radiation Safety



- monitoring of radiation and personnel
- dose estimates and **work planning for service** in activated areas
- characterization of removed components
- ~100×TLD/CR39 dosimeters
- 12+4 remotely readable dosimeters
- 10 hand and foot monitors at exits
- ….

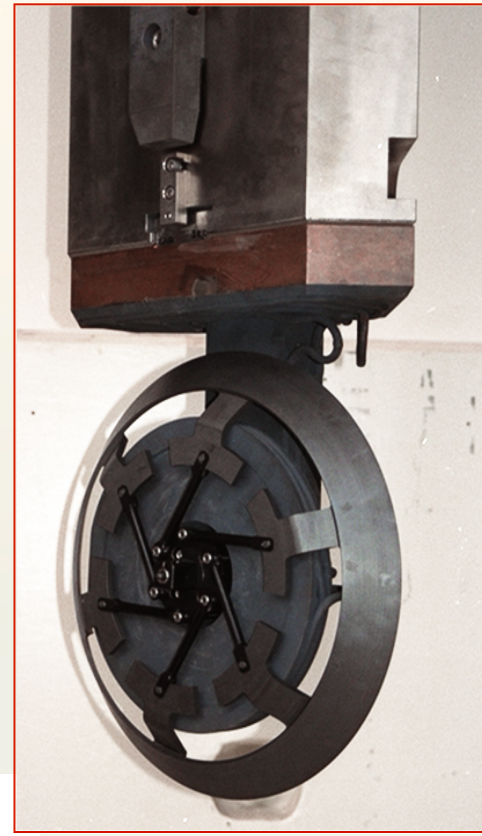


Meson Production Target

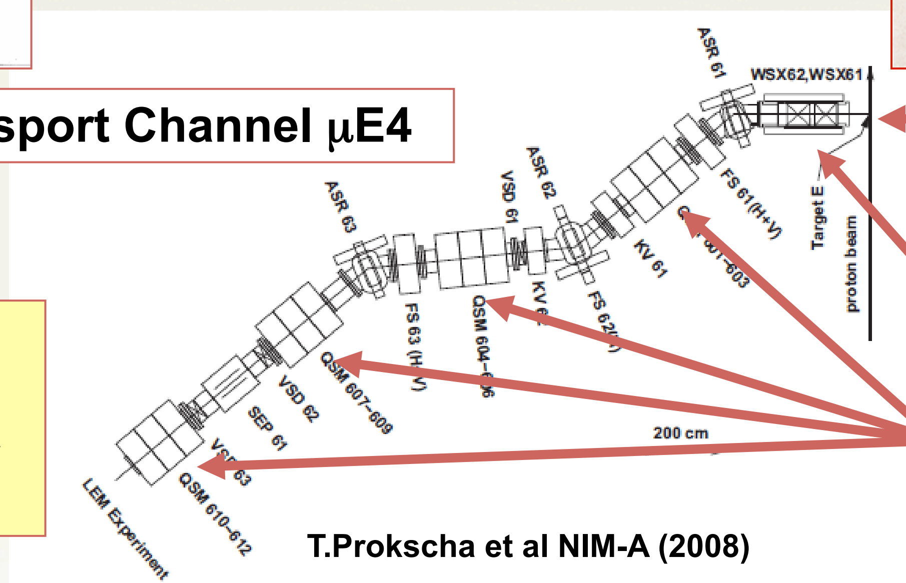


TARGET CONE

Mean diameter:	**450 mm**
Graphite density:	1.8 g/cm^3
Operating Temp.:	**1700 K**
Irrad. damage rate:	0.1 dpa/Ah
Rotation Speed:	**1 Turn/s**
Target thickness:	**40 mm**
	7 g/cm^2
Beam loss:	12 %
Power deposit.:	20 kW/mA



Muon Transport Channel μE4



T.Prokscha et al NIM-A (2008)

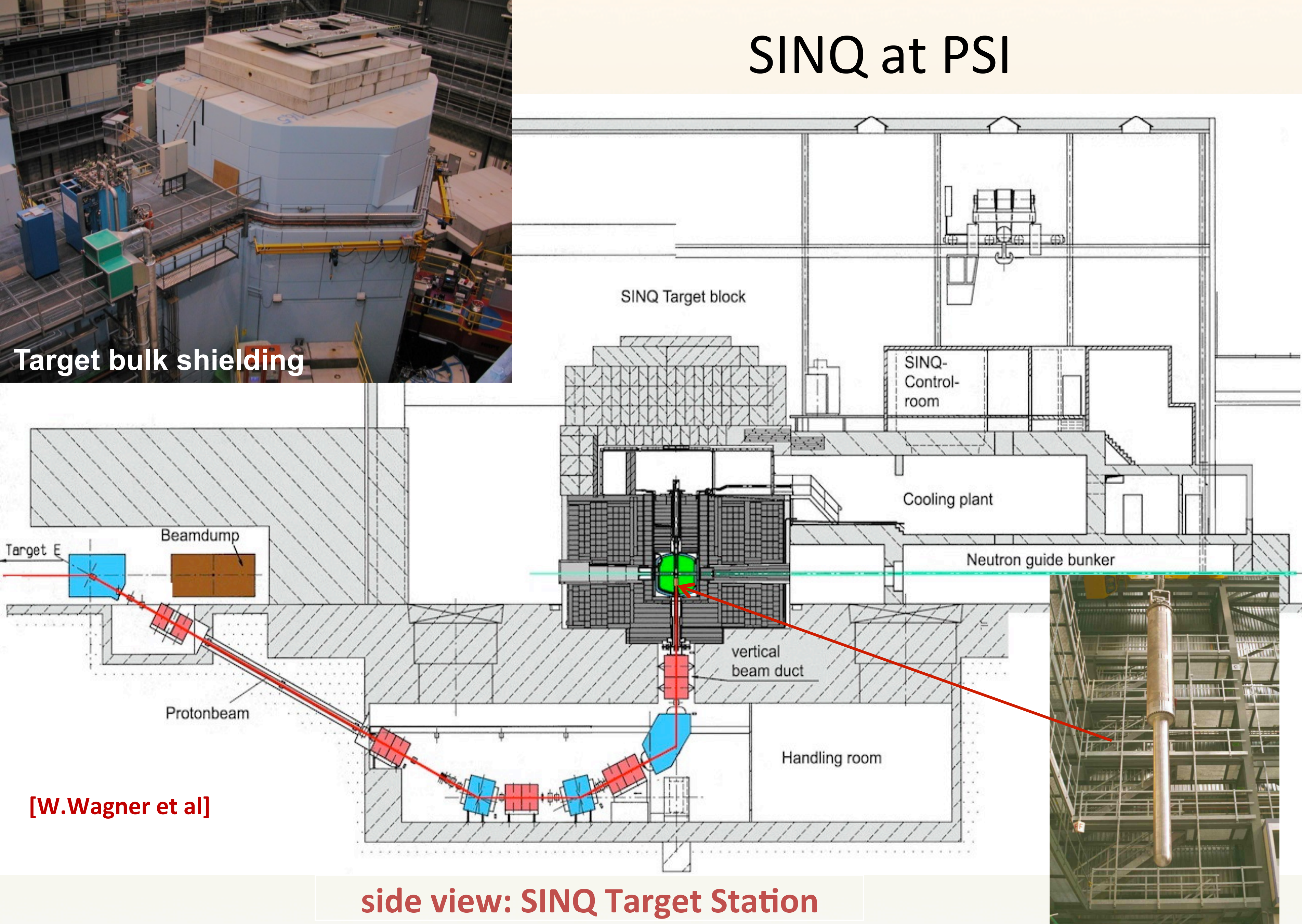
target, d=40mm

solenoids

quadrupoles

Muon Rate:
4.6E8 μ$^+$/sec
@ p=29.8 MeV/c

SINQ at PSI



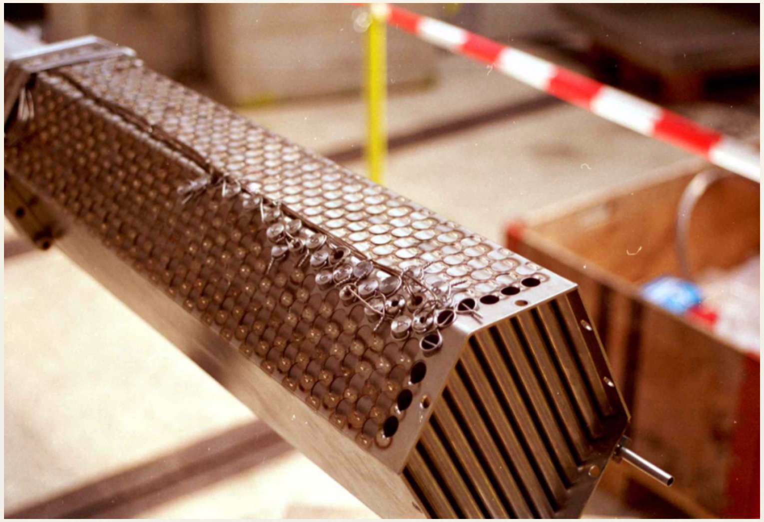
SINQ - Target

[W.Wagner et al]

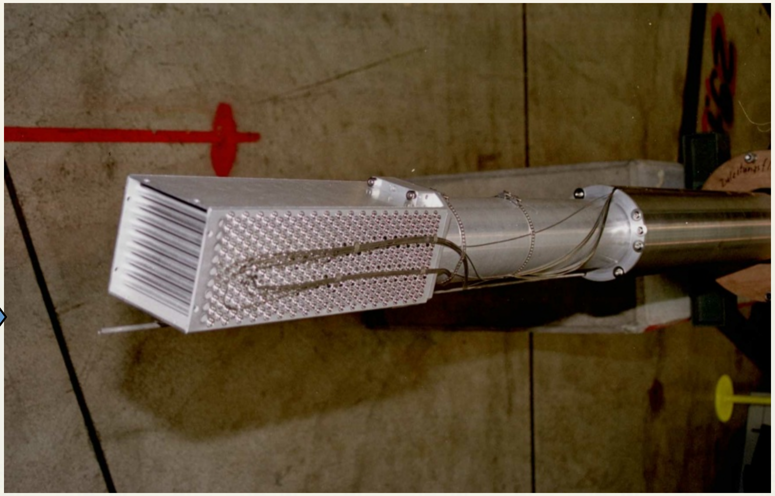
side view: SINQ Target Station

Target Evolution at SINQ

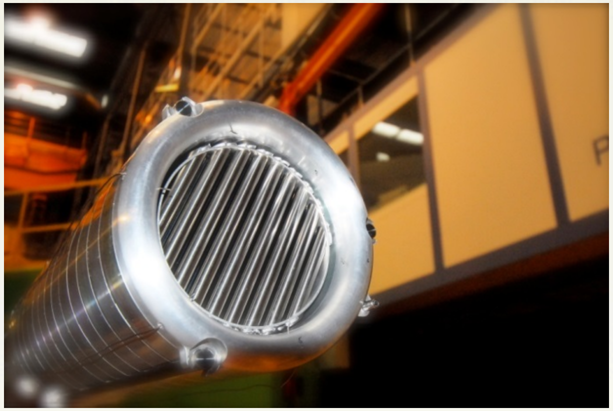
1997-1999: Target Mark I
Water-cooled Zircaloy rods



2000 - 2003:Target Mark II:
Lead rods, steel clad
42% increase in neutron yield



2004 – 2008:Target Mark III
hybrid Pb SS & Pb Zr-clad



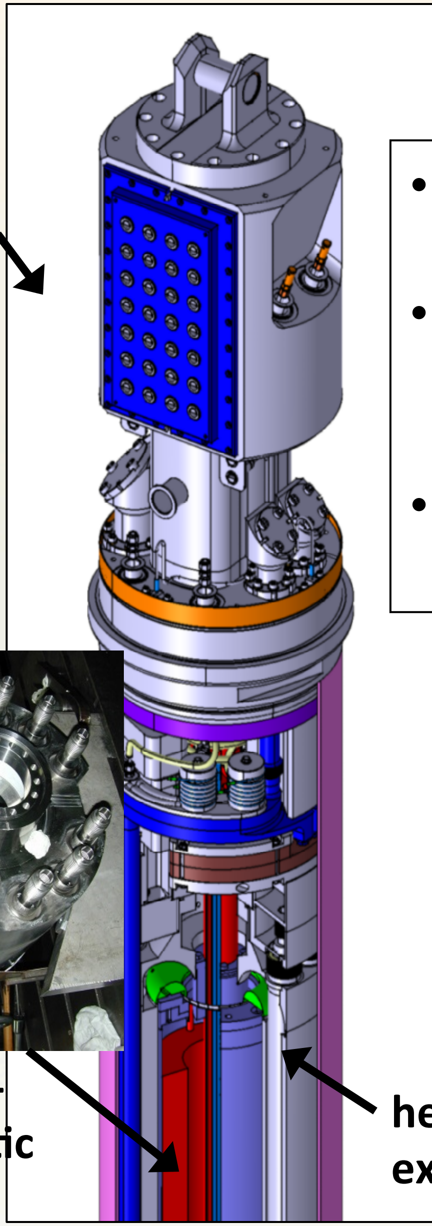
2009 – present: Target Mark IV
Lead rods, with Zr clad, blanket

Aug - Dec 2006: **MEGA**watt **Pi**lot **E**xperiment:
high performance liquid metal target, see next slide

MEGAPIE – Liquid Metal Target

- Lead-Bismuth-Eutectic (LBE), T_m=125°C
- in operation at PSI for 4 months in 2010 @ ≈1MW beampower
- factor 1.8 in neutron flux

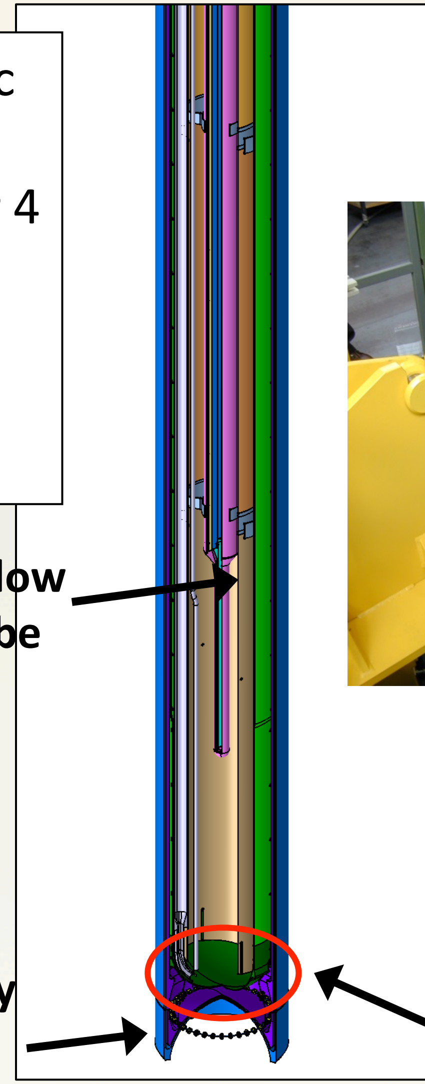
target head



electro-magnetic pumps

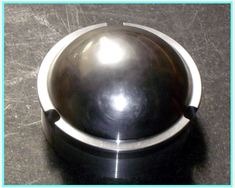
heat exchanger

central flow guide tube



safety hull

lower target assembly

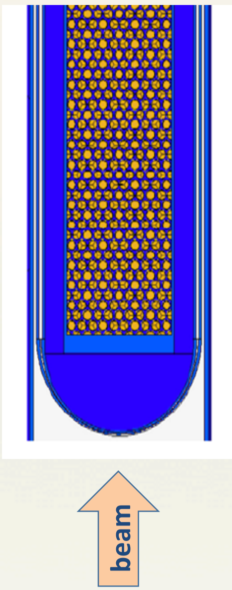


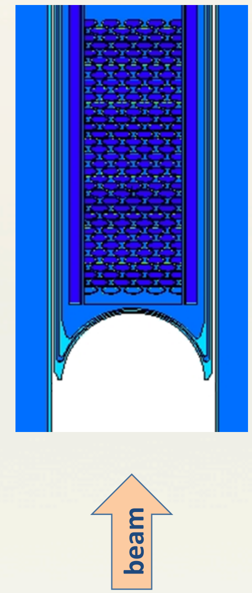
beam window

[M.Wohlmuther et al]

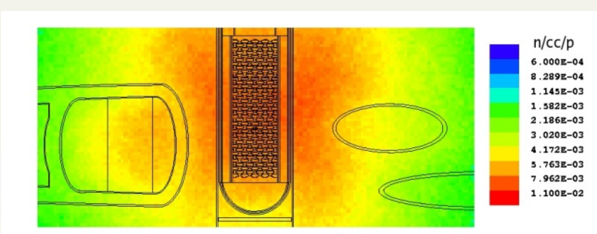
improved conversion efficiency of spallation target

old | **new**

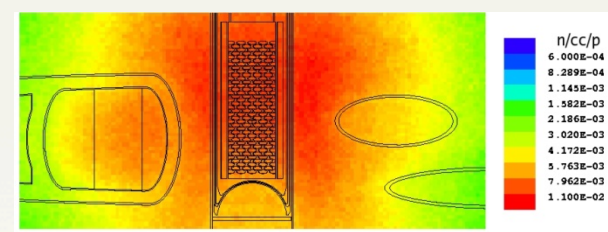




measure	**gain**
Zr cladding instead steel	**12%**
more compact rod bundle	**5%**
Pb reflector	**10%**
inverted entrance window	**10%**
total gain factor	**1.42**

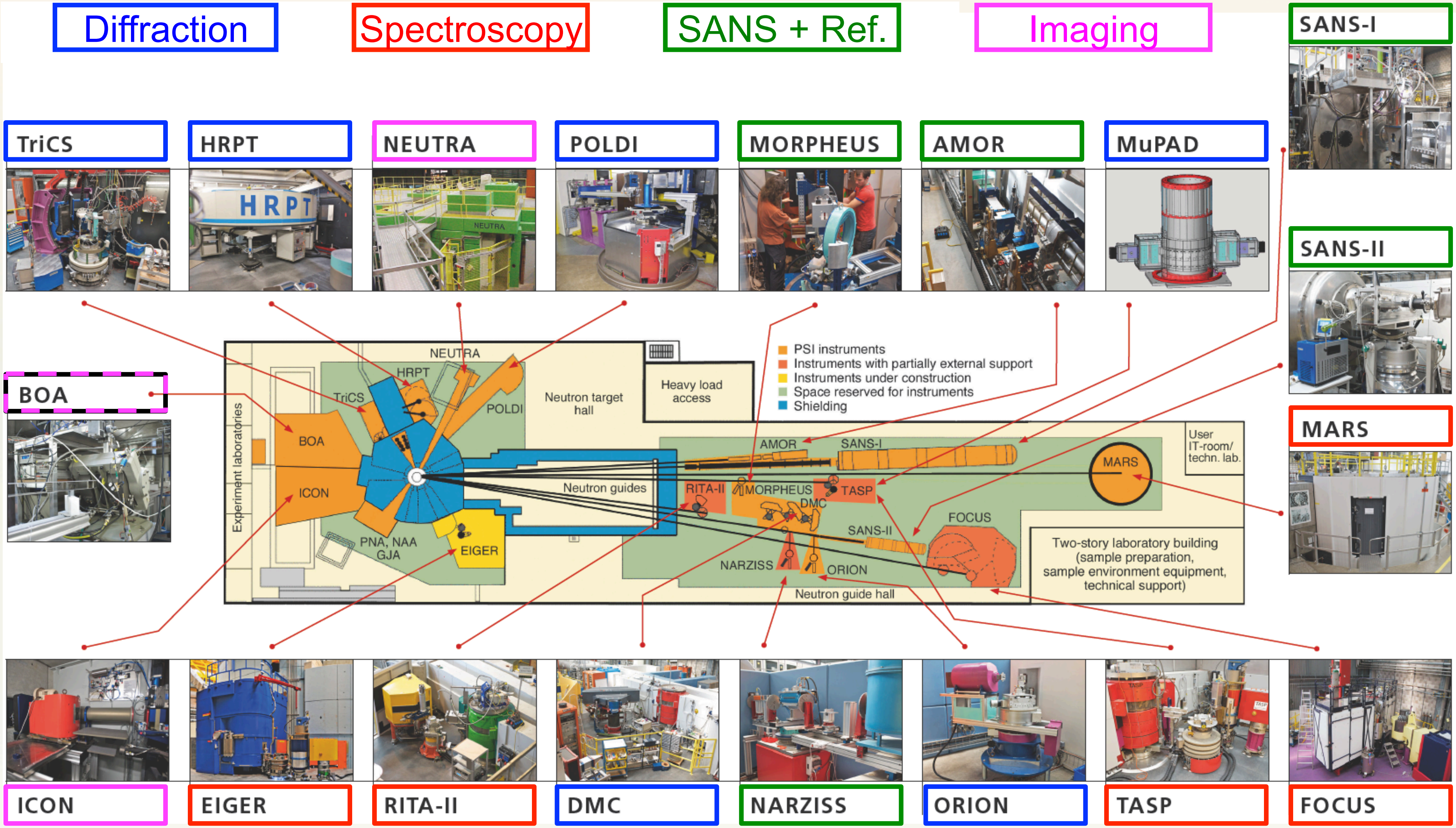


color code: neutron density on same scale (MCNPX)



[M.Wohlmuther, PSI]

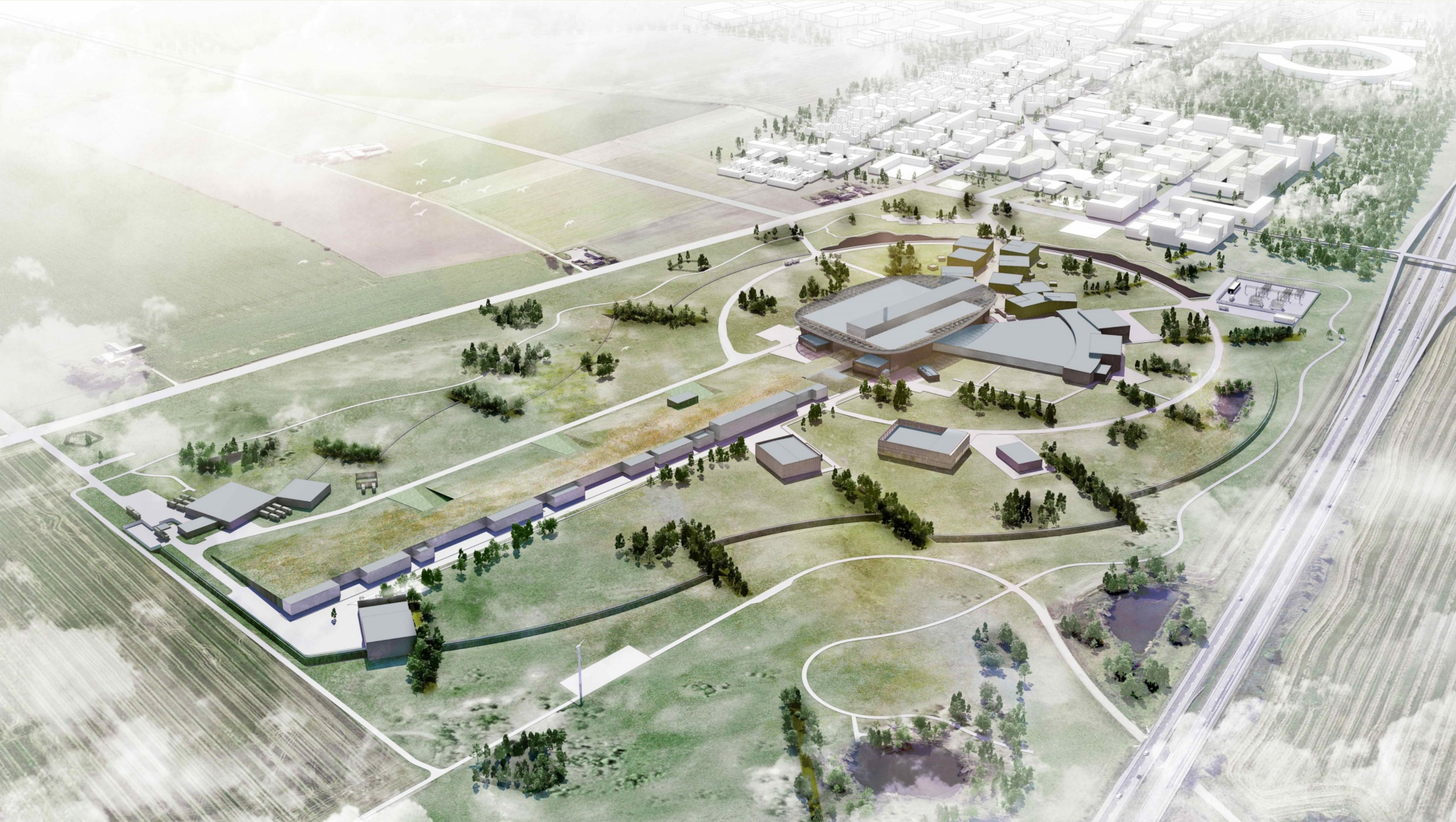
Spallation Neutron Source SINQ - Instruments

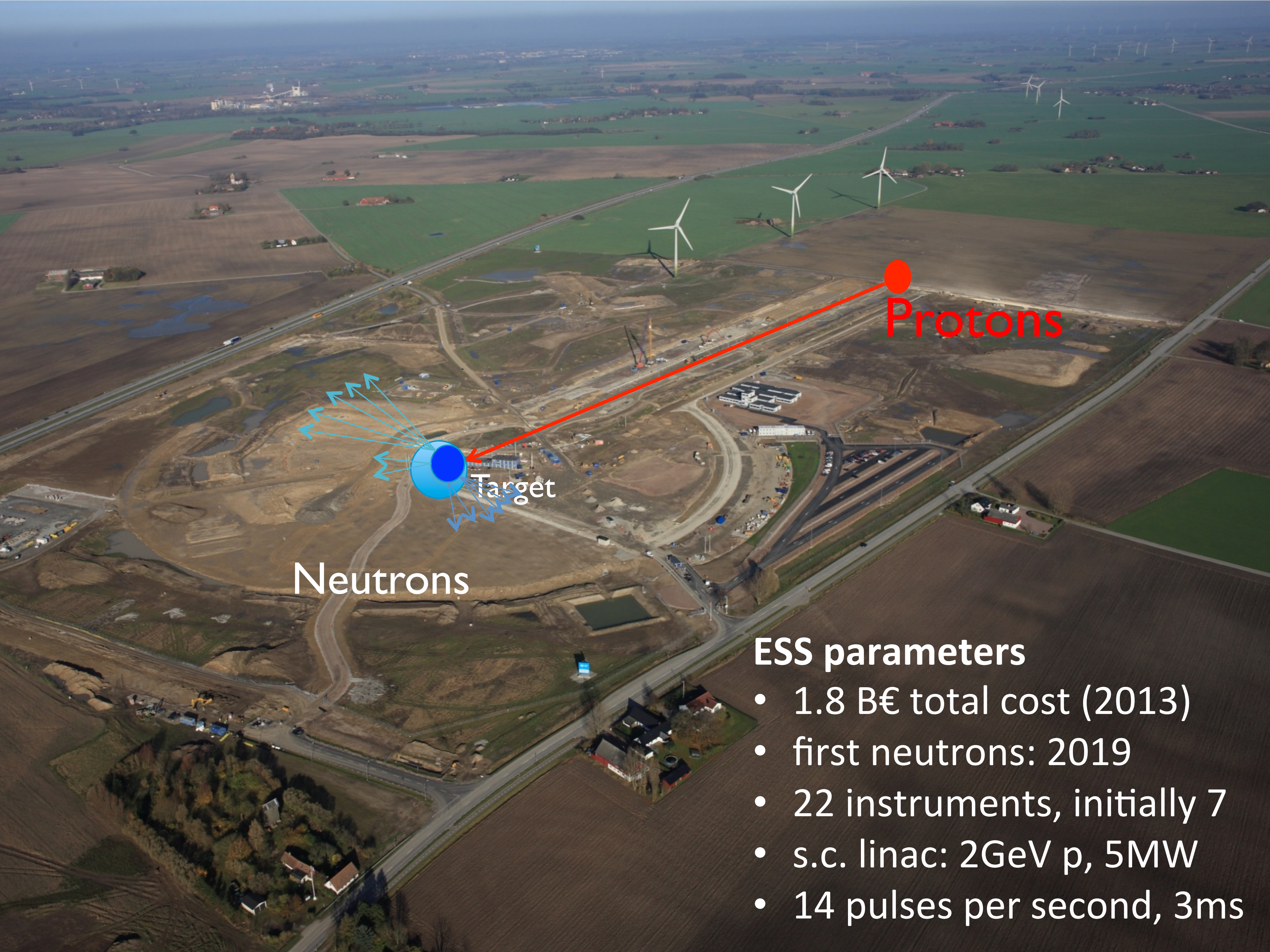


[Ch.Rüegg, PSI]

next: review of European Spallation Source (ESS)

key parameters, linac accelerator, target, schedule





ESS parameters

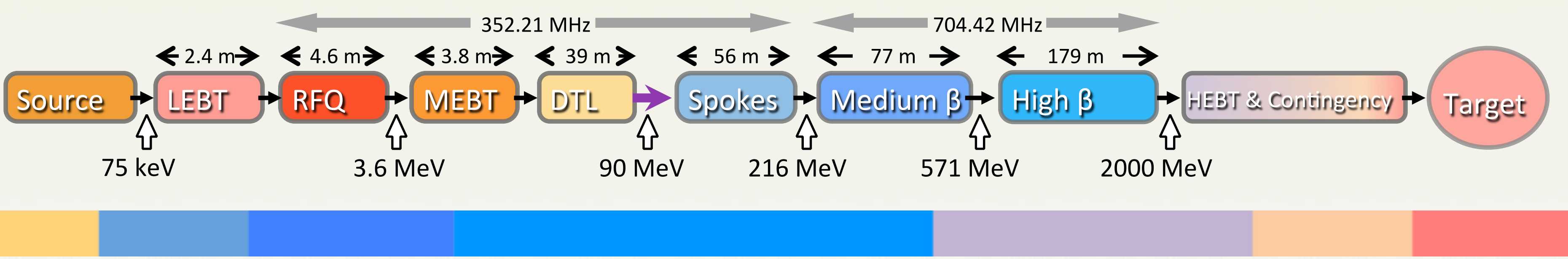
- 1.8 B€ total cost (2013)
- first neutrons: 2019
- 22 instruments, initially 7
- s.c. linac: 2GeV p, 5MW
- 14 pulses per second, 3ms

ESS: accelerator - a 5 MW SCRF linac

Design Drivers:

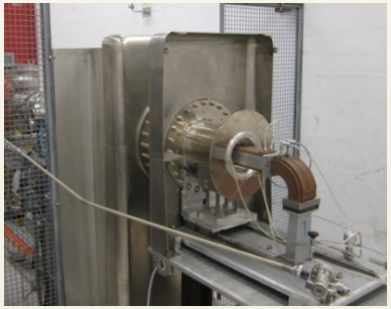
High Average Beam Power
5 MW
High Peak Beam Power
125 MW
High Availability
> 95%

Key parameters:
- -2.86 ms pulses
- -2 GeV
- -62.5 mA peak
- -14 Hz
- -Protons (H+)
- -Low losses
- -Minimize energy use
- -Flexible design for future upgrades

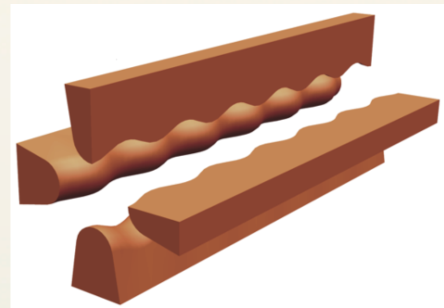


[M.Lindroos]

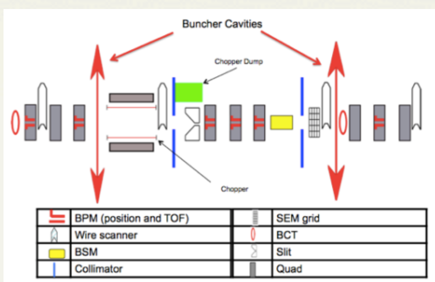
ESS: Ion Source and Normal-Conducting Linac



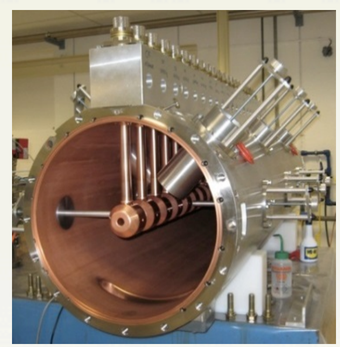
Prototype proton source operational, and under further development, in Catania. Output energy 75 keV.



Design exists for ESS RFQ similar to 5 m long IPHI RFQ at Saclay. Energy 75 keV->3.6 MeV.



Design work at ESS Bilbao for MEBT with instrumentation, chopping and collimation.



DTL design work at ESS and in Legnaro, 3.6 ->90 MeV.

Picture from CERN Linac4 DTL.

[M.Lindroos]

ESS: Cavity Prototypes

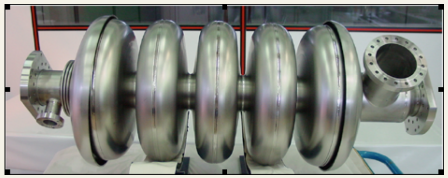
The 3 spoke cavities prototypes:

named: Romea, Giulietta and Germaine

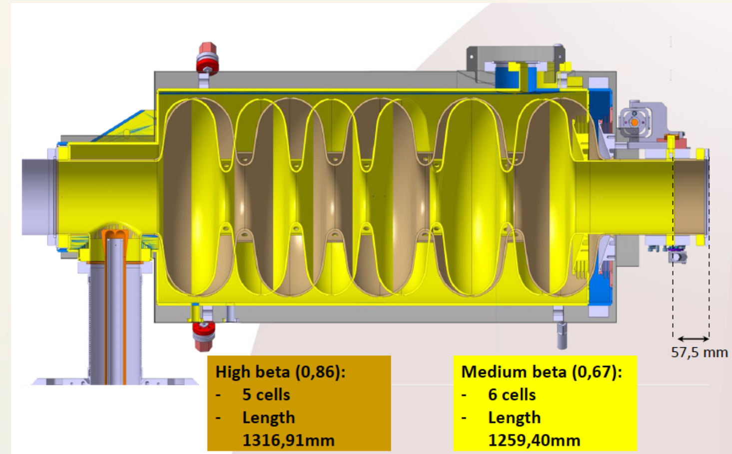
[M.Lindroos]

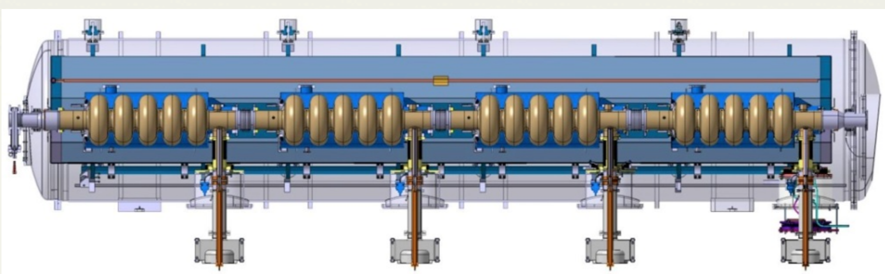
View of the cavity inside: the spoke bars

ESS: Elliptical Cavities and Cryomodules



Superconducting five-cell elliptical cavity (not ESS). Two families, for beta = 0.67, energy 216->561 MeV and beta = 0.86, energy 561->2000 MeV.





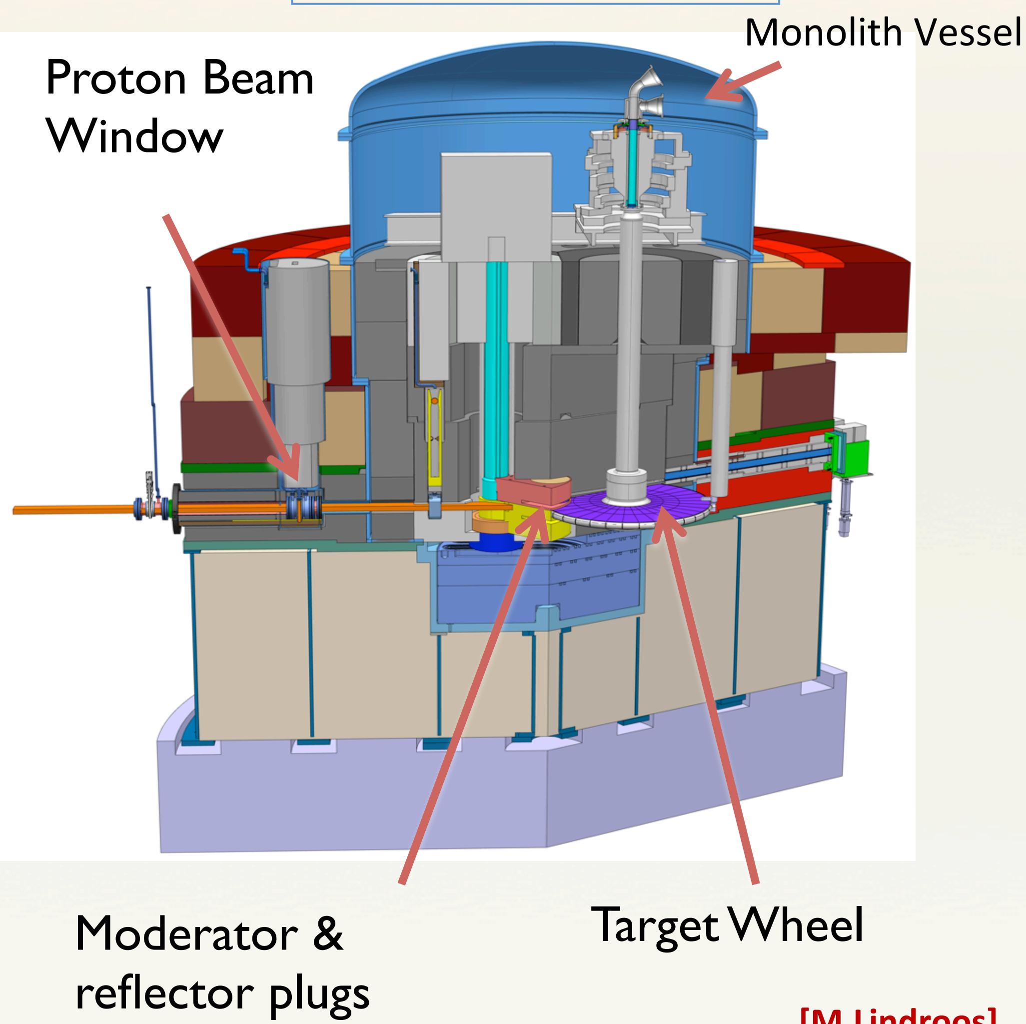
ESS elliptical cryomodule (not final) with 4 5-cell cavities and 4 power couplers for up to ~1 MW peak RF power.

[M.Lindroos]

ESS: Target Station

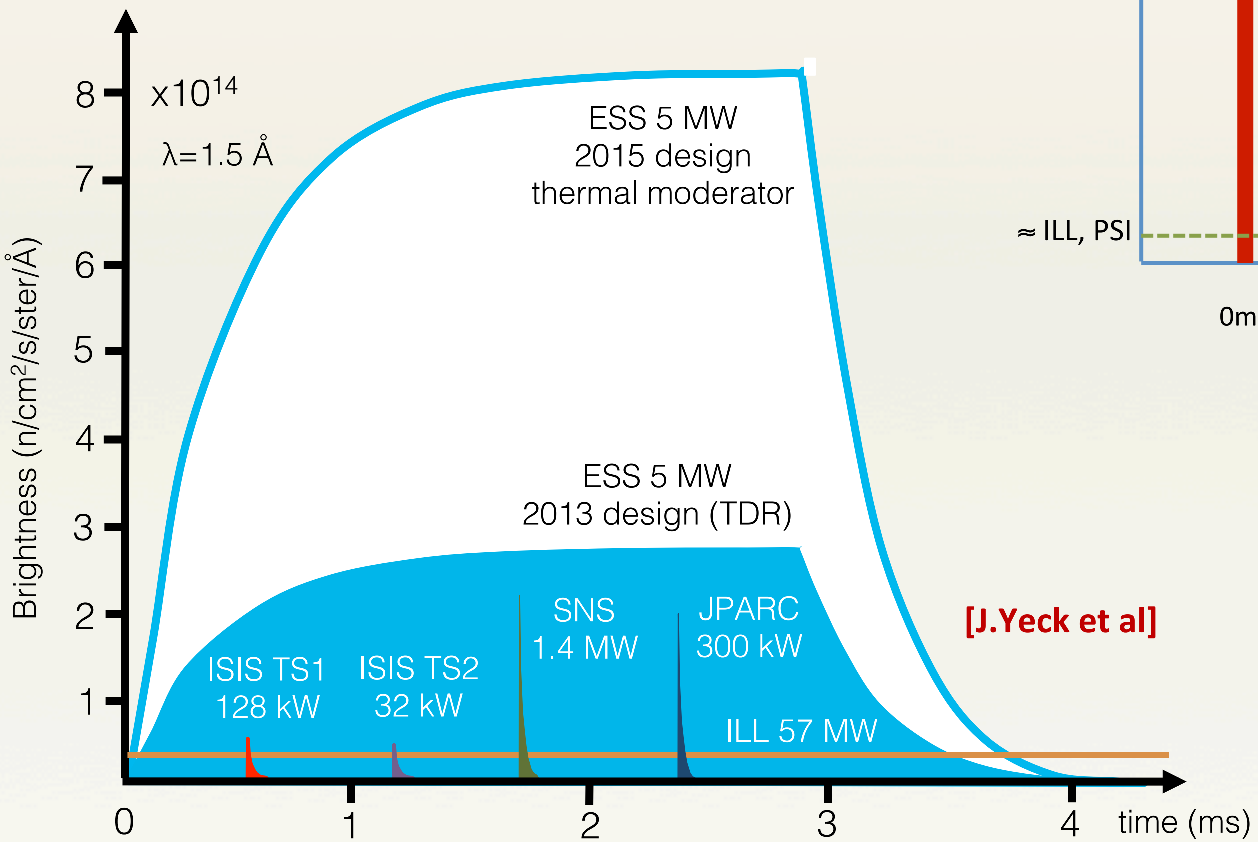
- rotating tungsten target
- helium cooling for target
- high brightness neutron moderators

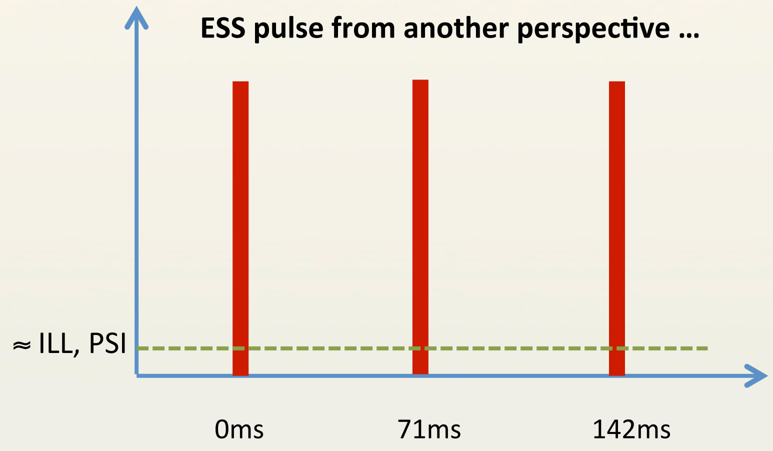
Target Monolith



[M.Lindroos]

ESS: Pulse Structure in comparison with other sources

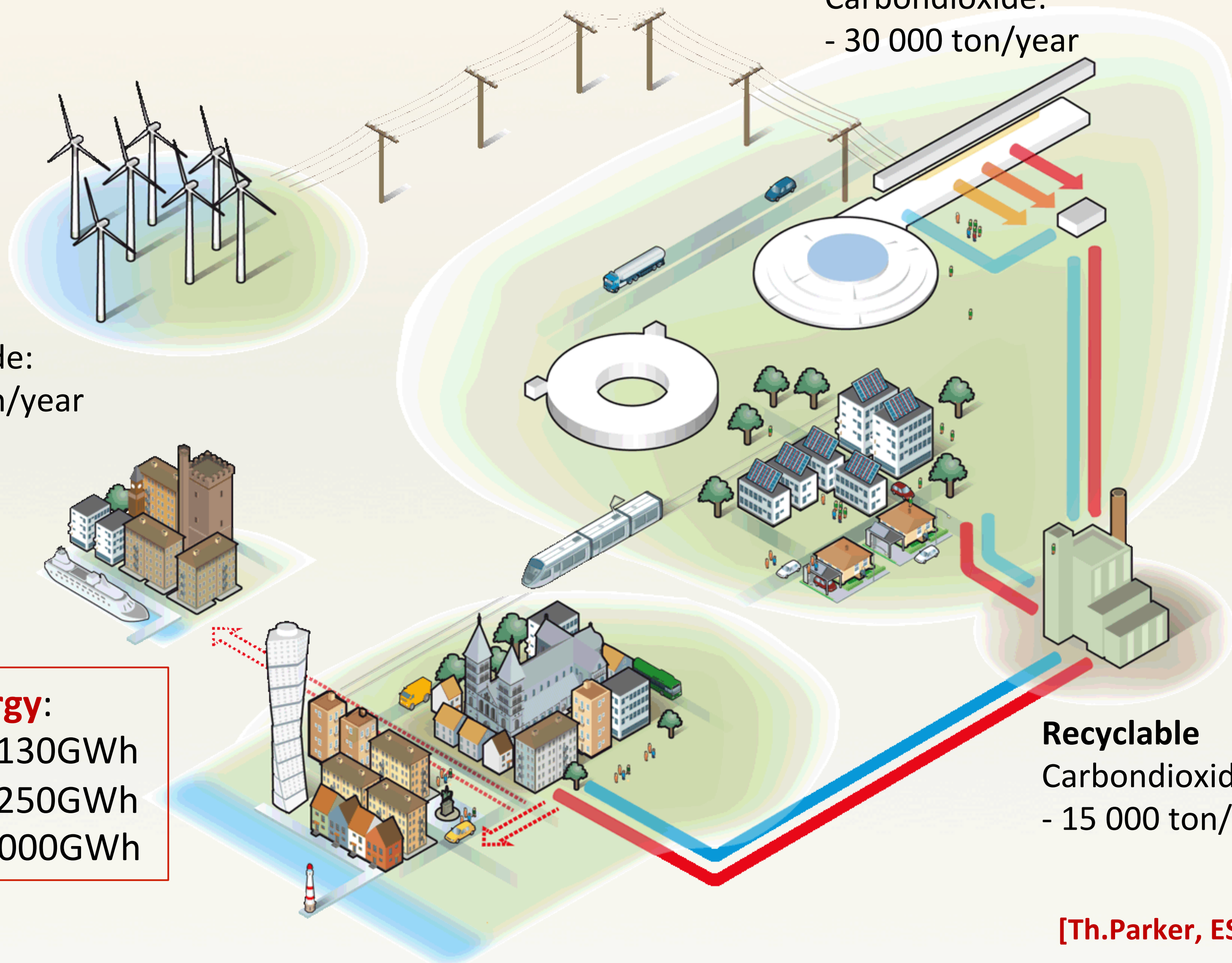




ESS: A sustainable research facility

Responsible
Carbondioxide:
- 30 000 ton/year

Renewable
Carbondioxide:
- 120 000 ton/year



Recyclable
Carbondioxide:
- 15 000 ton/year

yearly energy:

PSI tot.:	130GWh
ESS:	250GWh
CERN:	1000GWh

[Th.Parker, ESS]

summary

- accelerators = complex tools for basic research, reliability is more important than record intensity
- superconducting linacs, cyclotrons and synchrotrons (rapid cycling) can generate high beam intensity
- secondary radiation is used at multiple beamlines: Accelerator → Protons → Neutrons/Muons
- high beam power and high efficiency are important to offer a broad range of applications
- PSI-HIPA = continuous beam (like reactor), ESS+SNS = pulsed beam, each has specific applications


thank your for your attention !