Accelerators for ADS

Mike Seidel, PSI

Outline

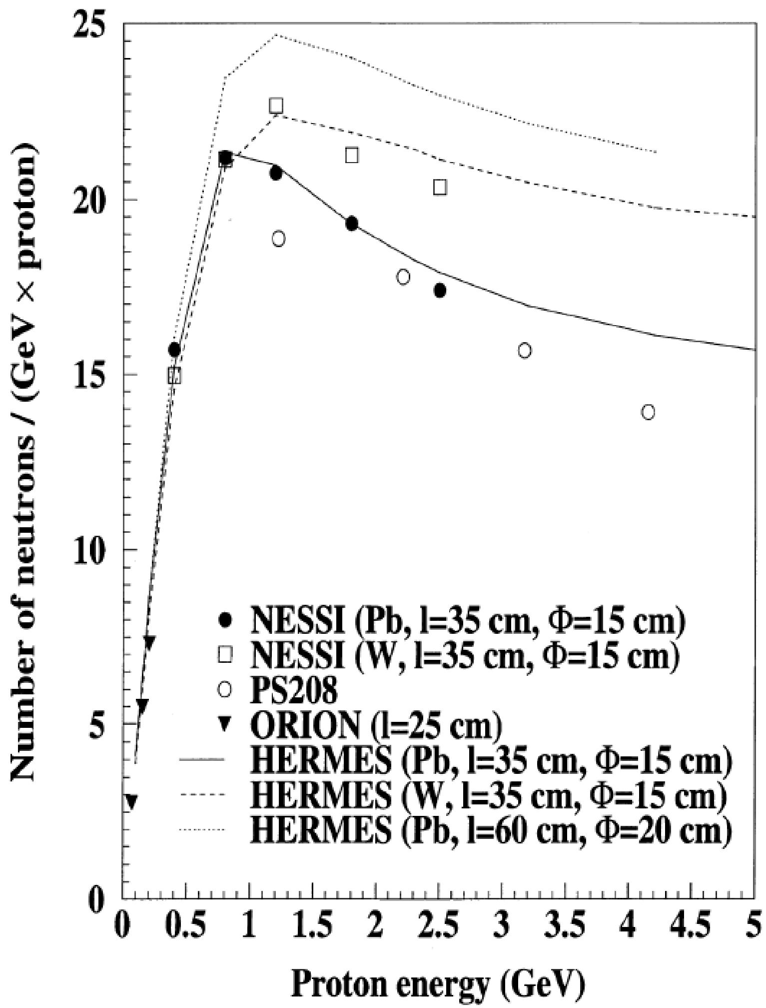
- Requirements for ADS Accelerators
  - power/energy, reliability/trip statistics, efficiency, size/cost
- Suited Accelerator Concepts
  - Sc.linacs, cyclotrons, rapid cycling synchrotrons, FFAG
- General High Power Aspects
  - technical/personnel safety, activation and service, legal requiremens and disposal
- Conclusion and Remarks
  - summary on Linear vs. Circular

Requirements for ADS Accelerators

- **energy**: flat optimum ≈1.2GeV; however 0.8 .. 2.5GeV under discussion
- **power**: 2...10MW; $P_{therm} = P_{beam} \times G/(1-k)$
- **low losses**: ≈ 1W/m; PSI: 100W at critical location
- **reliability**: 0.01...0.1 trips per day(!)
- **efficiency**: as best as possible, $\eta = P_{beam}/P_{grid}$= 20...30%
- **cost:** as low as possible; optimize for series production; modern nuclear power plant: O(5B€)

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:

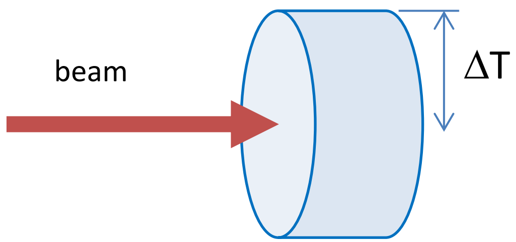
- LINACS: may be easier to achieve high power at higher energy, since throughput per RF-coupler is lower if Linac is longer
- CYCLOTRONS: need radius increase per turn for extraction; 1GeV seems feasible; 0.8GeV much better
- TARGET: geometrical aspects!; density, stopping power and dE/dV?; n-distribution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

Pulsed vs. CW

- targets with pulsed heating are challenging
- liquid targets suffer from cavitation; damage $\propto P^{3.5}$ (SNS studies)
- pulsed RF power generation is less reliable
- space charge effects are weaker in CW operation, since typ. bunch charge is much lower for same power

→ for ADS applications CW beams are preferential

Conceptual estimate for cyclic heating:



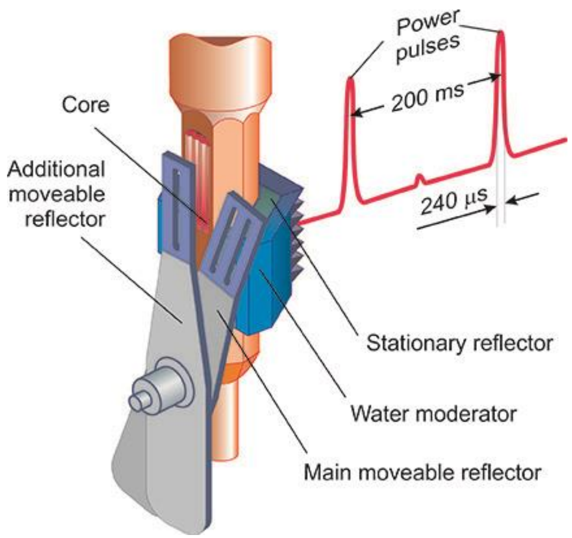
$$\sigma_{\mathrm{cyc}} = \frac{1}{2}\alpha E \Delta T$$

$Cu_{0.1}Mo$: ΔT_{max} = 200°C
$Ti_{15}Mo$: ΔT_{max} = 900°C

reliability, trip performance

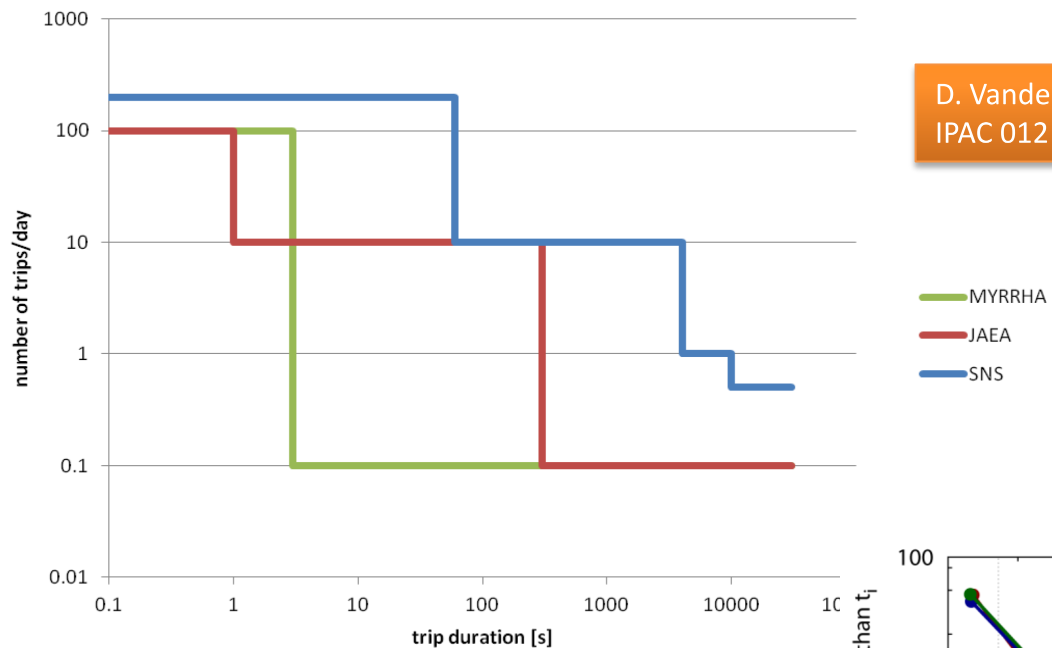
- todays trip performance of accelerators is orders of magnitude worse than desired for ADS, e.g 10…100d^{-1} achieved vs. 0.01…0.1d^{-1} desired by reactor experts
- in recent years discussions took place and requirements were somewhat relaxed:
  - fatigue failure of fuel elements is not seen extremely critical anymore
  - short trips (few seconds) can be accepted; shorter than thermal time constants
- accelerator and reactor developers must find compromises, my impression: reactor community in general not very flexible due to strict safety rules; e.g. studying fast reactor startup, bridging trips

IBR-2 pulsed reactor demonstrates fast cycling

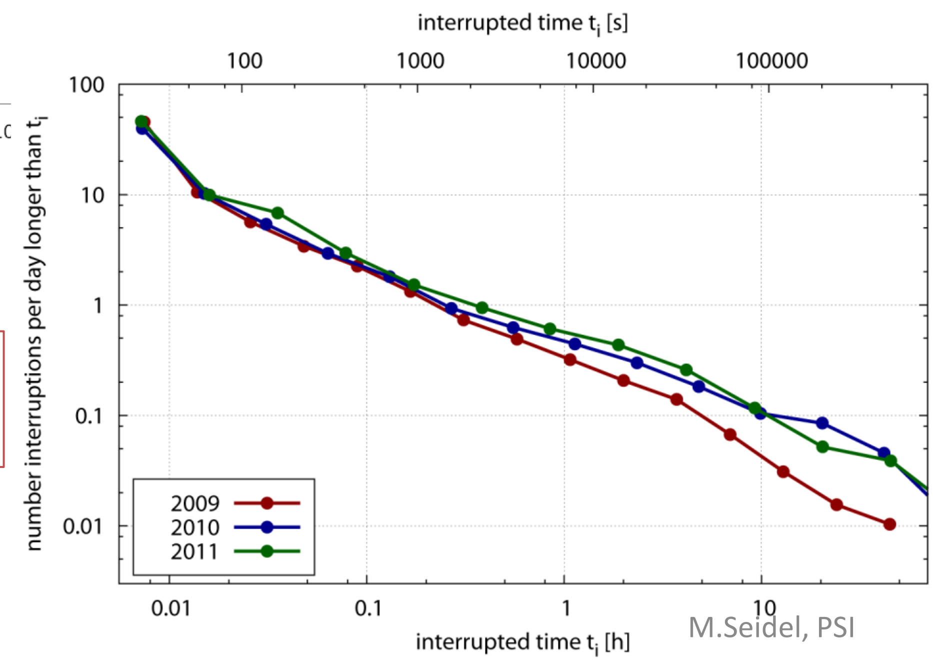


even without technical reasons, for industrial power production (and consumption) reliability is very important !

reliability, todays performance



D. Vandeplassche, Proc. IPAC 012



PSI analysis of trip-periods

reliability, concepts

- **conservative approaches** with all technical parameters, e.g. cavity gradients, amplifier rating, cooling reserves, dedicated diagnostics for monitoring minor failures, prophylactic maintenance [→ conventional reliability measures]
- **redundancy** and automatic readjustments; in Linac: cavity failure is compensated by redistribution of lost energy gain; with cyclic accelerator or injector: use more than one accelerator

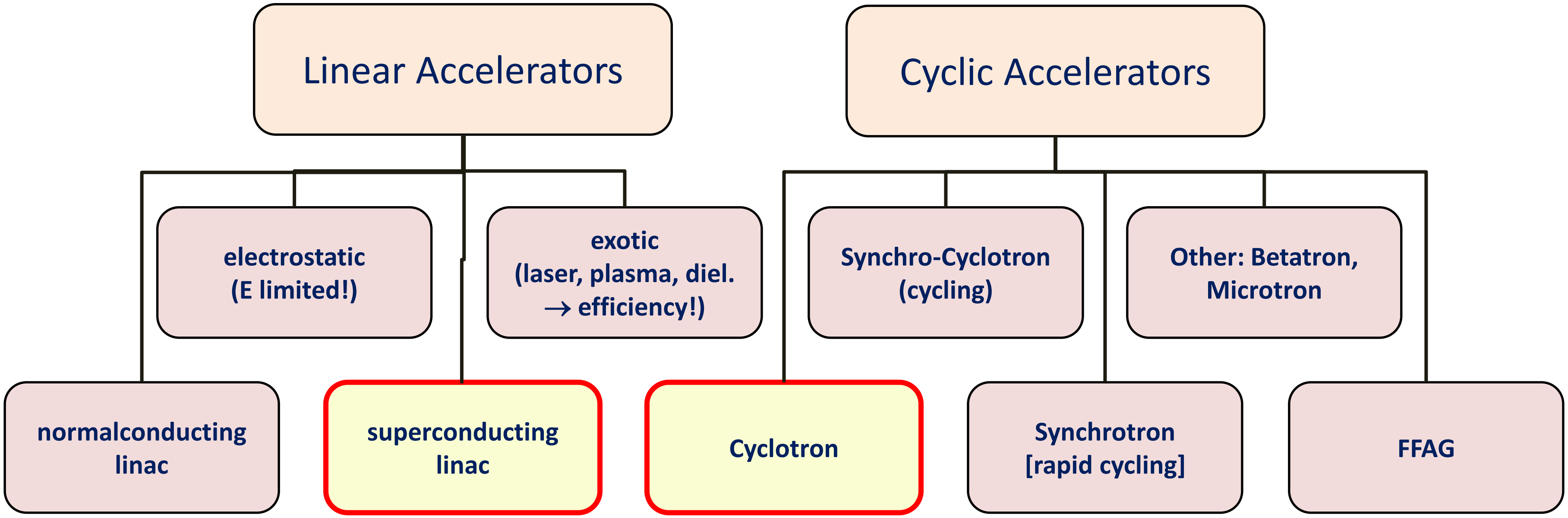
numerical example:
tube: MTBF=5000h; MTTR=8h

- Linac with 80 tubes, accepting 0 fault:
  $MTBF_{eff}$ = 62h
- Linac with 80 tubes, accepting 1$^{(k=2)}$ fault:
  $MTBF_{eff}$ = 1.074h
- Linac with 80 tubes, accepting 2 faults:
  $MTBF_{eff}$ = 26.067h
- cyclotron with 4 tubes, accepting 0 faults:
  $MTBF_{eff}$ = 1.250h

binomial distribution,
***B_p* = incomplete Beta Function**

$$P_{\mathrm{eff}} = \sum_{m=k}^{n} \binom{n}{m} p^m (1-p)^{n-k} = B_p(k, n-k+1)$$

Suited Accelerator Concepts?



- pulsed
- CW: very low gradient

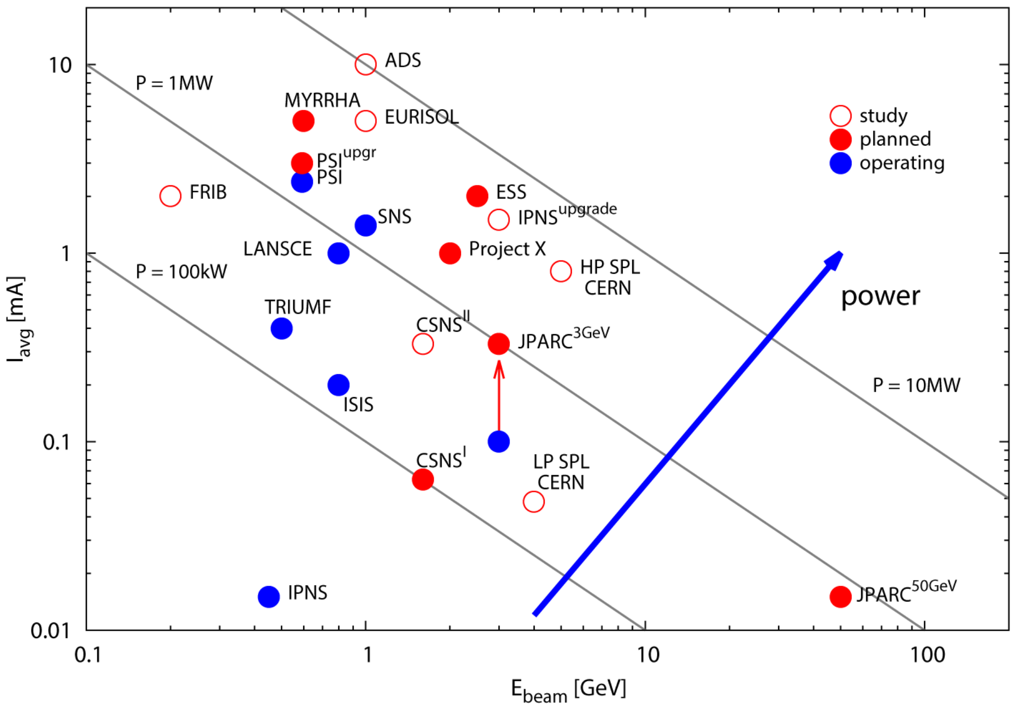
- CW possible
- cooling power!
- cost!

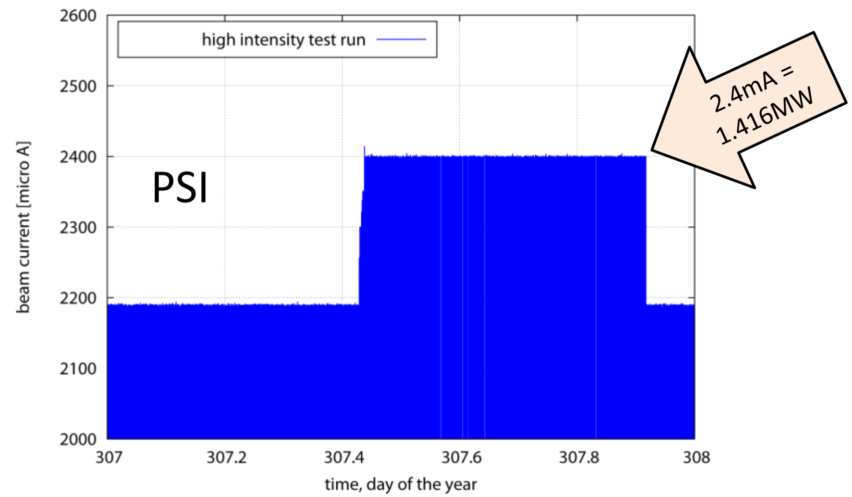
- CW possible
- beam dynamics!
- extraction!

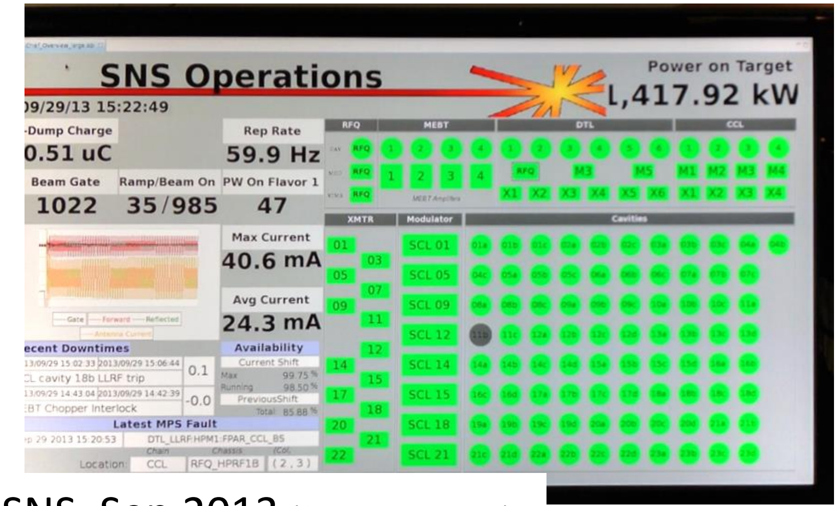
- pulsed
- power limited (1MW?)

- compact
- cycling / CW questionable
- no demonstrator

High Intensity Accelerator Landscape

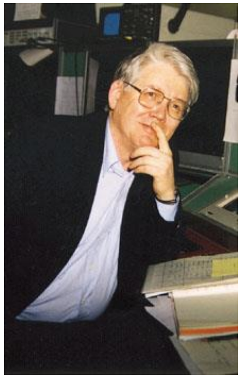






SNS, Sep 2013 (for limited time)

Superconducting Linac



[B.H.Wiik, †1999]

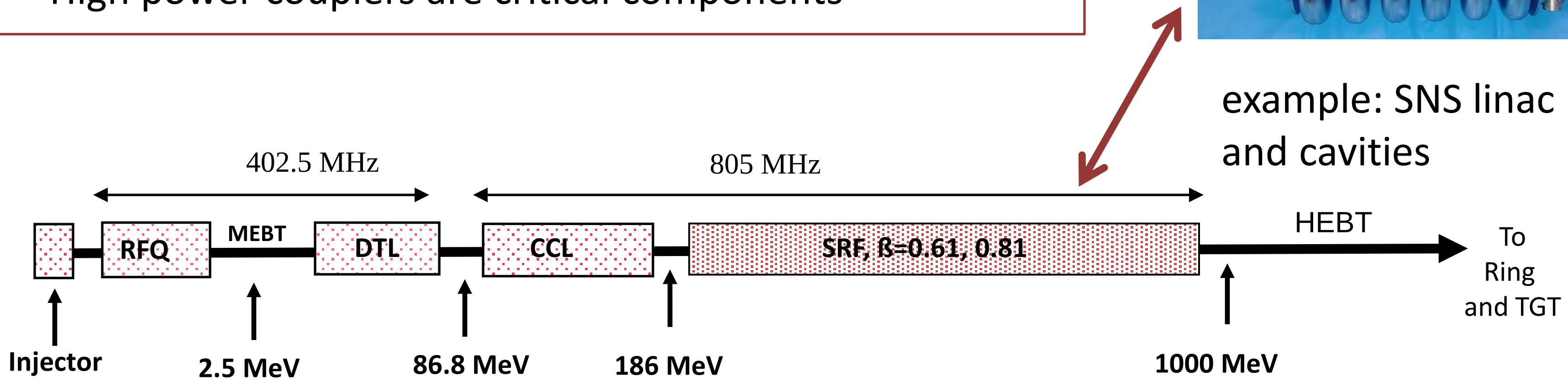
Why suited for high intensity accelerator?

- tremendous progress in technology over two decades! (DESY & TESLA collab.)
- high duty cycle of CW operation possible, because of small RF losses (beware efficiency, next slide)
- low beam impedance, thus large apertures possible; important for low losses
- efficient power transfer; no overhead power for structures and couplers

Disadvantages?

- Linac is lengthy object; choice of site; building; shielding
- Expensive and sensitive technology
- High power couplers are critical components

example: SNS linac and cavities



energetic efficiency of s.c. Linacs

- contrary to s.c. coils, s.c. resonators are not loss free
  nevertheless losses are low; numerical example for Q=10^{10}:
  a church bell with f = 500Hz would be damped by factor *e* after 8.5 months!

- losses are described by the surface resistance R_s with two components:

$$R_s = R_{\mathrm{BCS}}(T) + R_{\mathrm{res}}(H_{\mathrm{ext}}) \qquad Q_0 = \frac{\omega U}{P_{\mathrm{dissip}}} = \frac{G}{R_s}$$

- the relation between dissipated power and voltage is described through (R/Q):

$$\left(\frac{R}{Q}\right) = \frac{U_a^2}{P_{\mathrm{dissip}} Q}$$

- cooling power at room temperature is much higher due to Carnot efficiency

$$P_{\mathrm{cryo}} = \frac{P_{\mathrm{cold}}}{\eta_c \eta_p} \approx 700 P_{\mathrm{dissip}} @ 2\mathrm{K}$$

energetic efficiency of s.c. Linacs

numerical example for 1GeV Linac,
simplified: 100% single s.c. cavity type:

E_f	1 GeV
U_a per cavity (1m)	15 MeV
(R/Q)	1020Ω
Q	10^{10}
P_{dissip}	22W + 5W(static)
CoP(2K)	700
P_{cryo}	18.9kW
η_{RF}	55%
η_{tot}(1mA, P_{beam} = 1MW)	32%
η_{tot}(5mA, P_{beam} = 5MW)	48%

$$\eta_{\rm tot} = \frac{P_{\rm beam}}{P_{\rm RF} + P_{\rm cryo}}$$

[Advertisement]

Energy efficiency of particle accelerators –
a network in the European program EUCARD-2

coordinator: M.Seidel, PSI

network related to:

efficient and cost effective utilization of electrical power in accelerator based research facilities

http://www.psi.ch/enefficient

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

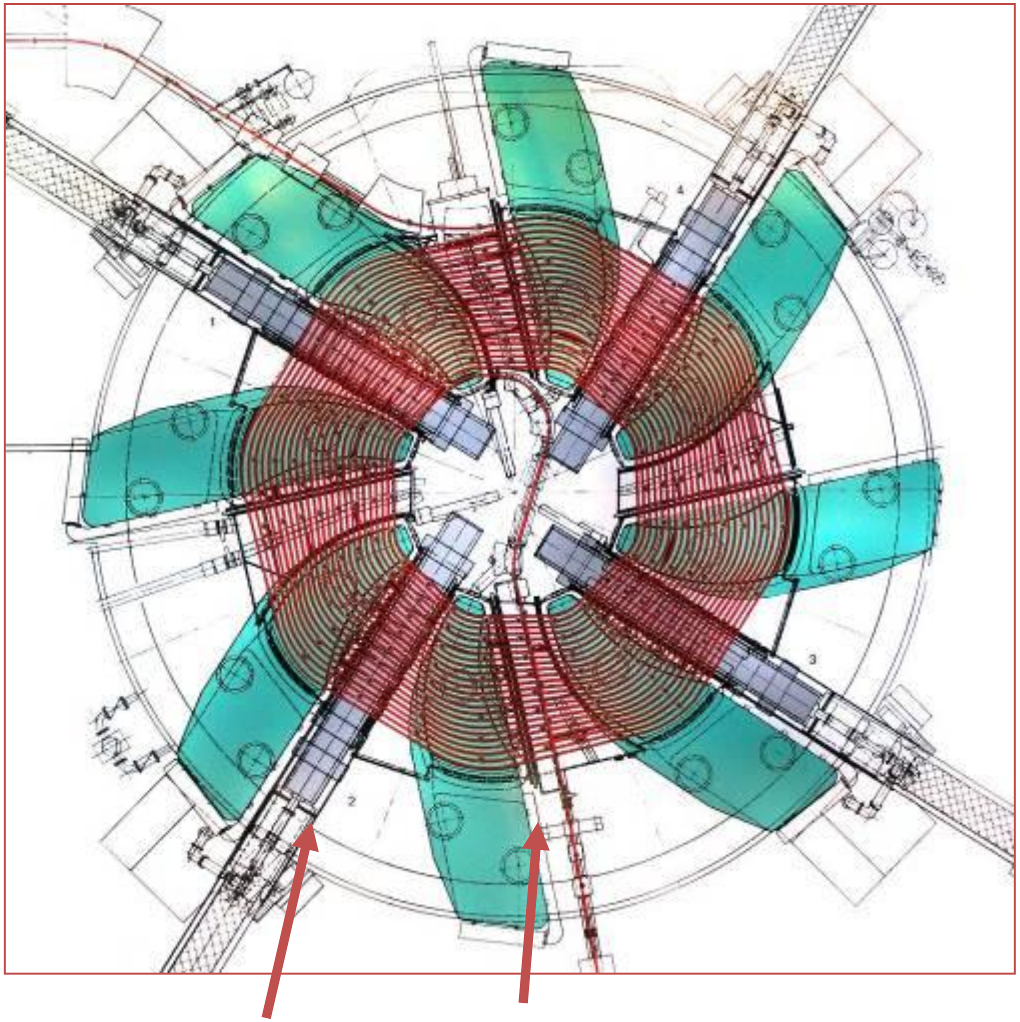
classification of circular accelerators

	bending radius	bending field vs. time	bending field vs. radius	RF frequency vs. time	operation mode (pulsed/CW)	comment
betatron						induction
microtron						varying *h*
classical cyclotron						simple, but limited E_k
isochronous cyclotron						suited for high power!
synchro-cyclotron						higher E_k, but low P
FFAG						strong focusing!
a.g. synchrotron						high E_k

Separated Sector Cyclotrons

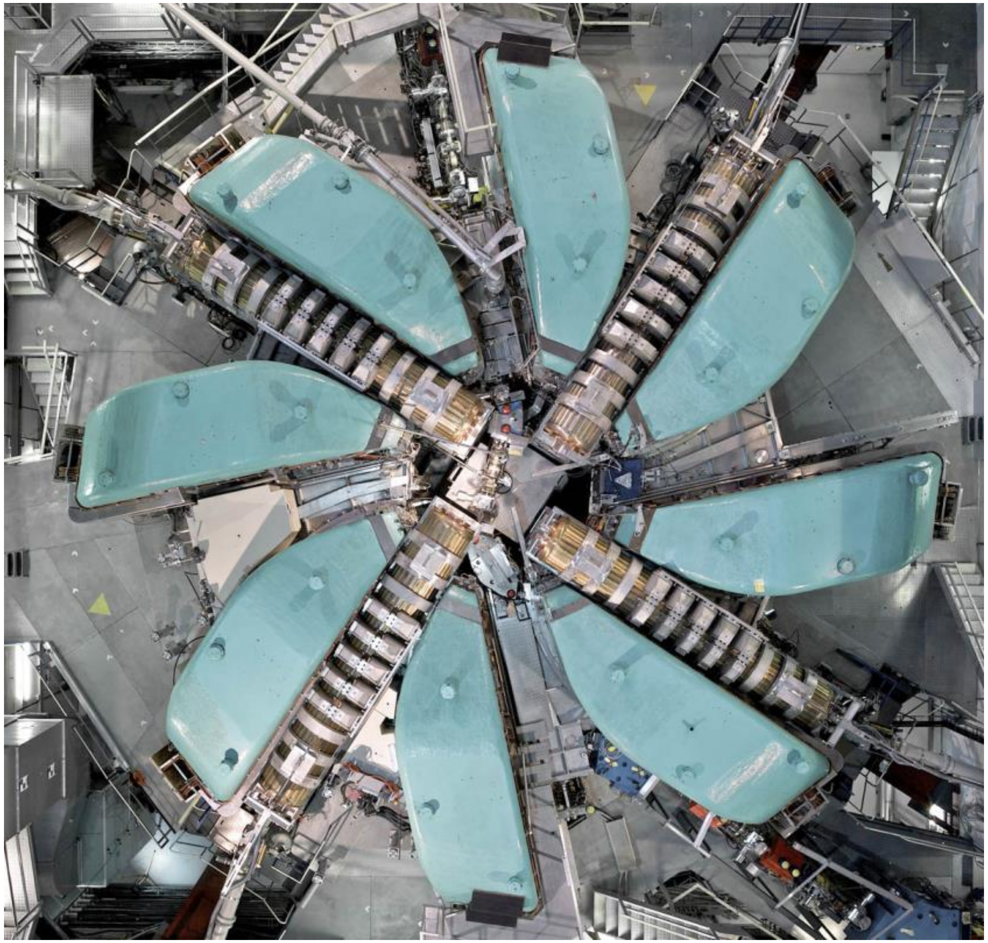
- **edge+sector focusing**, i.e. spiral magnet boundaries (angle ξ), azimuthally varying B-field (flutter F)
$Q_y^2 \approx -R/B\ dB/dR + F\ (1+2\cdot\tan^2(\xi))$
- **modular layout** (spiral shaped sector magnets, box resonators)
- **electrostatic elements** for extraction / external injection
- **radially wide vacuum chamber**; inflatable seals
- detailed **field shaping for focusing and isochronisity** required

- strength: **CW acceleration**; high **extraction efficiency** possible: 99.98% = $(1 - 2\cdot10^{-4})$
- limitation: **kin.Energy ≤ 1GeV**, because of relativistic effects



PSI Ring Cyclotron

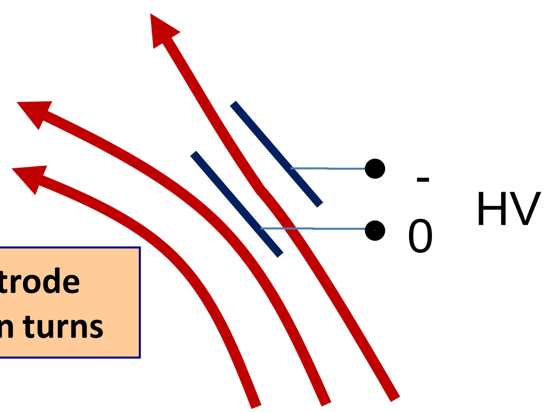
8 Sector Magnets:	1 T
Magnet weight:	~280 tons
4 Accelerator Cavities:	860 kV (1.2 MV)
1 Flat-Top Resonator	150 MHz
Accelerator frequency:	50.63 MHz
harmonic number:	6
kinetic beam energy:	72 → 590 MeV
beam current max.:	2.4 mA
extraction orbit radius:	4.5 m
outer diameter:	15 m
RF efficiency Grid/Beam	0.90×0.64×0.55 = 32%
rel. losses @ 2.2mA:	-~1..2·10^{-4}
transmitted power:	0.32 MW/Res.



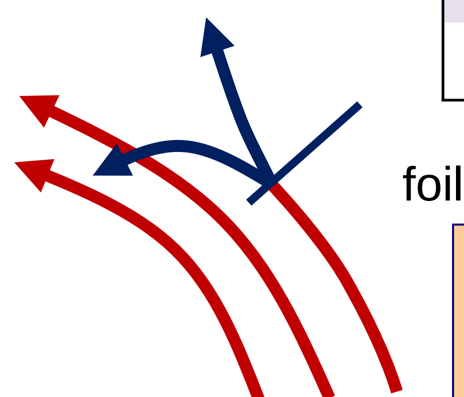
critical: injection/extraction schemes

- deflecting element should affect just one turn, not neighboured turn → critical, cause of losses
- often used: electrostatic deflectors with thin electrodes
- alternative: charge exchange, stripping foil; accelerate H^- or H_2^+ to extract protons (problem: significant probability for unwanted loss of electron; Lorentz dissociation: B-field low, scattering: vacuum 10^{-8}mbar)

binding	**energies**
H^-	H_2^+
0.75eV	15eV



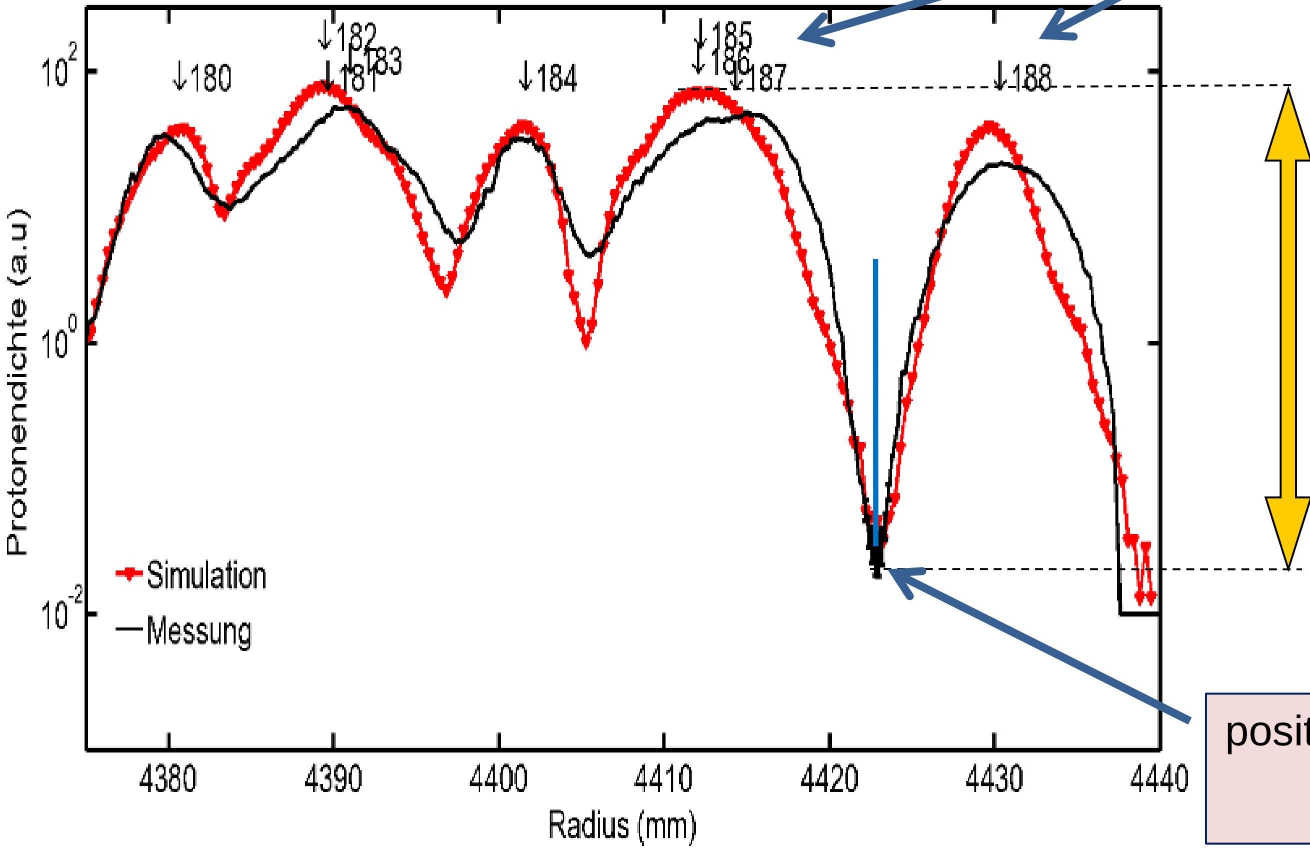
extraction electrode placed between turns



extraction by charge exchange in foil
eg.: $H^- \rightarrow H^+$
$H_2^+ \rightarrow 2H^+$

extraction profile measured at PSI Ring Cyclotron

red: tracking simulation [OPAL]
black: measurement



turn numbers

from simulation

dynamic range:
factor 2.000 in
particle density

position of extraction septum

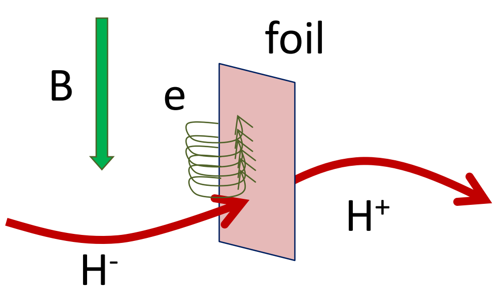
d=50µm

[Y.Bi et al]

issues with extraction foil

- thin foil, e.g. C, removes the electron(s) with high probability and brings the ion on a new trajectory → separation from circulating beam
- lifetime of foil is critical due to heating, fatigue effects, radiation damage
- conversion efficiencies, e.g. generation of neutrals, in case of H_2^+ the excitation of long living excited modes must be considered carefully

electrons removed from the ions spiral in the magnetic field and may deposit energy in the foil



How much power is carried by the electrons?

→ velocity and thus γ are equal for *p* and *e*

$$E_k = (\gamma - 1)E_0$$

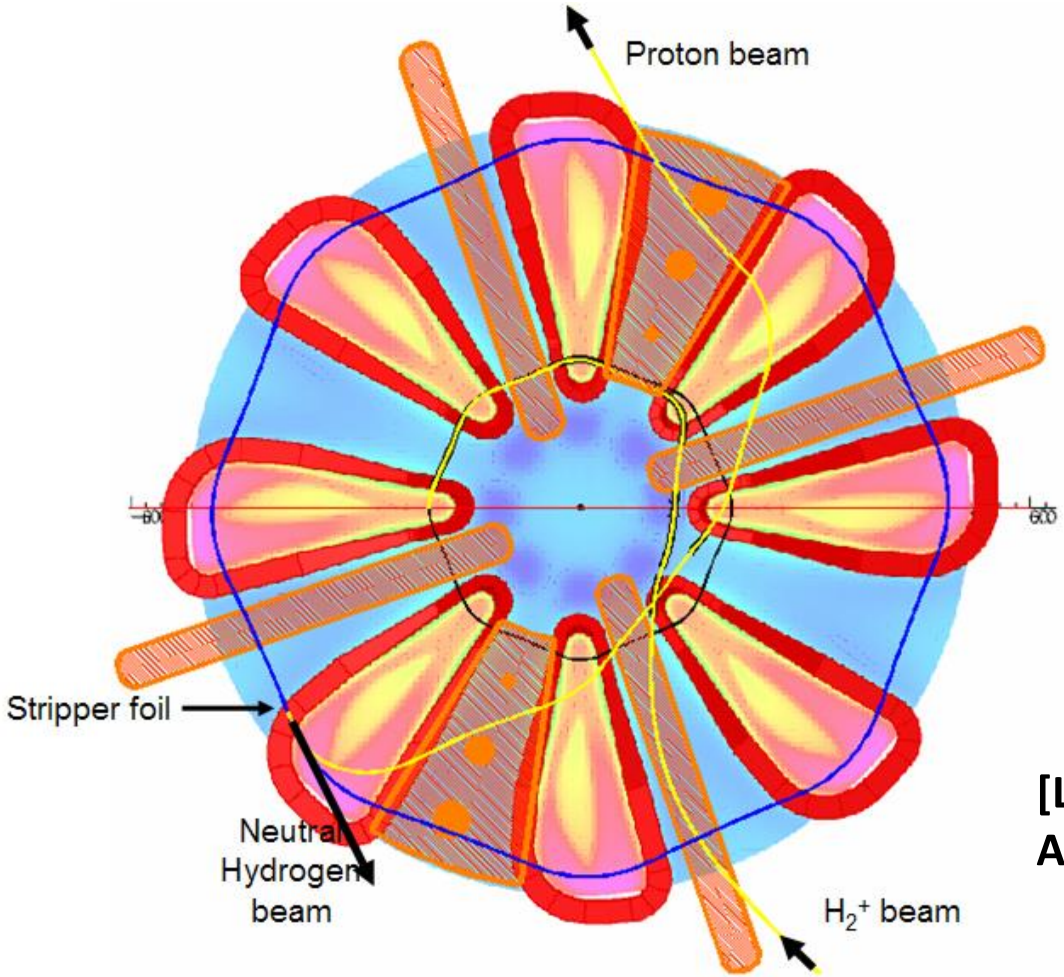
$$\rightarrow E_k^e = \frac{E_0^e}{E_0^p} E_k^p = 5.4 \cdot 10^{-4} E_k^p$$

Bending radius of electrons?

$$\rho^e = \frac{E_0^e}{E_0^p} \rho^p$$

→ typically mm

ideas I: H_2^+ Daedalus cyclotron [neutrino source]



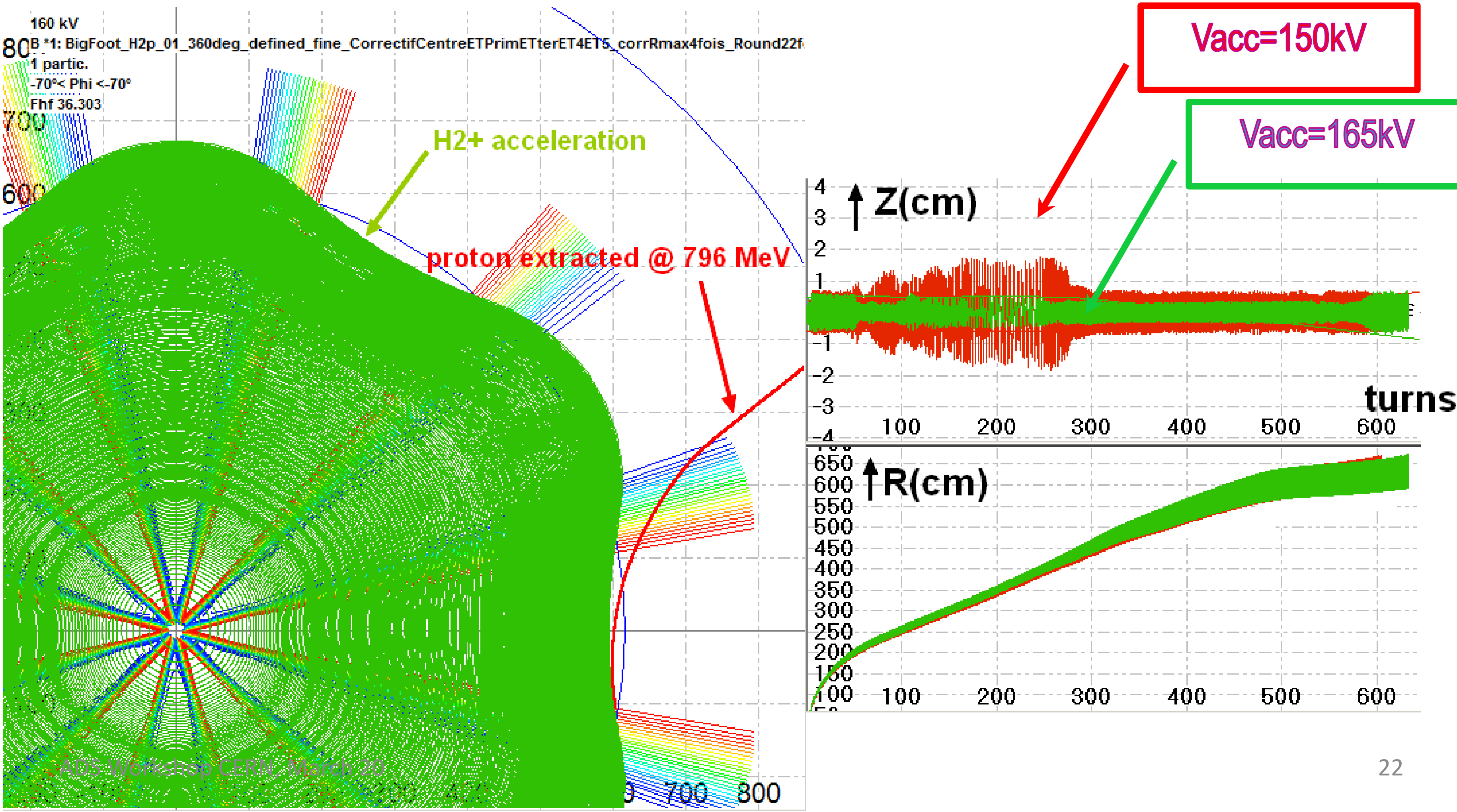
purpose: pulsed high power beam for neutrino production

- 800MeV kin. energy
- 5MW avg. beam power

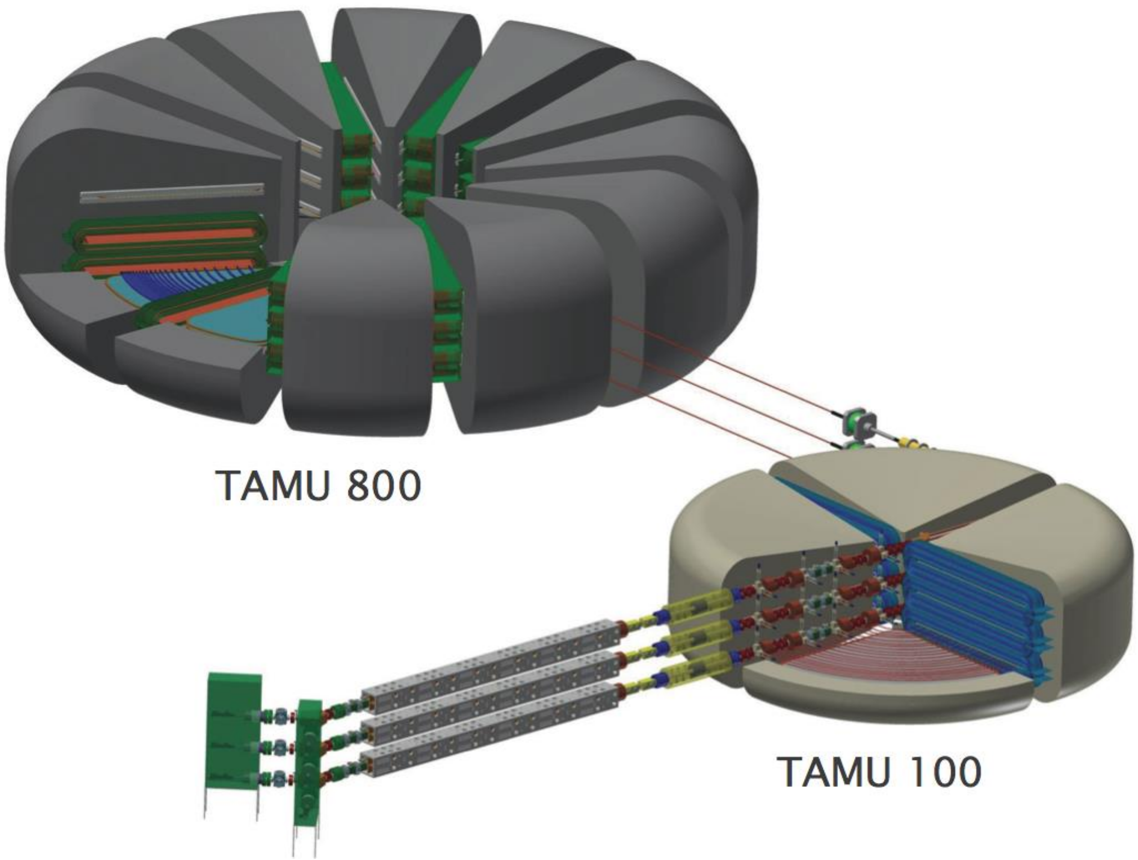
[L.Calabretta, A.Calanna et al]

ideas II: H_2^+ AIMA Cyclotron w reverse bend and multiple 60keV injection [P.Mandrillon]

The reverse valley B-field concept avoids the internal loop (cf. DAEdALUS extraction) for the stripped proton beam from H2+.



ideas III: TEXAS A&M: 800 MeV SUPERCONDUCTING STRONG-FOCUSING CYCLOTRON

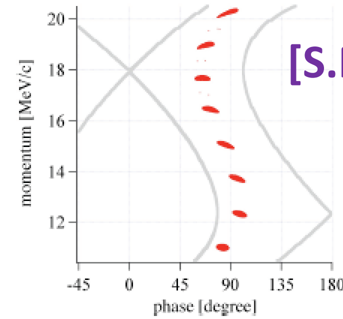


[P.McIntyre, Texas A&M]

- Two Stages Cyclotron: 100 MeV SF injector + 800 MeV SF booster.
- Stack of 3 Cyclotrons in //
- Booster: 12 Flux coupled stack of dipole magnet sectors
- 10 Superconducting 100 MHz RF cavities providing a 20 MeV Energy Gain/turn
- multiple power couplers per cavity
- Large turn separation allowing to insert SF beam transport channels made of Panofsky Qpoles (G=6T/m)

ideas IV: FFAG Serpentine channel acceleration

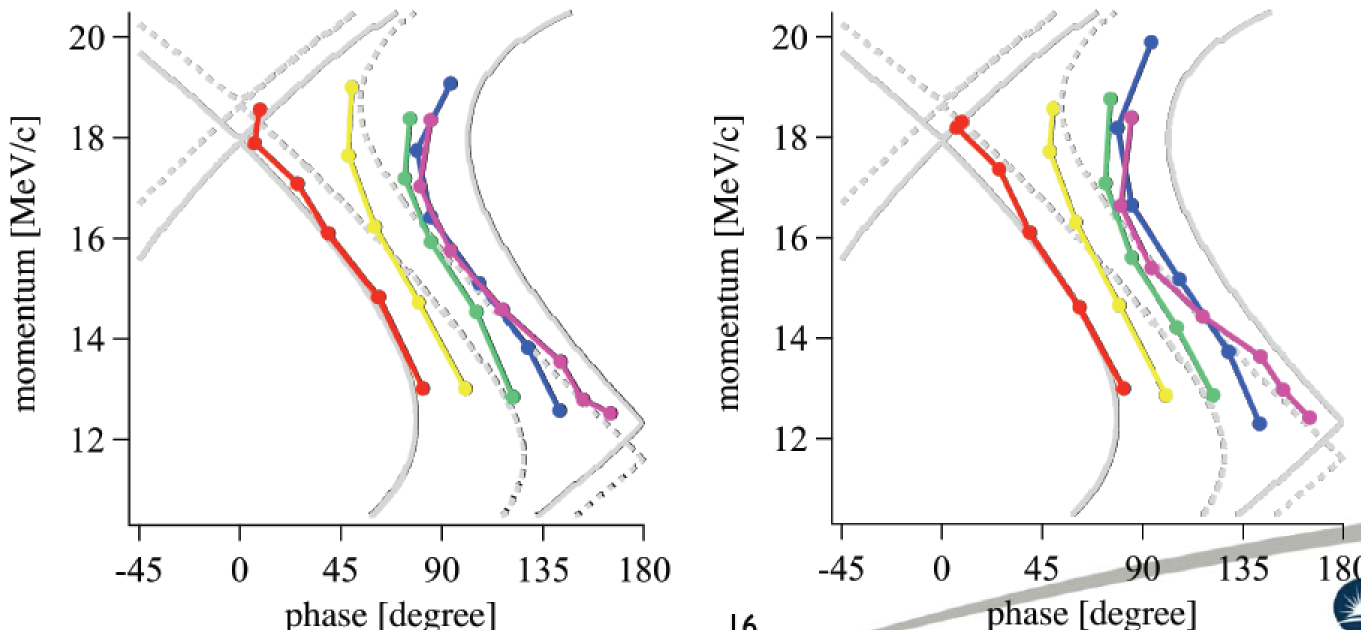
Serpentine channel acceleration outside rf bucket



[S.Machida: FFAG, EMMA]

Highlight 2

Longitudinal trajectory measured experimentally.



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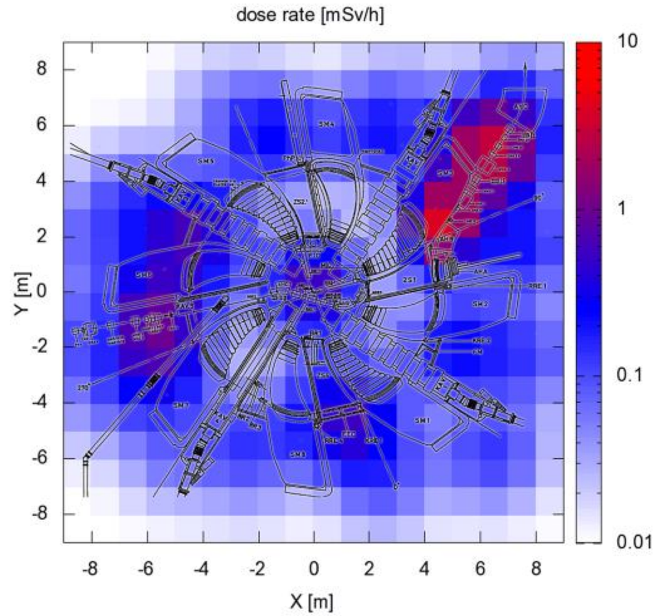
Science & Technology Facilities Council

next: comments about general challenges of high power operation

The Challenge of High Power

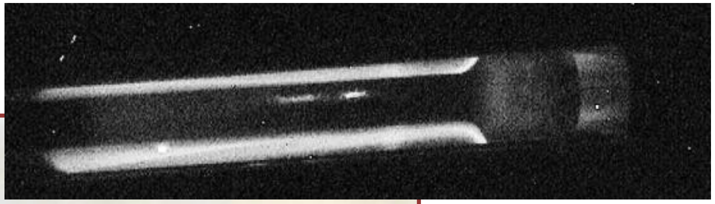
main activation at extraction of Ring

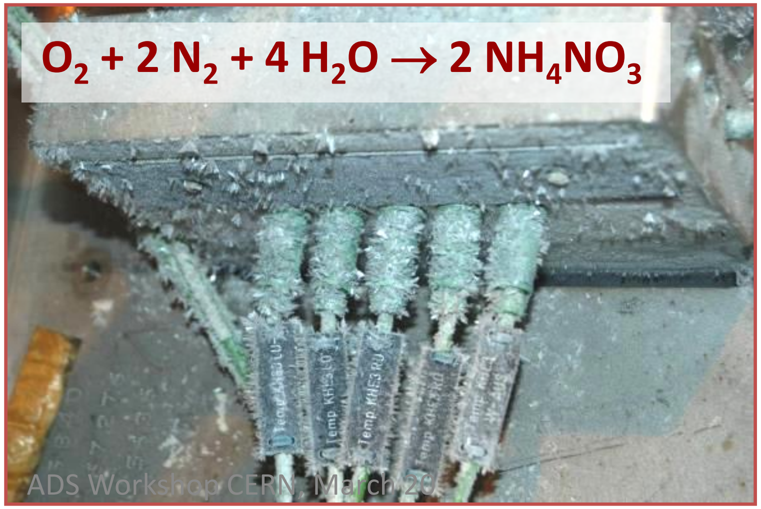


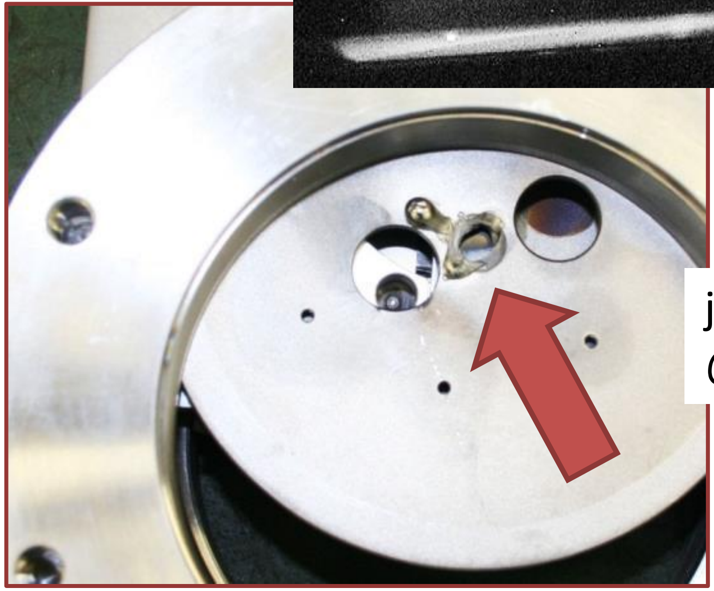
incomprehensive list:

- beam losses must be low, ≈ 100W, to avoid excessive activation
- high power RF has side effects: Plasma discharges, Multipacting, heating …
- a megawatt beam is a dangerous beast, melts steel in 10ms, interlocks!
- Ammonium Nitride and much more …

light emitted by plasma discharges

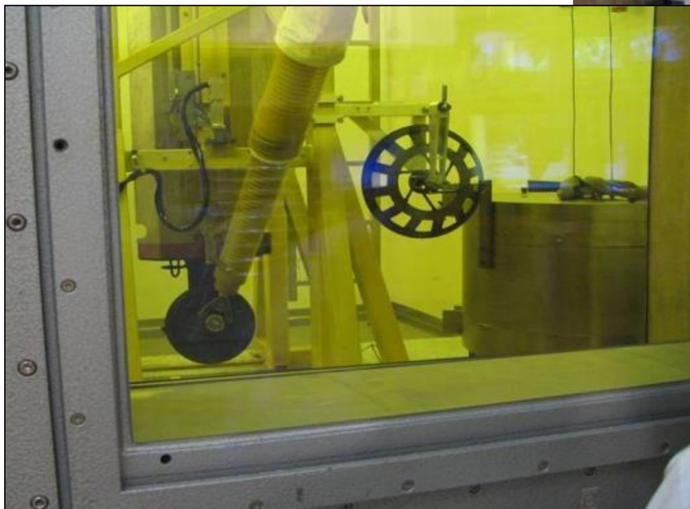


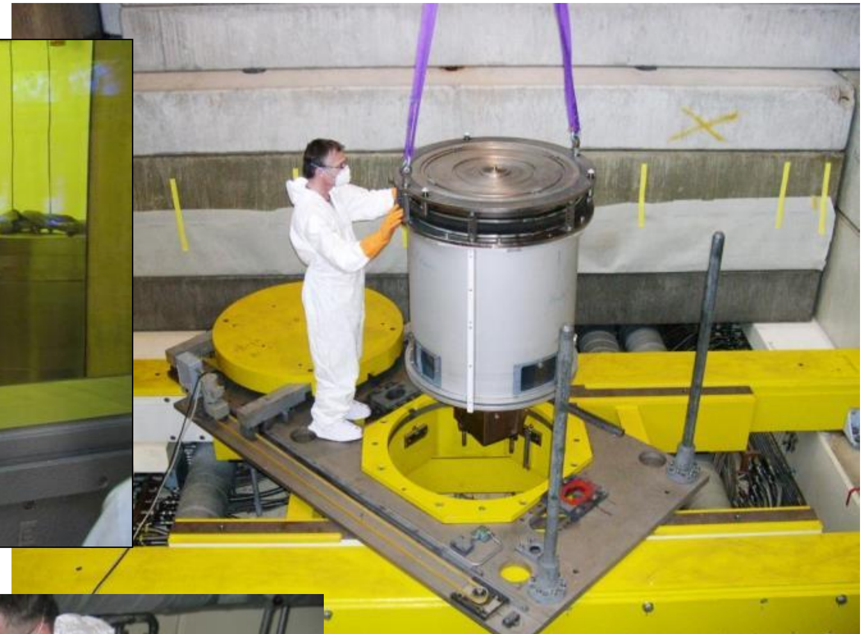




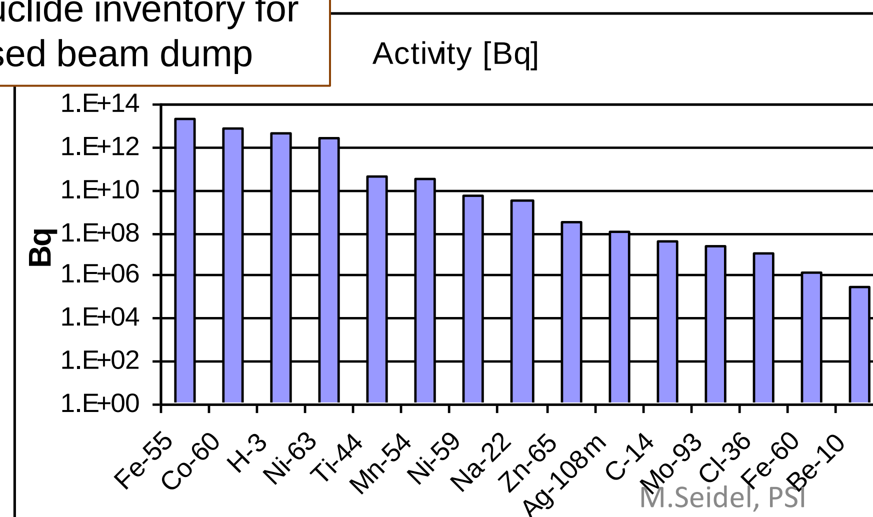
just 10kW @870keV

Handling and Disposal



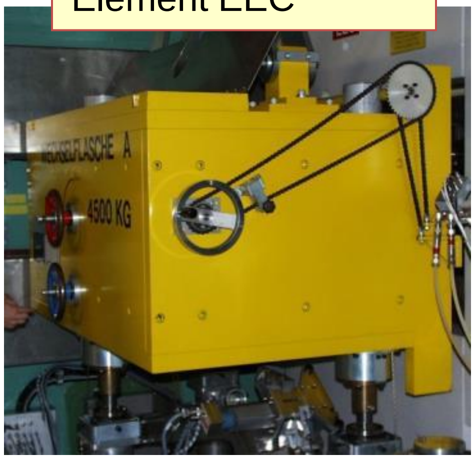


example: predicted nuclide inventory for used beam dump



exchange flasks – important tools

for Electrostatic Element EEC



Collimator KRE

exchange flask for Meson production target E

for beam splitter EHT

Target M flask

Summary – ADS Accelerators

Linear Accelerators

- s.c. linac is well developed and has most potential
- large aperture, low losses, CW possible
- cryo losses favour high currents; then efficiency can approach RF efficiency, e.g. 40%
- couplers are critical, e.g. 10mA→150kW/cavity?
- intensity limit by space charge and instabilities likely very high!

Circular Accelerators

- cyclotrons most promising <1GeV
- classical PSI scheme good for 5MW
- $\eta \leq 30\%$; reliability problematic (→ 3 machines?); complex beam dynamics (bending, space charge), tuning
- many new concepts under investigation, incl FFAG
- highly optimized cyclotron can be cost effective through repetitive usage of RF systems

Accelerator community should act coherently, should support ADS concepts and should stay open for new ideas!

thank you for the attention!