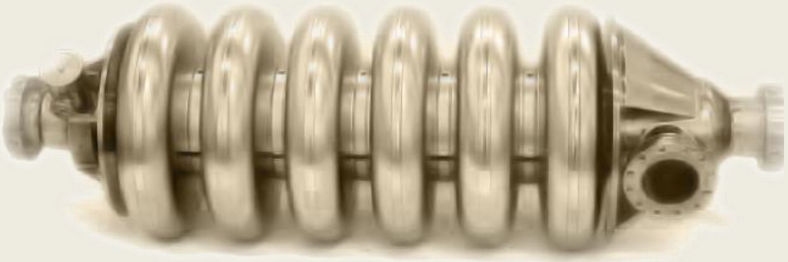
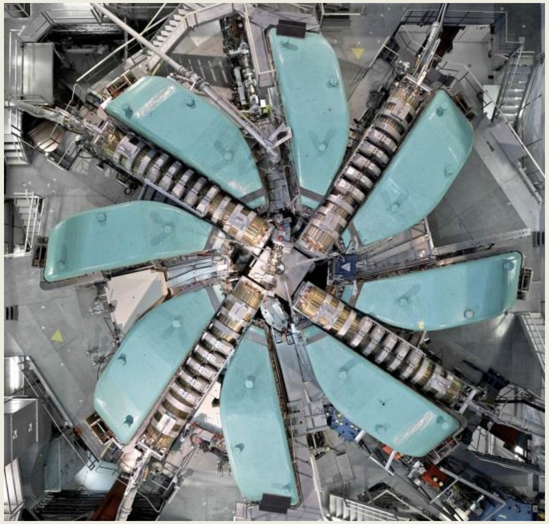
Cyclotrons and superconducting linacs as high intensity driver accelerators

Mike Seidel, PSI

International Conference on Cyclotrons and their Applications

Zürich, Sep 16





Outline

- Proton Drivers and their Applications
- Specific technology aspects of cyclotrons and superconducting linacs
  - parameter reach (power/energy)
  - technology, complexity
  - energy efficiency
  - reliability/trip statistics
  - economy, size/cost
- Conclusion and Remarks
  - Pro's and Con's on Linear vs. Circular

Applications and Requirements for Proton Driver Accelerators

proton drivers are needed to generate **secondary radiation**, typically: **neutrons, muons, neutrinos**

applications are:

ADS, particle physics- and solid state physics research

- **energy**: ADS, Neutron Sources around 0.8..2GeV, others up to ~100GeV
- **power**: 1...15MW; ADS: $P_{therm} = P_{beam} \times G/(1-k)$
- **beam losses**: $\approx$ 1W/m; PSI: 100W at critical location
- **reliability**: ADS: 0.01...0.1 trips per day(!)
- **efficiency**: as best as possible, $\eta=P_{beam}/P_{grid}$= 20...50%
- **cost:** as low as possible; ADS: compare nuclear power plant: $\mathcal{O}$(5B€)

optimum p-energy for neutron production?

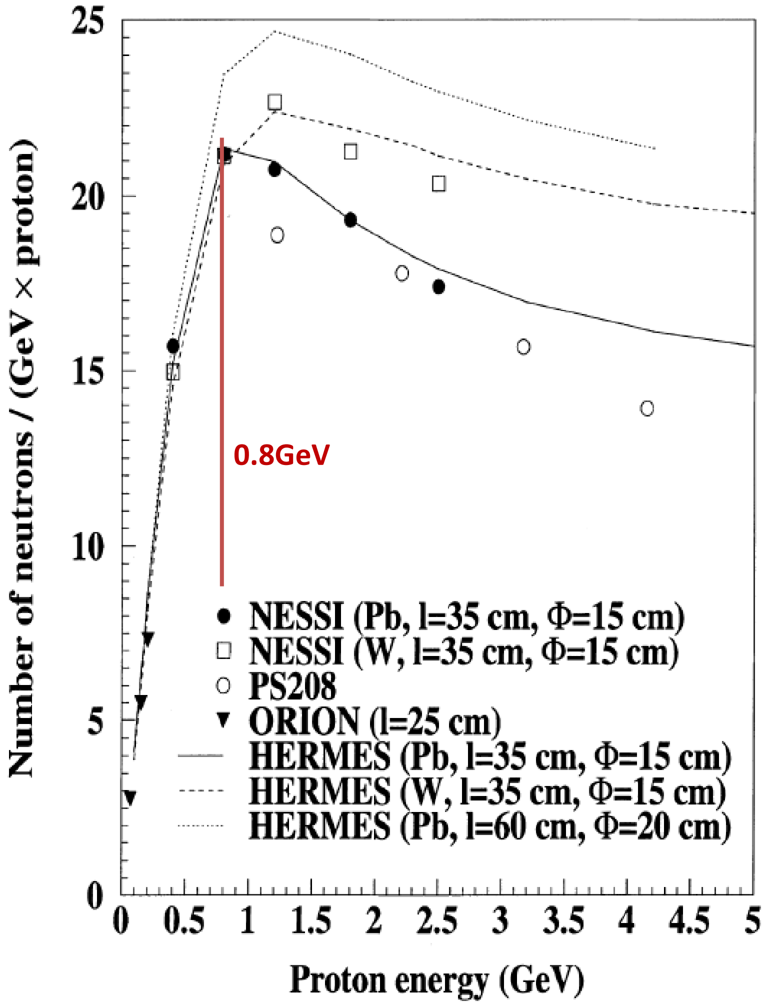


figure: n-production per particle and energy

flat maximum around 1..1.2GeV

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

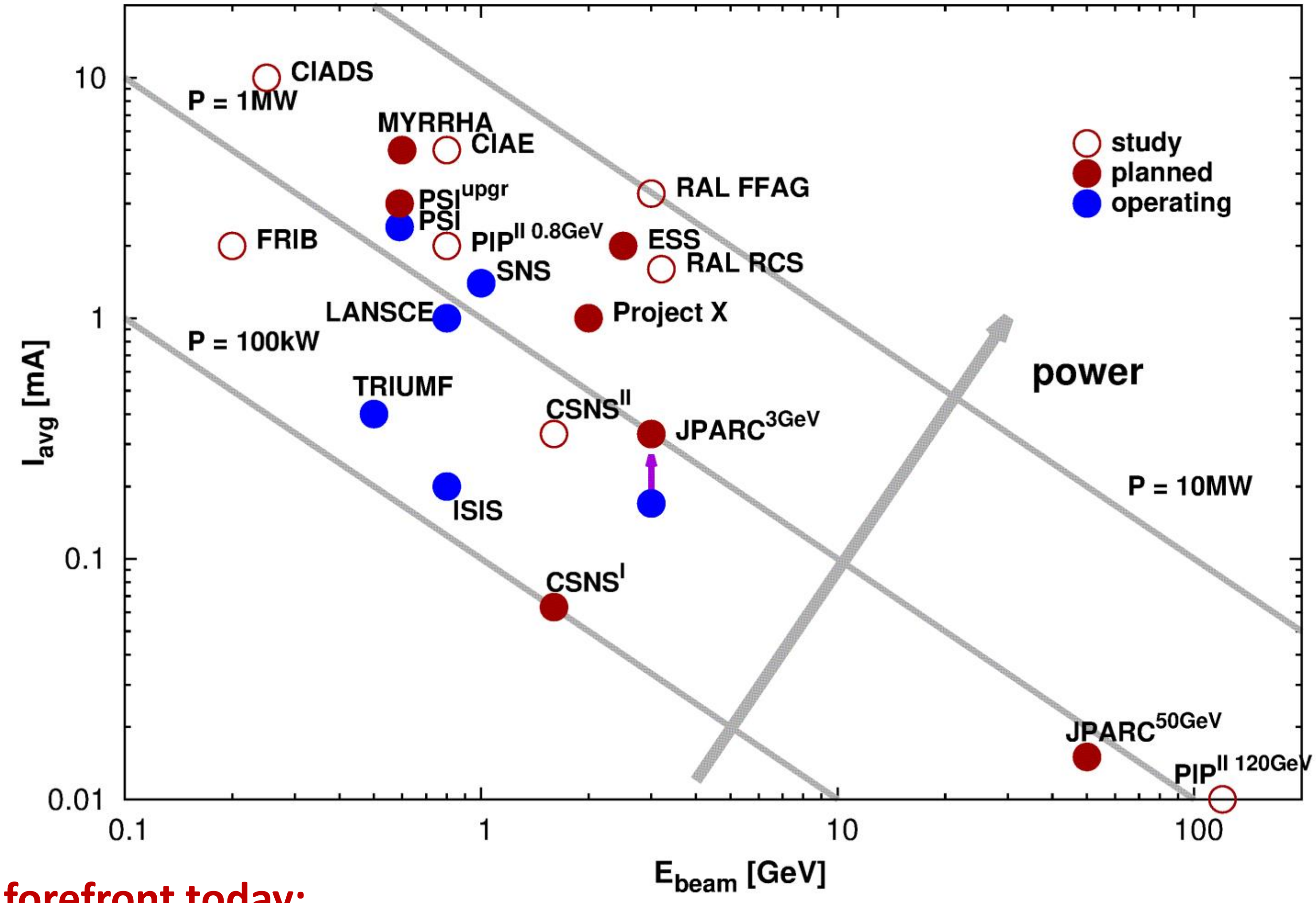
Proton Drivers – Concepts & Applications

	Neutrino	Muons	Neutrons	ADS	RIB‘s
Cyclotron	Daeδalus[1]	PSI-HIPA TRIUMF	PSI-HIPA CIAE	AIMA[2] TAMU-800[3]	TRIUMF RIKEN GANIL
RCS		J-PARC	J-PARC ISIS CSNS		
FFAG				KURRI +ongoing studies[4]	
s.c. Linac	PIP II [5]	PIP II [5]	SNS ESS ISNS[6]	ADSS[7] CIADS[8]	FRIB

[1] Decay-at-Rest Experiment for δcp studies At the Laboratory for Underground Science, MIT/INFN-Cat. et al
[2] Accelerators for Industrial & med. Applications, reverse bend cyclotron, AIMA company
[3] Cyclotron 800MeV, flux coupled stacked magnets, s.c. cavities, strong focusing channels, Texas A&M Univ.
[4] FFAG studies, e.g. STFC
[5] SRF linac, Proton Improvement Plan-II (PIP-II), Fermilab, Batavia
[6] Indian Spallation Neutron Source, Raja Ramanna Centre of Advanced Technology, Indore, India
[7] Accelerator Driven Sub-critical System at Bhaba Atomic Research Centre (BARC), Mumbai,India
[8] China Initiative Accelerator Driven System, Huizhou, Guangdong Prov. & IMP, Lanzhou, China

operating
in construction
concept study

High Intensity Landscape



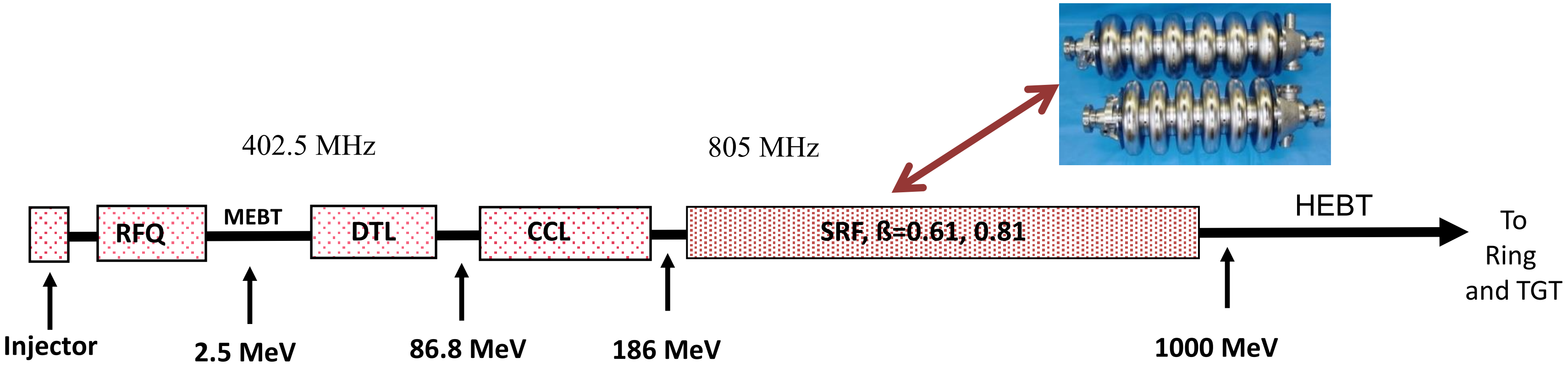
intensity forefront today:

- **SNS Linac: 1.4MW pulsed**
- **PSI cyclotron: 1.4MW CW**
- **J-PARC RCS: 0.5MW…1MW pulsed**

Superconducting Linac

+ low RF losses (high Q) → effective energy transfer
+ large aperture (5..10cm) → low beam losses
+ strong focusing using quadrupole lattice→ very high intensity possible
+ very high energy possible by adding length

- significant cryo losses at low T → limits overall energy efficiency
- each structure passed only once by beam → poor economy
- lengthy machine & building; complex and expensive technology

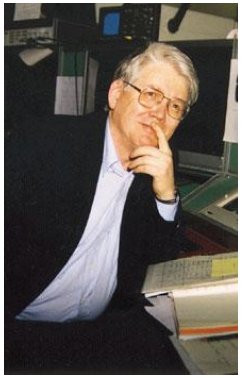


superconducting RF technology

Advantages of s.c. technology:

- tremendous progress over two decades! (DESY & TESLA collab.)
- CW operation possible, small RF losses (beware cryo efficiency)
- efficient power transfer; no overhead power for structures / couplers
- promising outlook for future dev.: high Q, high Tc materials, e.g.

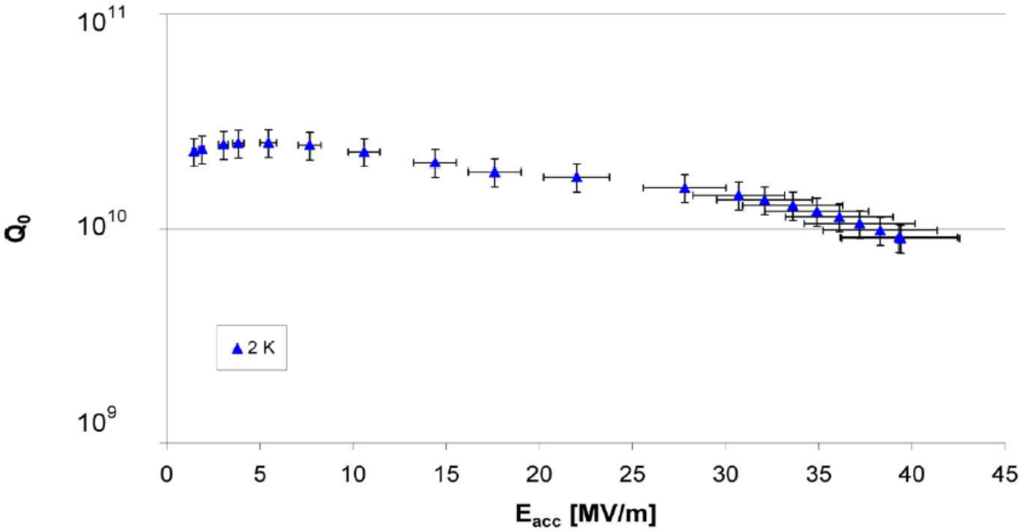
High Q_0 Development, A.Grassellino (FNAL), IPAC15



[B.H.Wiik, DESY director, †1999]

s.c. resonators have extremely high Q, e.g. 2E10@1.3GHz (E-XFEL)

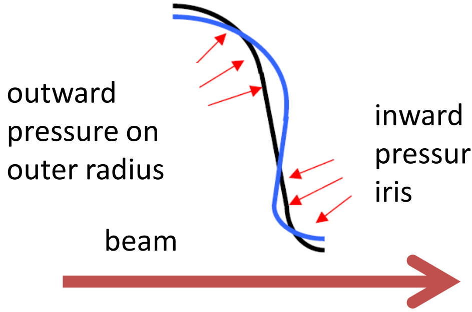
at this Q a church bell would ring for 2 years(!)

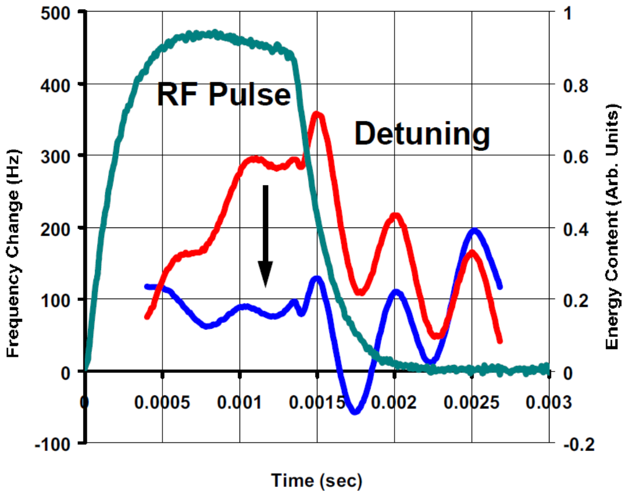


s.c. cavity Lorentz force detuning

High fields generate a pressure on the **cavity walls**; due to the narrow resonance at high Q the frequency shift is significant

$$\Delta f \propto E^2$$





Example SNS high beta cavity without and with detuning compensation [Delayen et al]

energy efficiency of s.c. Linacs

- contrary to s.c. coils, s.c. resonators are not loss free, losses are described by the surface resistance R_s with two components R_{BCS}, R_{res}
  (G geometry constant, ca. 300Ω):

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

- the relation between dissipated power and voltage is given 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

Hypothetical 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%**

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

Comment: pulsed linacs have much lower efficiency

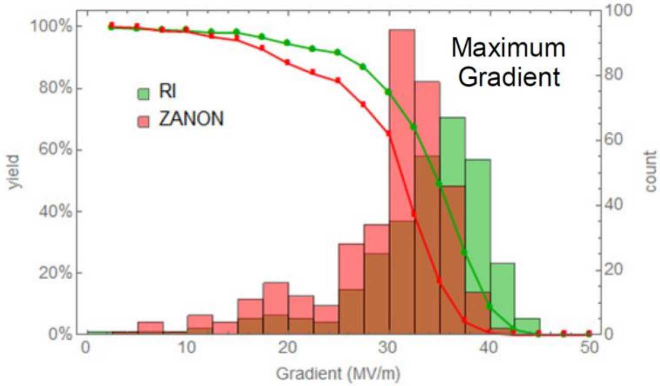
S.c.Linac: Parameter Examples

parameters* for high-β part of proton linac:

facility	E_{range} [MeV]	P_{beam} [MW]	avg Grad. [MV/m]	Freq [MHz]	n_{cav}	length [m]	$P_{coupler}$ [kW]
SNS	382-974	**1.4**	12,3	805	48	90	18
ESS	561-2000	**5.0**	19,0	704	84	177	43
CADS	367-1500	**15.0**	10,4	650	85	≈200	135

* taken from conf. papers, subject to adjustments

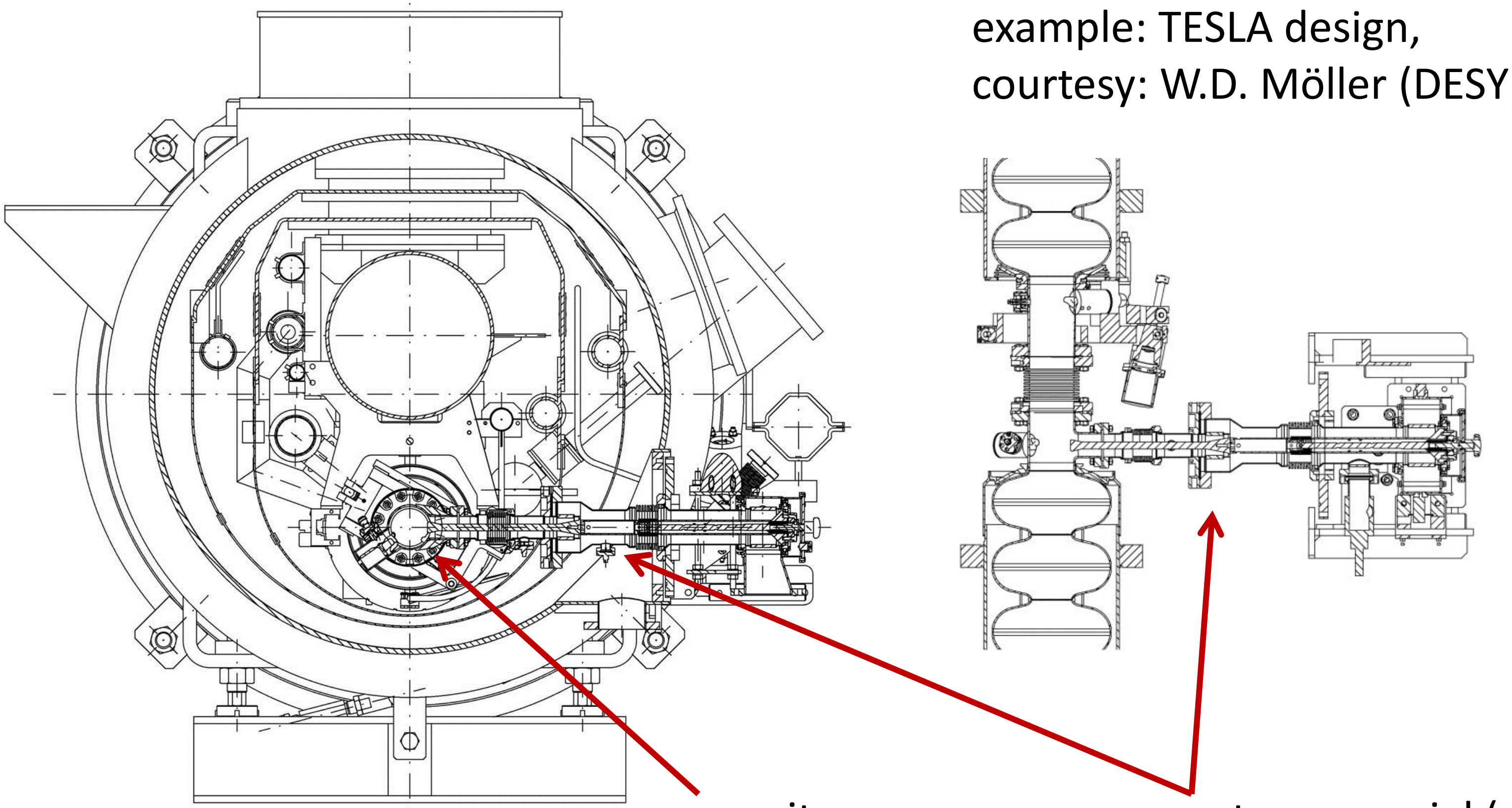
note: **these gradients** are moderate as compared to the electron linacs at 1.3GHz (20kW per coupler)



European XFEL, statistics as delivered, D.Reschke (DESY)

s.c. linac RF coupler

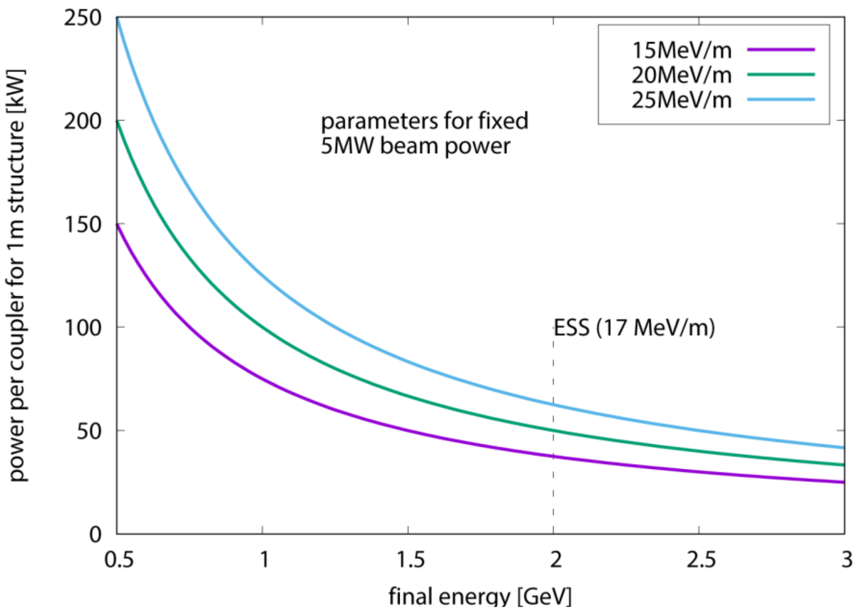
example: TESLA design,
courtesy: W.D. Möller (DESY)



cavity

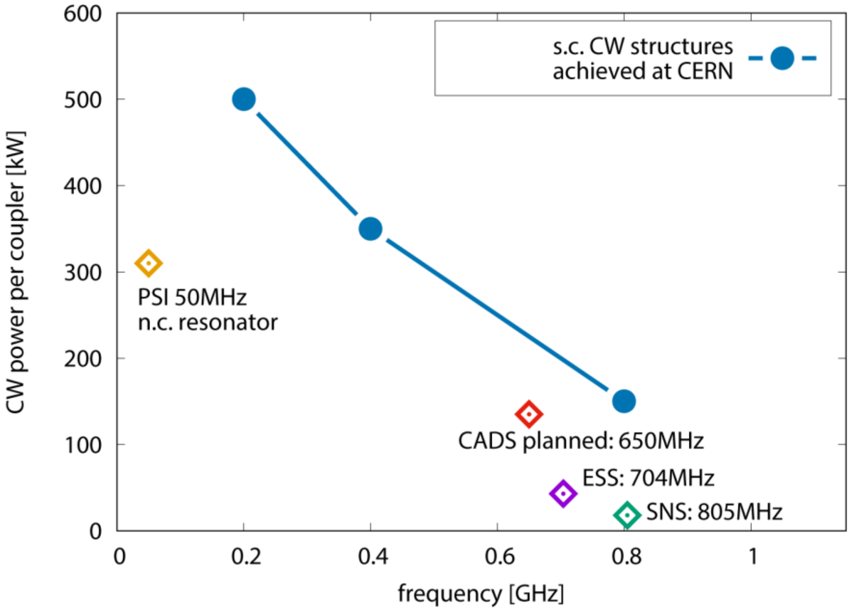
type: coaxial (antenna)
two ceramic windows,
intermittend vacuum,
Conditioning critical

limitation for s.c. linacs: power per coupler



→ high beam power at moderate energy is difficult due to limited power transfer per coupler

$$P_{\mathrm{tot}} = n \times P_{\mathrm{coupl}}$$



CW values achieved in tests at CERN: courtesy E.Montesino

→ established operating values are low today, e.g. SNS, E-XFEL

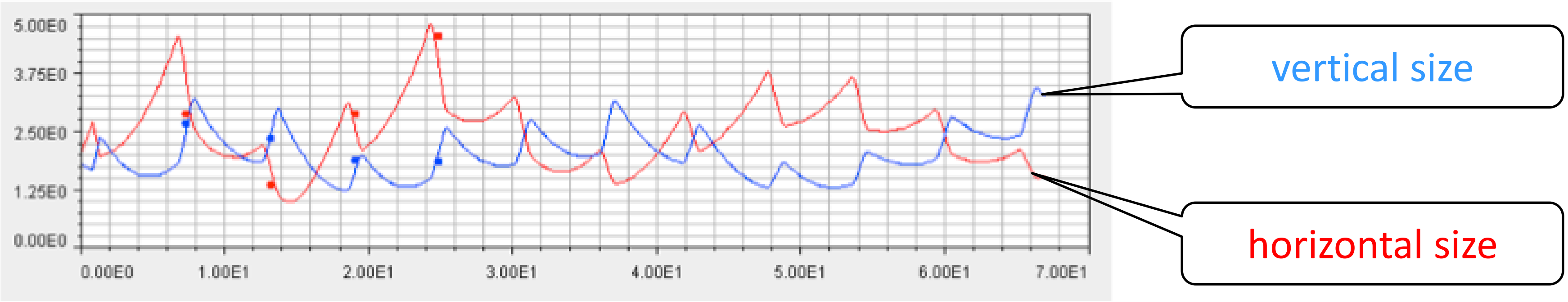
tuning experience in SNS Linac @ 1MW

Mike Plum, ORNL, HB2012:

empirically optimized for low losses, linac and transport lines

→ **beam core optics is obviously mis-matched, presumably beam tails "feel"deviating optics and are better transported in this case**

→ **also at PSI (cyclotron) we rely much on empirical tuning ☺**

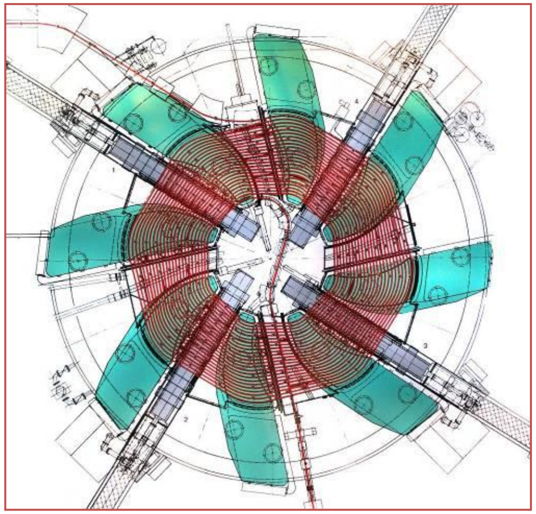


Summary s.c. linacs – specific aspects

	comment	performance	economy	technical challenge	outlook
high Q	low loss, but at low T, Lorentz force detuning	good	good	yes	
advanced cavity material	extremely pure Nb (energy!), advanced surface treatment		bad	yes	sputtering, coating
cooling efficiency	Cop(2K) ≈ 700(!)		bad		high Q, high Tc mats.
crucial coupler	for high current high power transfer required- bottleneck	bad	bad	yes	good CERN Results
multiple cav. per klystron	regulation problem, lowest cav. limits performance	bad	good		

Isochronous Separated Sector Cyclotron

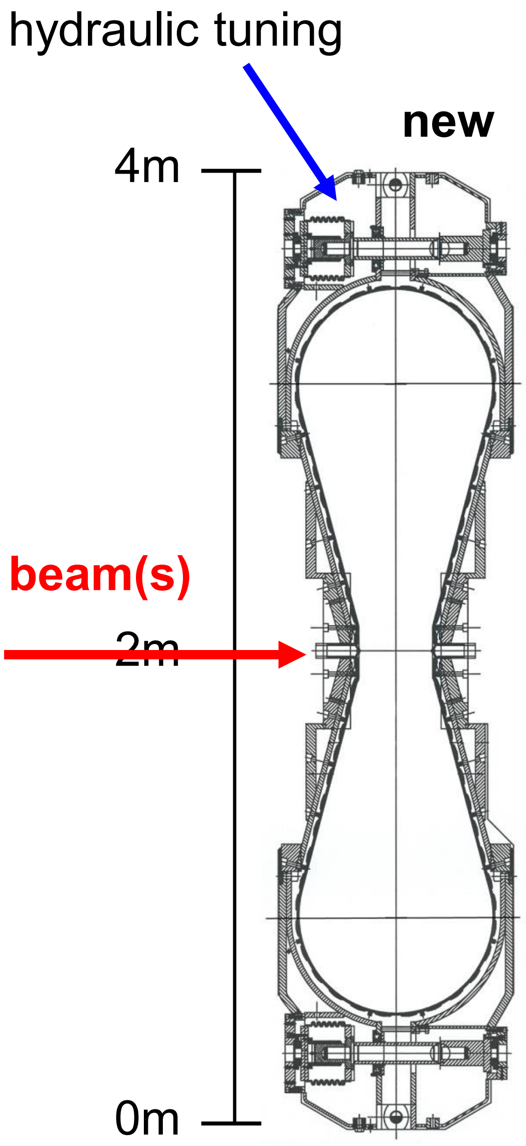
+ multiple acceleration with same resonators → economy
+ continuous wave acceleration naturally possible
+ relatively compact layout
+ good energy efficiency
- extraction critical → energy limitation (less severe for stripping extraction)
- relatively weak focusing → intensity limitation
- large radial orbit variation → wide vacuum chamber and magnets (forces!)



PSI Ring cyclotron:

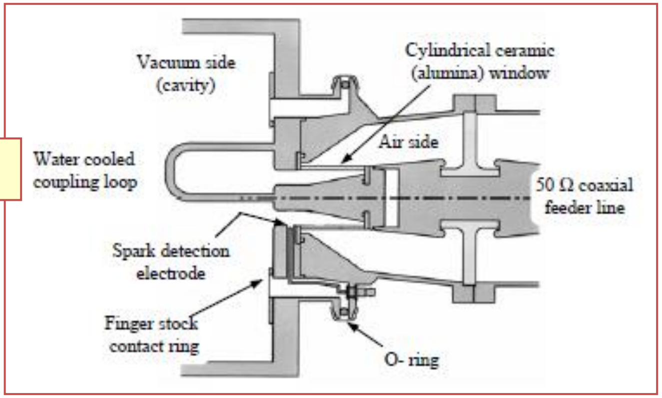
- 590MeV, 1.4MW
- diameter 15m, 186 turns
- extraction septum
- RF: Grid-to-beam: 32%

cyclotron technology: resonators



- **$f = 50.6$MHz; $Q_0 = 4{,}8 \cdot 10^4$; U_{max}=1.2MV** (presently 0.85MV)
- transfer of up to **½ A, 400kW power to the beam** per cavity
- Wall Plug to Beam Efficiency (RF Systems): **32%**

loop coupler @ 50MHz

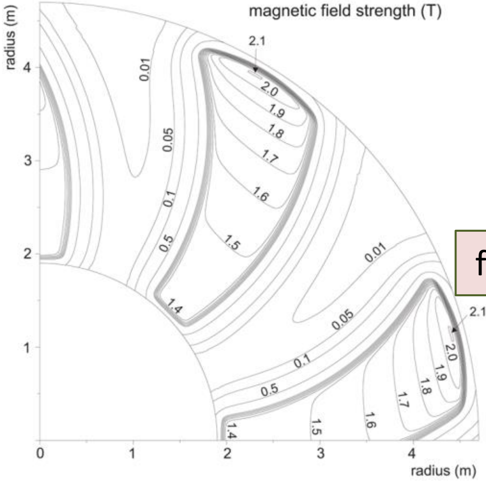


cyclotron technology: sector magnets

cyclotron magnets typically cover a wide radial range → magnets are heavy and bulky, thus costly

PSI sector magnet

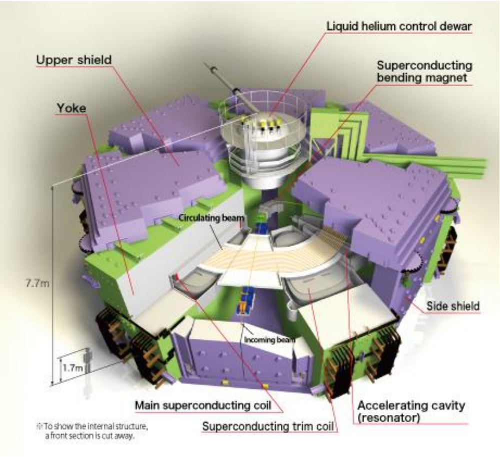
iron weight: 250 tons
coil weight: 28 tons
Field: 2.1T
orbit radius: 2.1…4.5 m
spiral angle: 35 deg

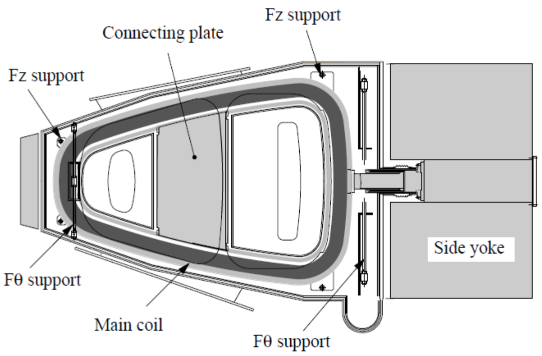


field map

Riken SRC sector magnet

weight: 800 tons
Field: 3.8T, 5000A
orbit radius: 3.6…5.4m





cyclotron extraction

for clean extraction of protons a large turn separation is of utmost importance

general scaling at extraction:

$$\Delta R(R_{\text{extr}}) = \frac{U_t}{m_0 c^2} \frac{R_{\text{extr}}}{(\gamma^2 - 1)\gamma}$$

desirable:

- limited energy (< 1GeV)
- high energy gain U_t
- large radius R_{extr}

scaling during acceleration:

$$\frac{dR}{dn_t} \approx \frac{U_t}{m_0 c^2} \frac{R}{\beta^2} \rightarrow \Delta R(R) \propto \frac{1}{R}$$

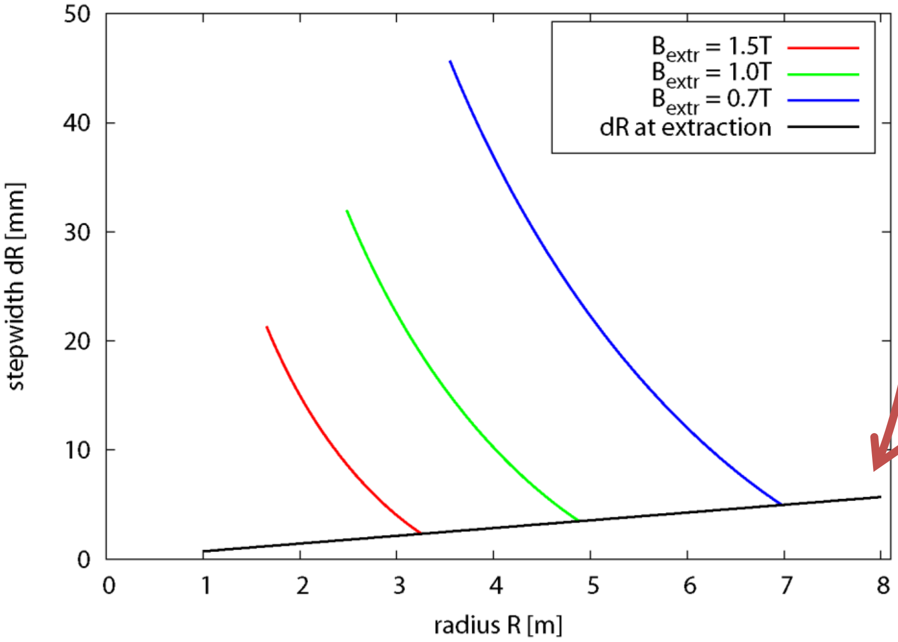
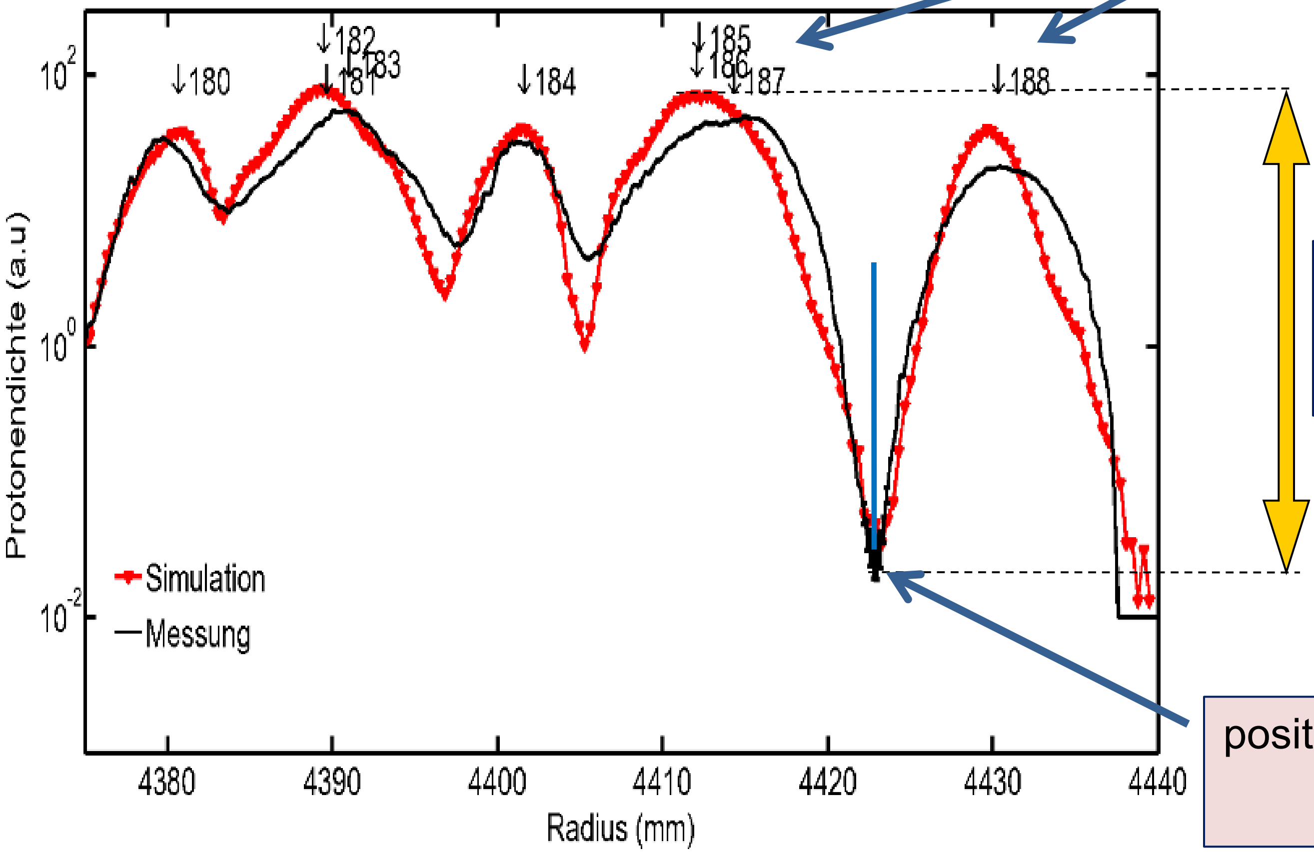


illustration:
stepwidth vs. radius in cyclotrons of different sizes;
100MeV inj → 800MeV extr

cyclotron extraction PSI
- tedious tuning

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]

Charge exchange extraction schemes

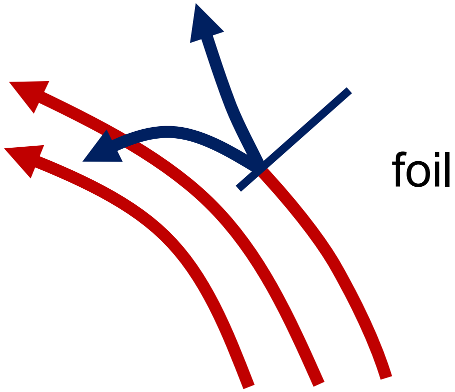
accelerate H^- or H_2^+ to extract protons

extraction by charge exchange in foil

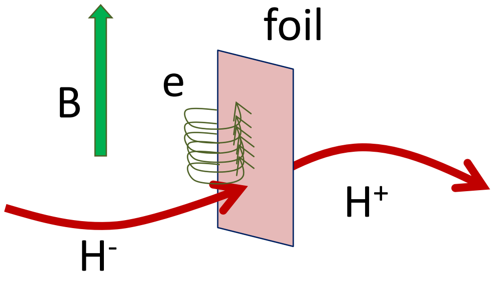
eg.: $H^- \rightarrow H^+$

$H_2^+ \rightarrow 2H^+$

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



stripped electrons may deposit energy in the foil, 1/2000 of beam power



Comments:

- H-: significant probability for unwanted loss of electron; Lorentz dissociation: B-field low, scattering: vacuum 10^{-8}mbar
- H2+: unfavorable charge to mass ratio (economy); complex extraction path or reverse bend needed
- e- may be deposited in foil

Cyclotron Intensity limitations: space charge

Longitudinal space charge → transverse tails → losses at extraction [Joho 1981]

$$\begin{aligned}\Delta U_{sc} &= \frac{8}{3} e I_p Z_0 \ln\left(4\frac{w}{a}\right) \cdot \frac{n_{\mathrm{max}}^2}{\beta_{\mathrm{max}}} \approx 2.800\Omega \cdot e I_p \cdot \frac{n_{\mathrm{max}}^2}{\beta_{\mathrm{max}}} \\ \frac{1}{\Delta R_{\mathrm{extr}}} &\propto n_{\mathrm{max}}\end{aligned}$$

→ Attainable current scales as Voltage^3

Transverse space charge → reduces focusing, tune shift

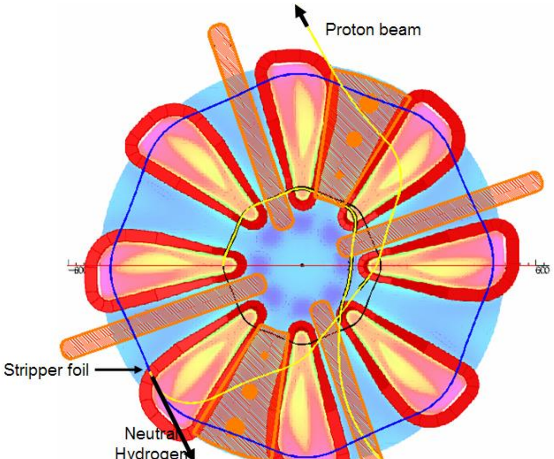
$$\ddot{y} + \left(\omega_c^2 \nu_{y0}^2 - \frac{n_v e^2}{\epsilon_0 m_0 \gamma^3}\right) y = 0$$

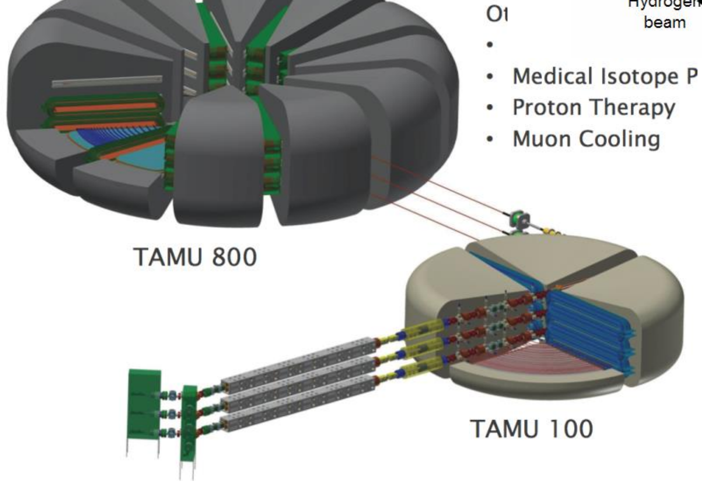
$$\Delta\nu_y \approx -\sqrt{2\pi}\frac{r_p R}{e\beta c \nu_{y0}\sigma_z}\frac{m_0 c^2}{U_t} I_{\mathrm{avg}}$$

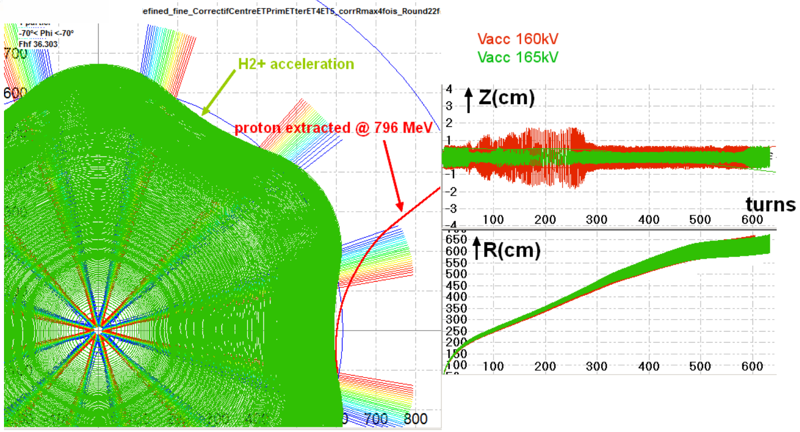
→ This limit is for cyclotrons more severe than for Linacs

High intensity cyclotrons: Studies

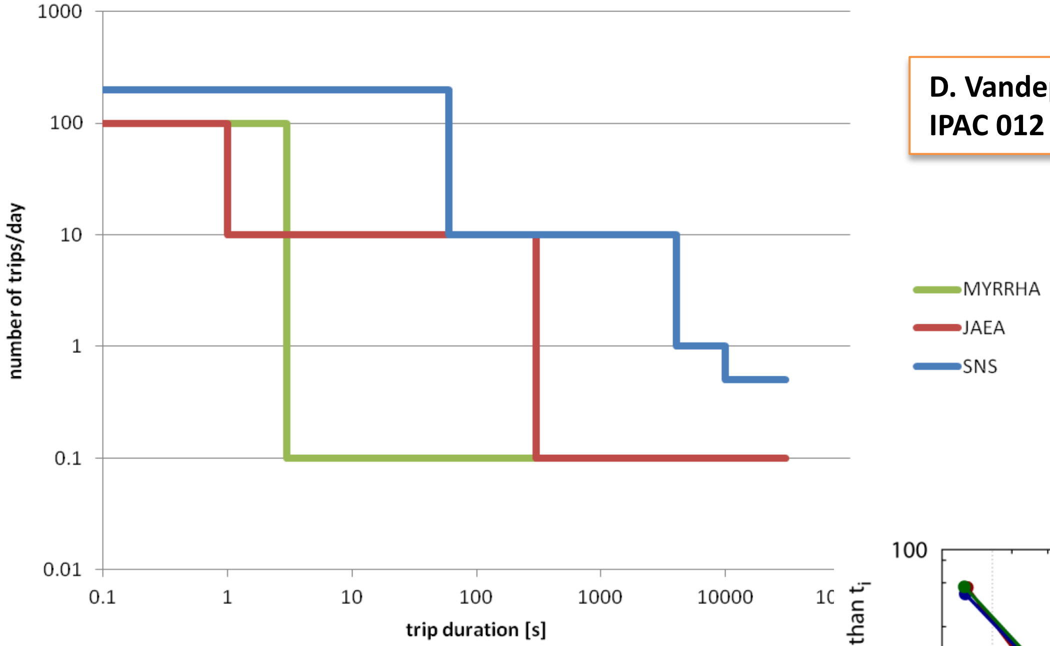
- H_2^+ AIMA Cyclotron w reverse bend, multiple 60keV injection [P.Mandrillon et al]
- H_2^+ Daedalus cyclotron [neutrino source, L.Calabretta et al]
- TAMU: s.c. magnet, stacked cyclotron w strong focusing [P.McIntyre et al]





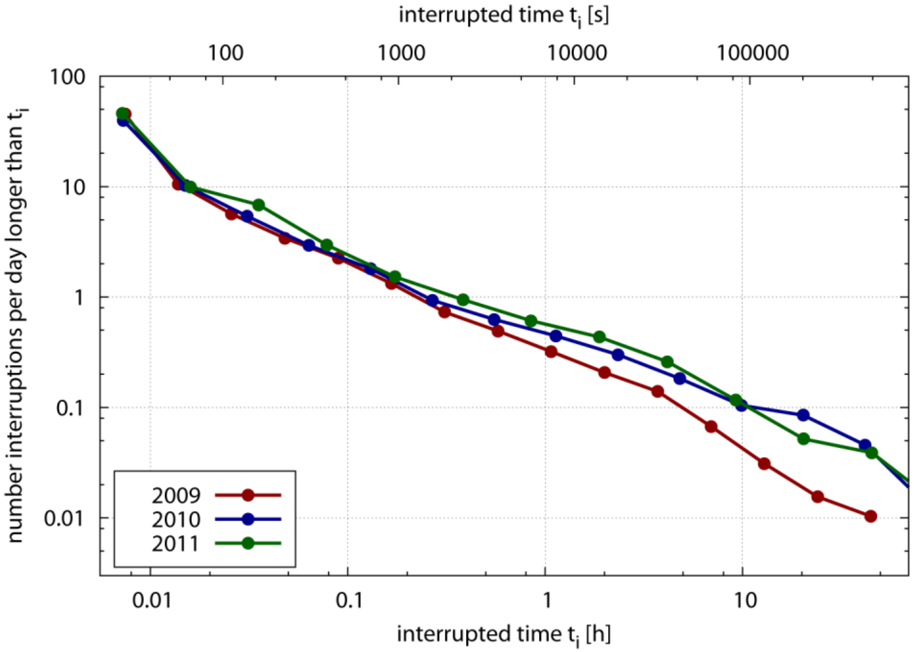


reliability, todays performance



D. Vandeplassche, Proc. IPAC 012

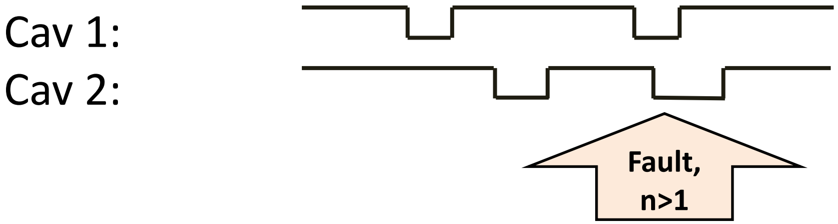
PSI analysis of trip-periods



→ Today at least 3 orders of magnitude missing, for both acc.types

reliability, concepts

proposed solution: **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,

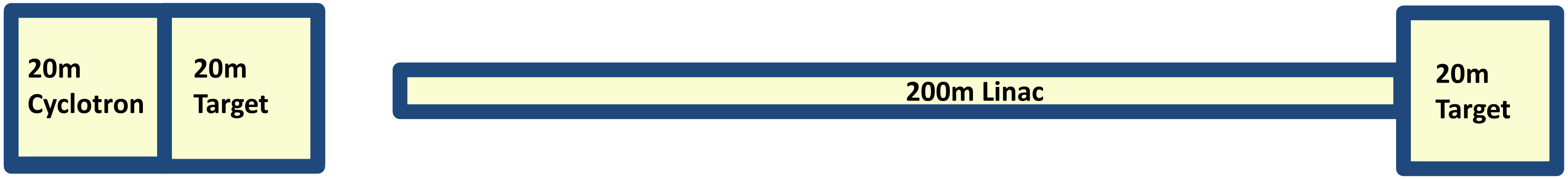
B_p = incomplete Beta Function

$$\begin{aligned} P_{\text{eff}} &= \sum_{m=k}^{n} \binom{n}{m} p^m (1-p)^{n-k} \\ &= B_p(k, n-k+1) \end{aligned}$$

facility size

cyclotron facility shielding, e.g. d=3m, 2x23mx23mx11m: 12.400m^3 concrete

linac facility shielding, e.g. d=3m, 8x8x200 + 23mx23mx11m: 25.800m^3 concrete



20m Cyclotron

20m Target

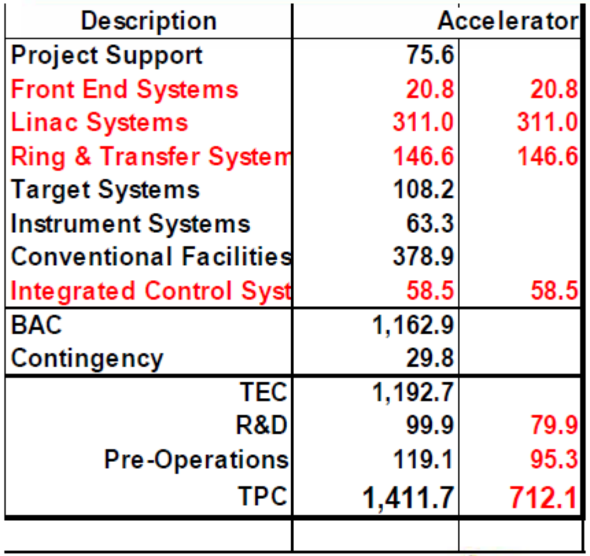
200m Linac

20m Target

- **cyclotrons should have an advantage in view of building size and shielding volume**
- **the lengthy character of the linac tunnel implies more restrictions on the choice of the construction site**

about cost

example SNS, courtesy:
N.Holtkamp [2006, USD]:



Description	Accelerator	
Project Support	75.6	
Front End Systems	20.8	20.8
Linac Systems	311.0	311.0
Ring & Transfer System	146.6	146.6
Target Systems	108.2	
Instrument Systems	63.3	
Conventional Facilities	378.9	
Integrated Control Syst	58.5	58.5
BAC	1,162.9	
Contingency	29.8	
TEC	1,192.7	
R&D	99.9	79.9
Pre-Operations	119.1	95.3
TPC	1,411.7	712.1

inflation 06-16 USA: ≈+22% → 870M$

example PSI-HIPA, courtesy:
U.Schryber [1995]:

	MCHF [1975/78]
Ring Cyclotron	31,1
Injector II Cycl. + CW	22,5
Buildings + Infrastructure	51,5
Sum accelerator:	53,6
+ inflation factor* 2016 (+120%):	**120MCHF**

*not reliable

cost estimates for new projects need detailed studies, thus focus on numbers for existing machines to give an impression on the possible cost range

Summary – p-Driver Accelerators

	isochronous cyclotron	s.c. linac
parameter reach	**-** - **E_k≈1GeV**, diminishing turn separation - **focusing limit, ≈5MW?**	**++** - large aperture → intensity - strong focusing - unlimited energy
reliability	**+** - simplicity, but.. - tedious tuning, extraction	**+** - redundancy possible, but .. - otherwise complex system
economy	**++** - comparably compact - classic technology - huge magnets	**--** - **many expensive cavities, cryogenics**, energy consum. - lengthy building
outlook	**+** - new concepts are discussed, community comparably weak	**++** - high Tc development - high Q treatments

Subjective: in community less cyclotron expertise than linac expertise → bias on choice of technology

PAUL SCHERRER INSTITUT

PSI

thank you for the attention!