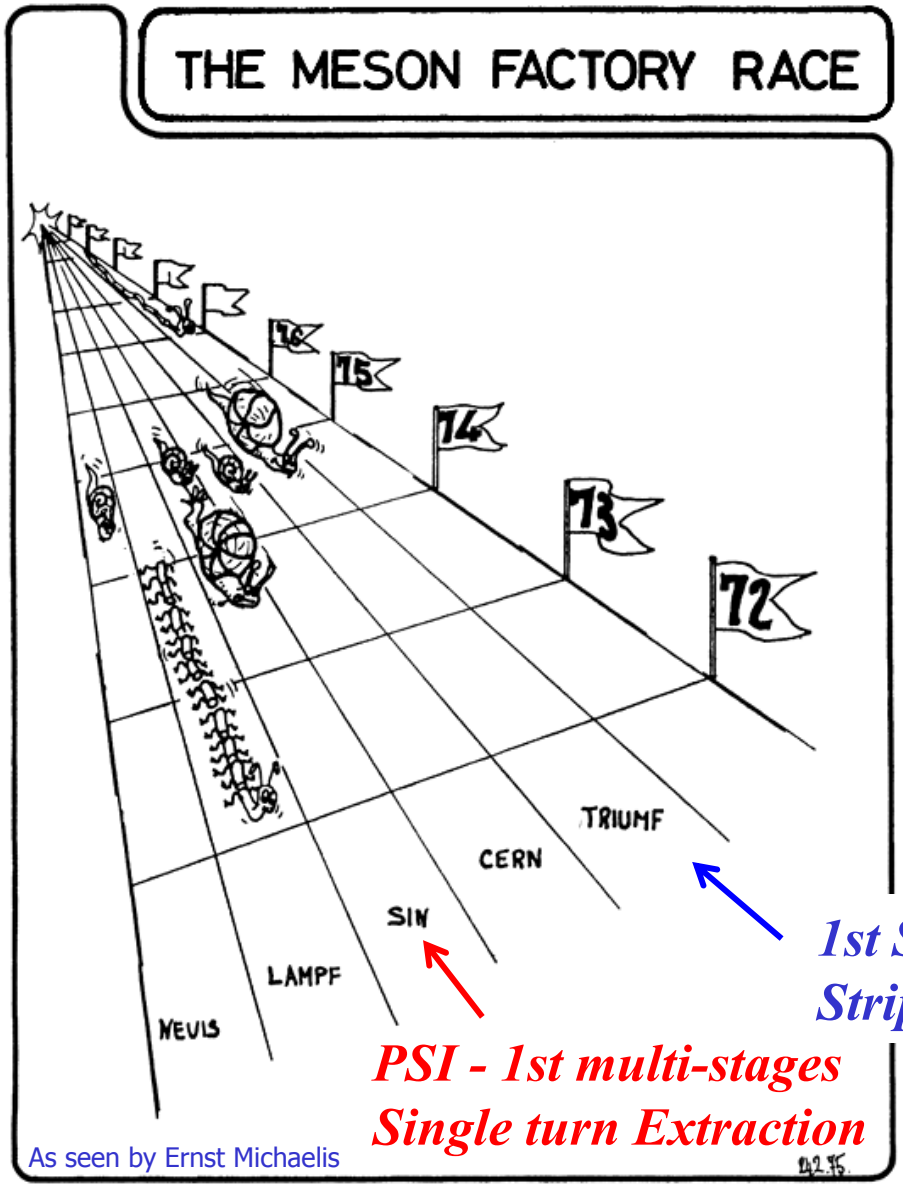
AIMA
Accelerators for Industrial and Medical Applications

Single Stage Cyclotron for an ADS demonstrator

P.Mandrillon and M.Conjat
AIMA-DEVELOPPEMENT
with the contribution of J.Mandrillon

ICC 2016,Zurich, 16 September 2016



ICC 1975 in Zurich !

1st Single stage with Stripping Extraction of H^-

PSI - 1st multi-stages Single turn Extraction

The requirements for an ADS Demo

-Beam Energy: in the 600 to 800 MeV protons to produce neutrons via spallation.

-Beam Power: 5-10 MWatt.

-Beam losses: internal losses < 200 Watt.

-Reliability (beam trips)

-Optimized Energy efficiency: $\eta = P_{beam}/P_{grid}$

-Costs.

AIMA
Accelerators for Industrial and Medical Applications

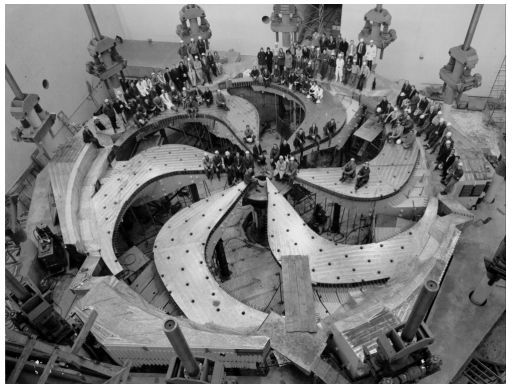
High intensity Cyclotrons: The lessons from the pioneers

PSI

1973

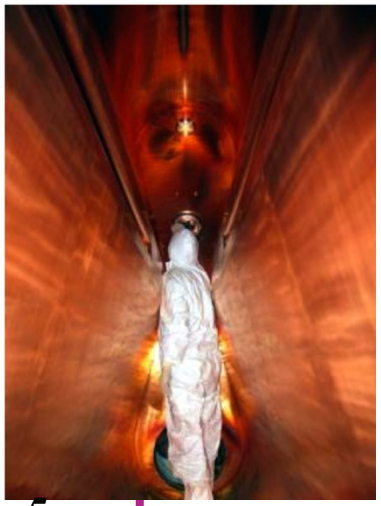
1 Hans Willax
2 Miguel Olivo
3 Thomas Stammbach
4 Werner Joho
5 Christa Markovits

TRIUMF 1974 (1st 500 MeV beam)



1) PSI: Single turn extraction

Excellent agreement simulations/measures

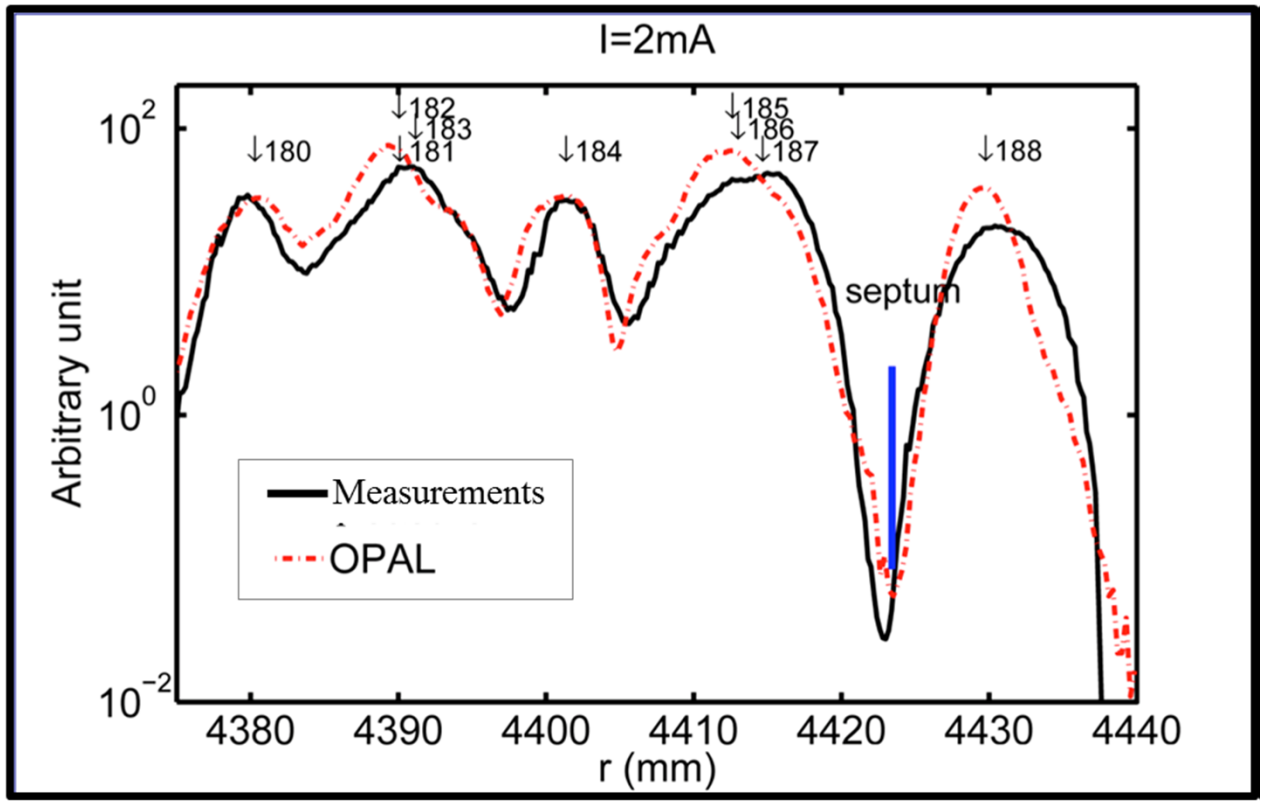


> Increasing the separation δ between turns

$$\delta = R/N*(\gamma/(\gamma+1))/\nu_r^2$$

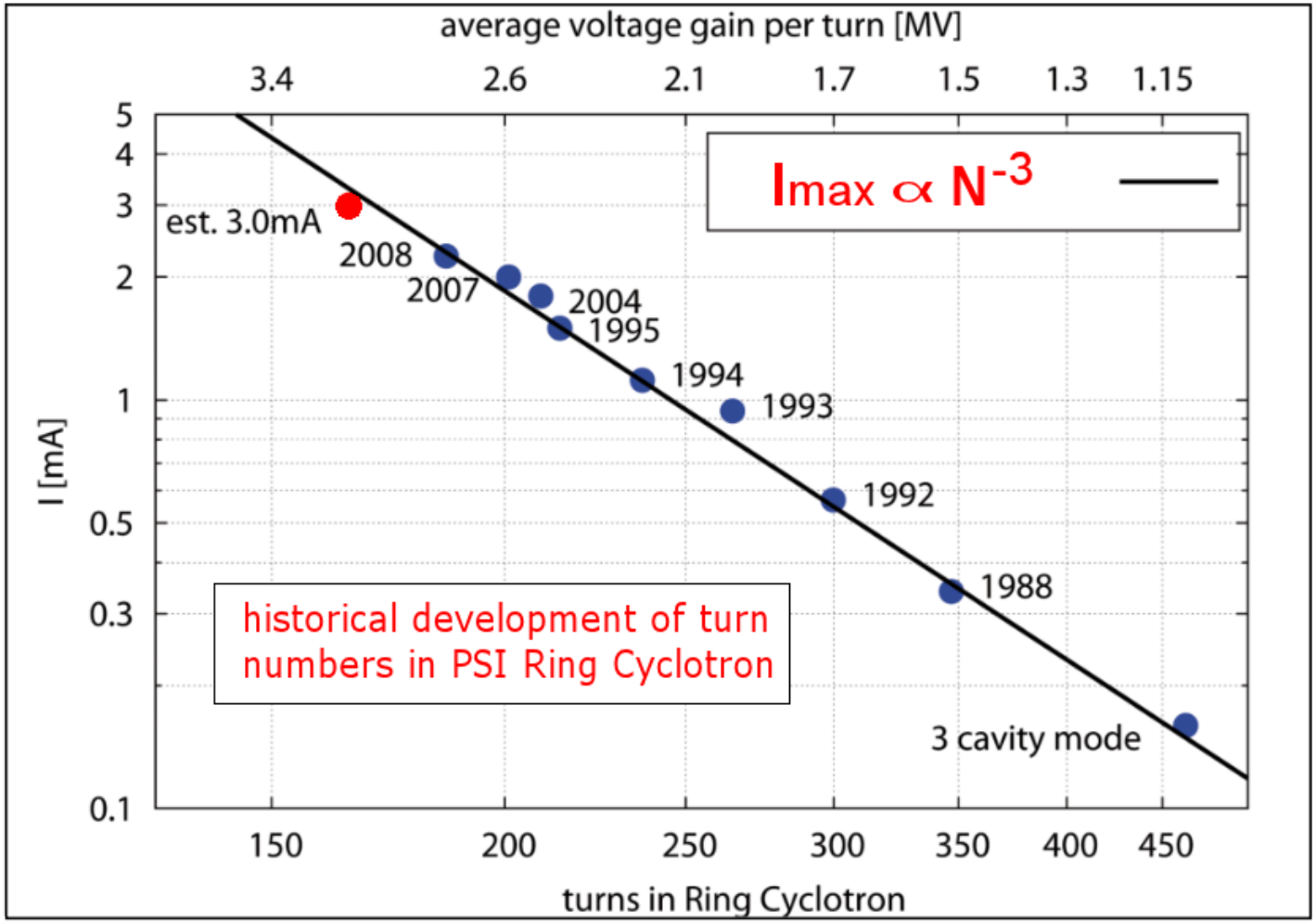
> Reducing the number of turns N with

High power new RF copper cavities.

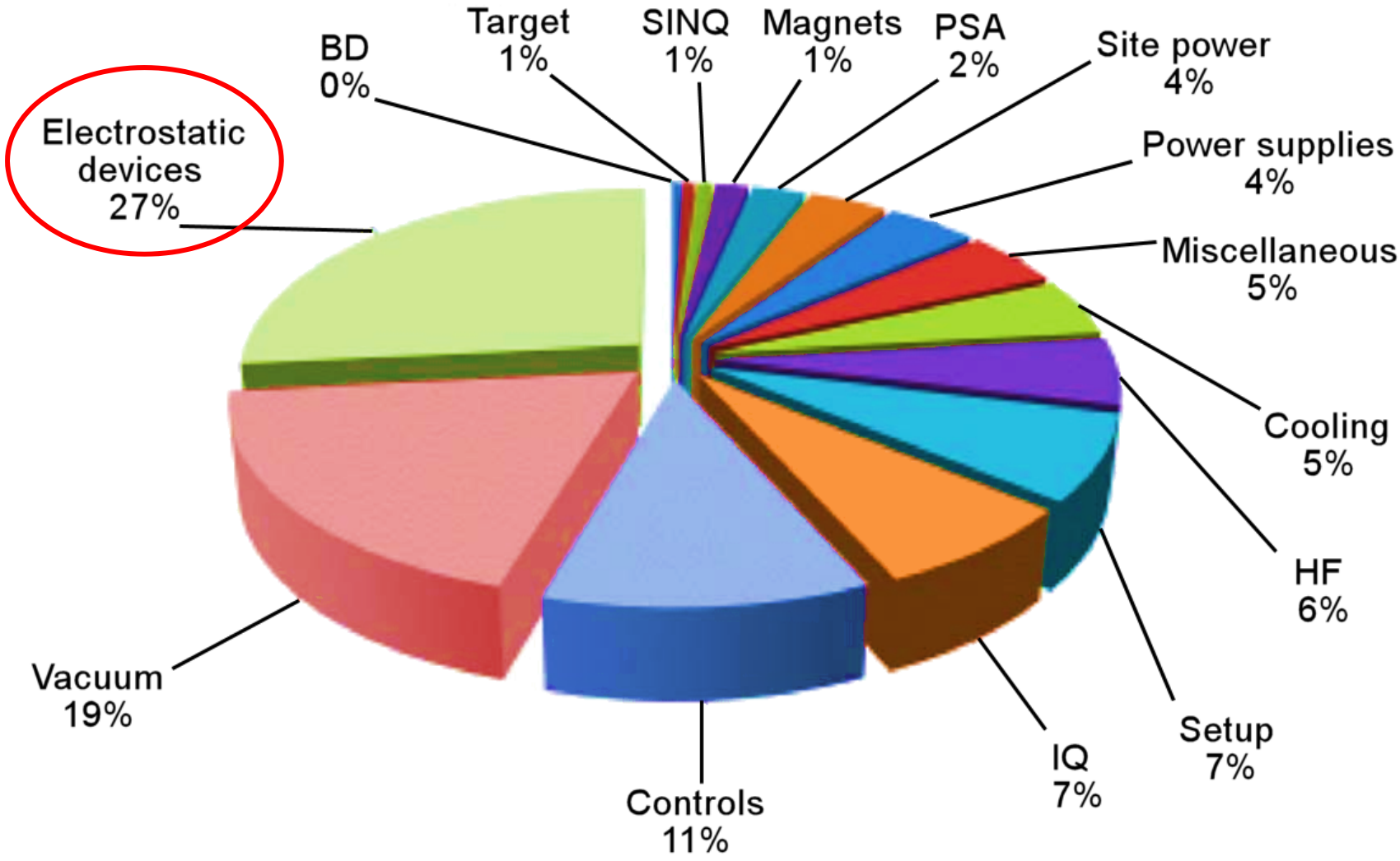


[Y.J.Bi (PSI & Tsinghua Univ.), A. Adelmann]

The successful Werner Joho law !



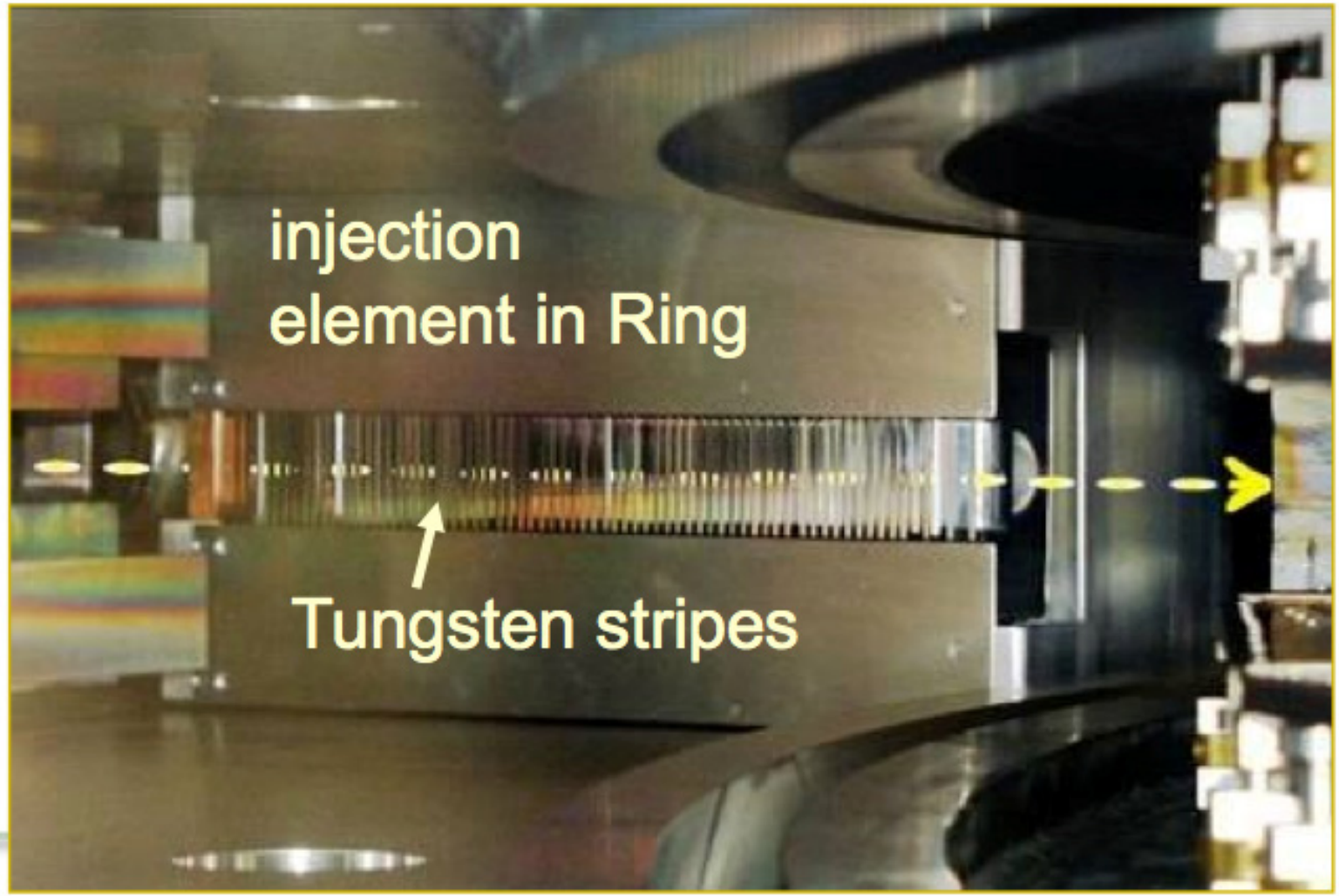
2) The main causes of downtime of a multi-stages cyclotron



From M.Seidel PSI in 2009

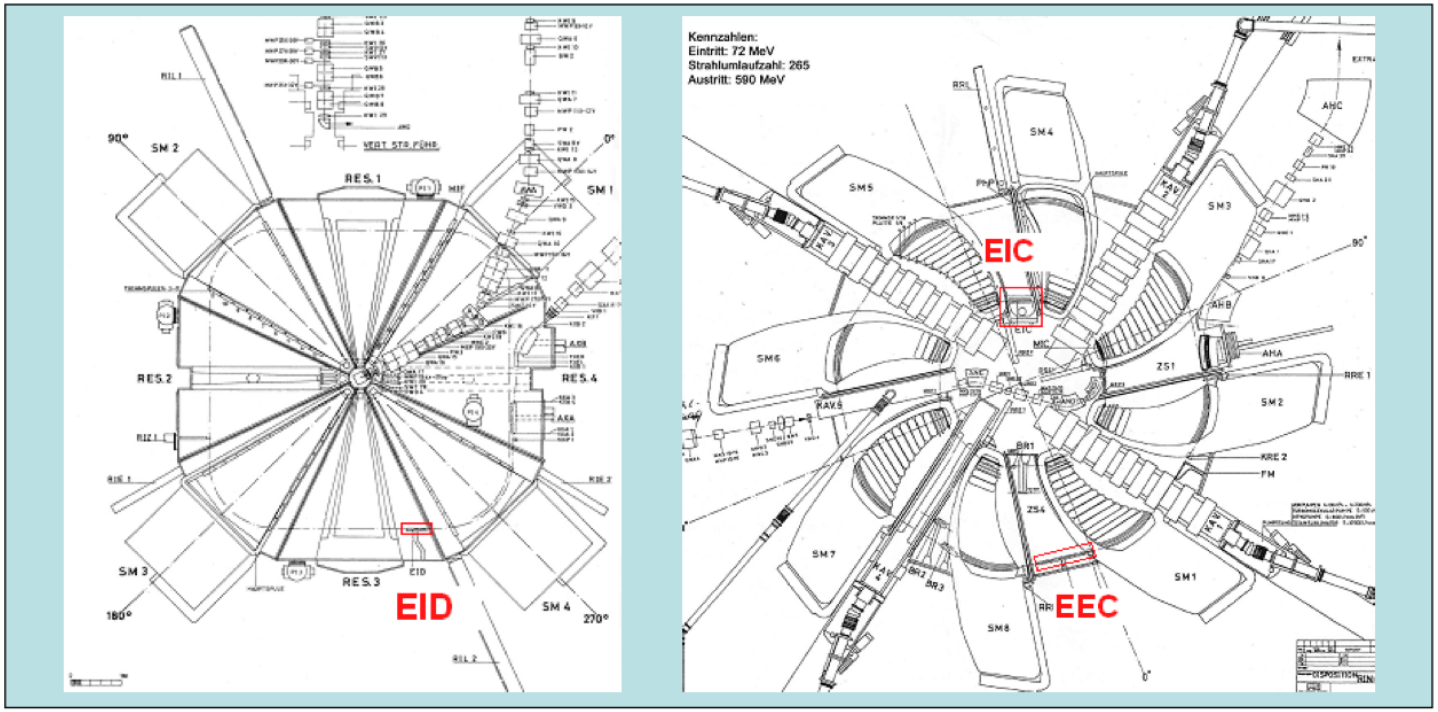
The High-Tech injection/extraction electrostatic channels

Emax = 90 KV/cm



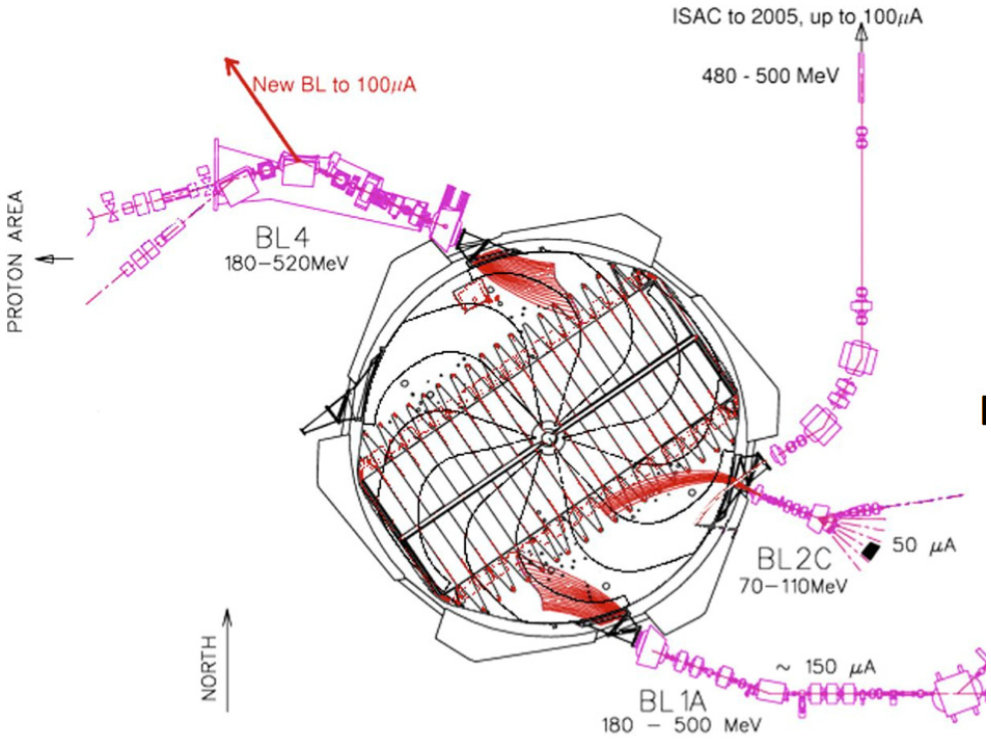
The injection/extraction devices of the multi-stages solution

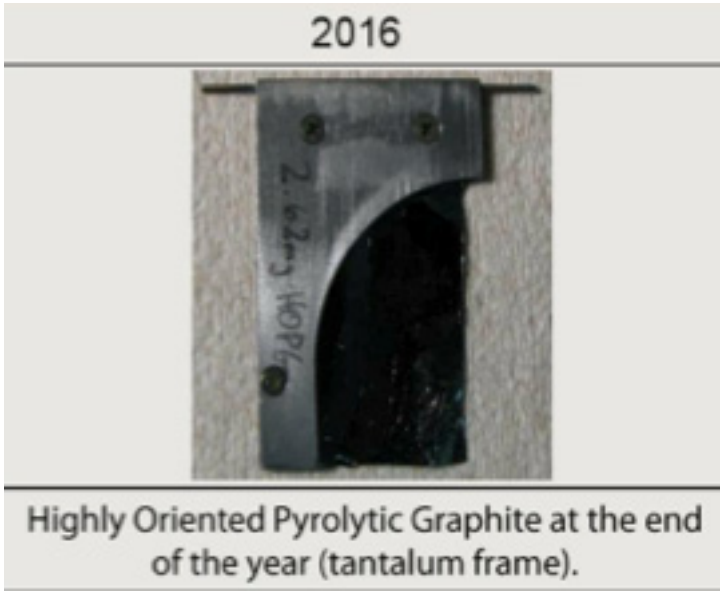
The PSI 2 stages geometry : a 72 MeV Injector and the 590 MeV Booster ring.
→ various injection and extraction channels



- **EID: Electrostatic deflector channel for 72 MeV Inj. II**
- **EIC: Electrostatic inflector channel for Ring machine**
- **EEC: Electrostatic extractor channel for Ring machine**

The overlapping turns extraction at TRIUMF by H- stripping





Highly Oriented Pyrolytic Graphite at the end of the year (tantalum frame).

500 mA*hours
The outstanding stripper foil lifetime !
Courtesy from Yuri Bylinskii

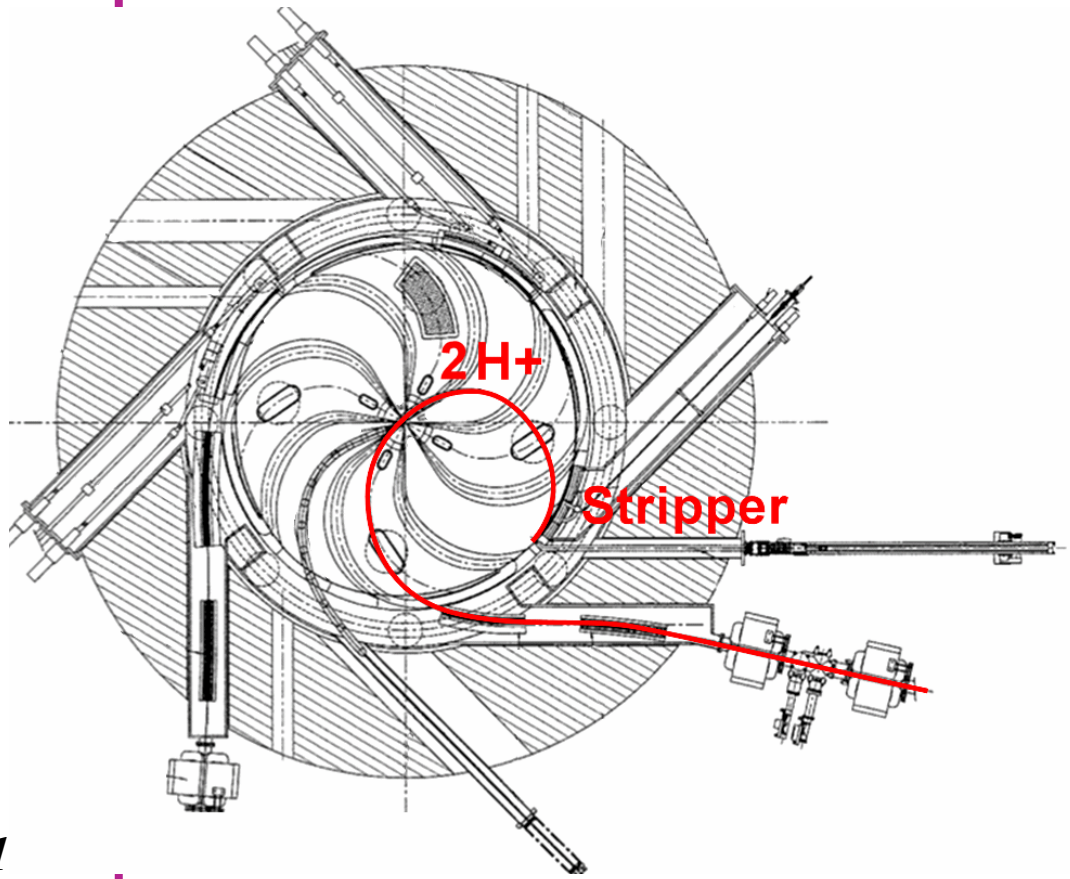
Well known method (low energy cyclotrons):
Drawback: The relativistic electromagnetic stripping of H- (0.754 eV)
➔ For 520 MeV, Bmax in the sectors 6 kGauss ➔ Large machine for 600 MeV

$H2^+$ acceleration and inwards extraction of H^+ by stripping

L.Calabretta and D.Rifuggiatto
ECPM, Groeningen, 1997

Important advantages of H2+ over H-:

- Reduced space charge at low energy
- High electron binding energy: 2.8 eV➔ High B
- 2 stripped protons/H2+ with half momentum
- e- thermal load per proton on the stripper: divided by 4



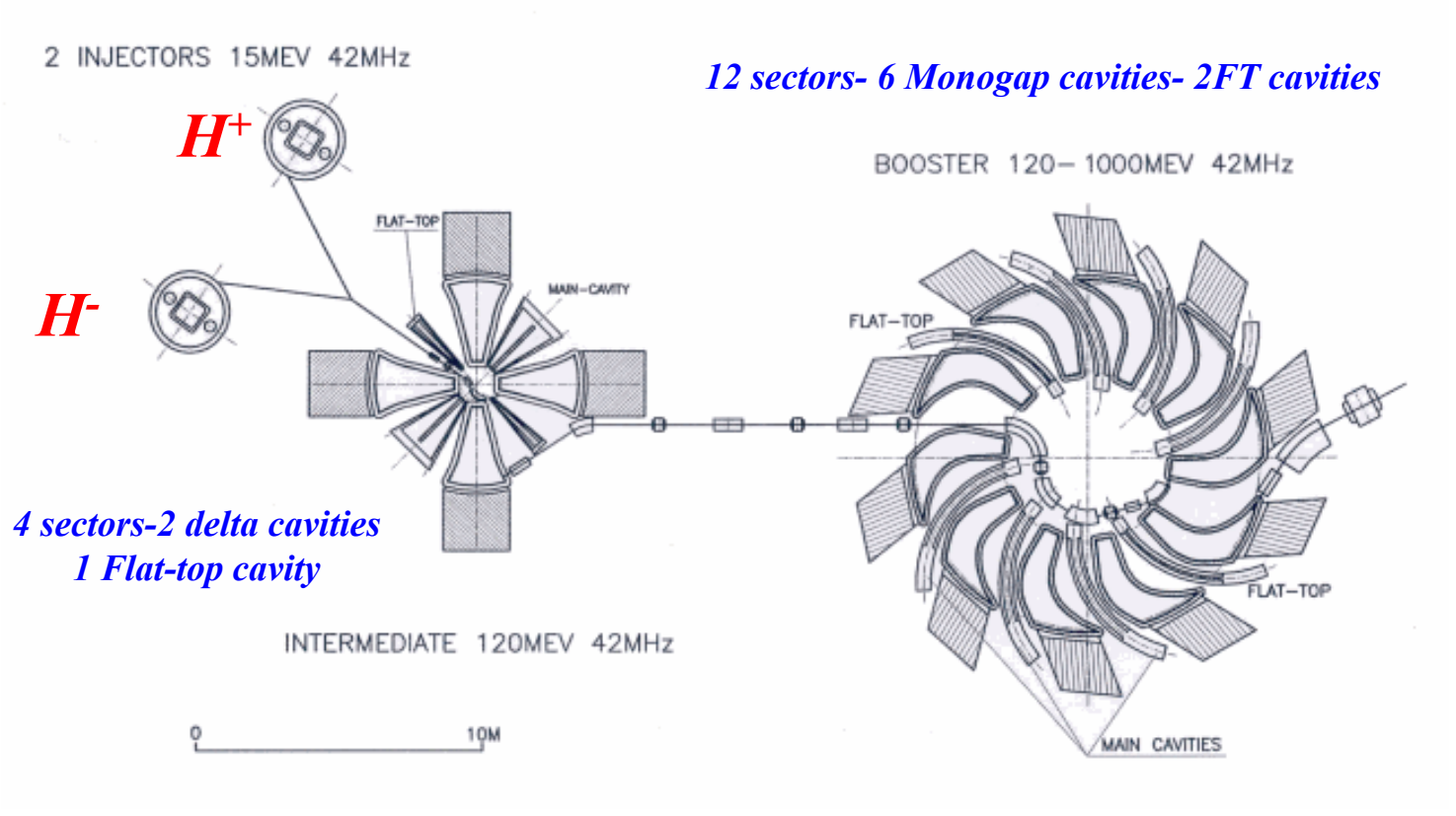
e.g. Trade driver proposal (ENEA - AIMA)
to deliver 2mA-110 MeV protons
by stripping of 1mA, 220 MeV H2+

Accelerators for Industrial and Medical Applications

Other examples of high power Cyclotrons:

1995: Inspired by PSI the early proposal for driving the Energy Amplifier with a 1 GeV 3 stages Cyclotron

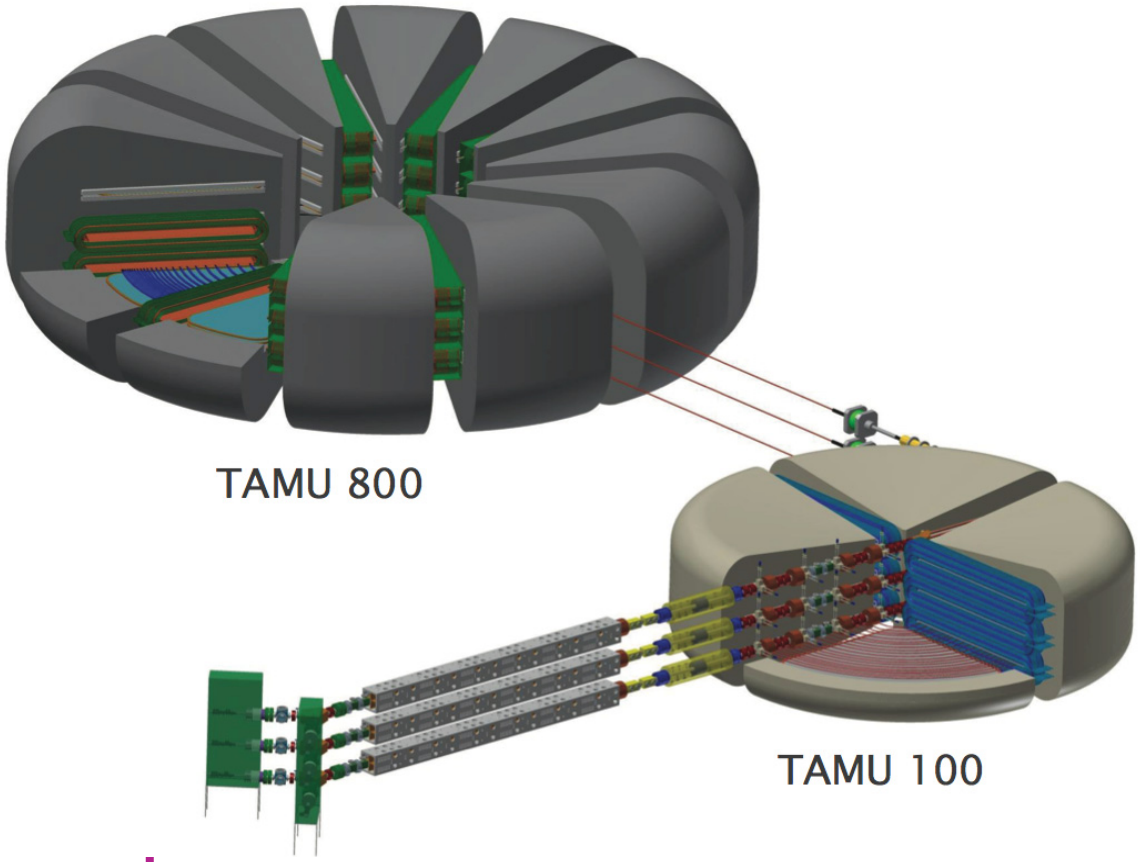
N.Fiétier and P.Mandrillon, Beam Dynamics and Space Charge aspects in the design of the accelerators for the Energy Amplifier, Proc. of the 14th ICC, Cape Town, 1995



800 MeV Superconducting Strong-Focusing Cyclotron

High current proton driver for ADS

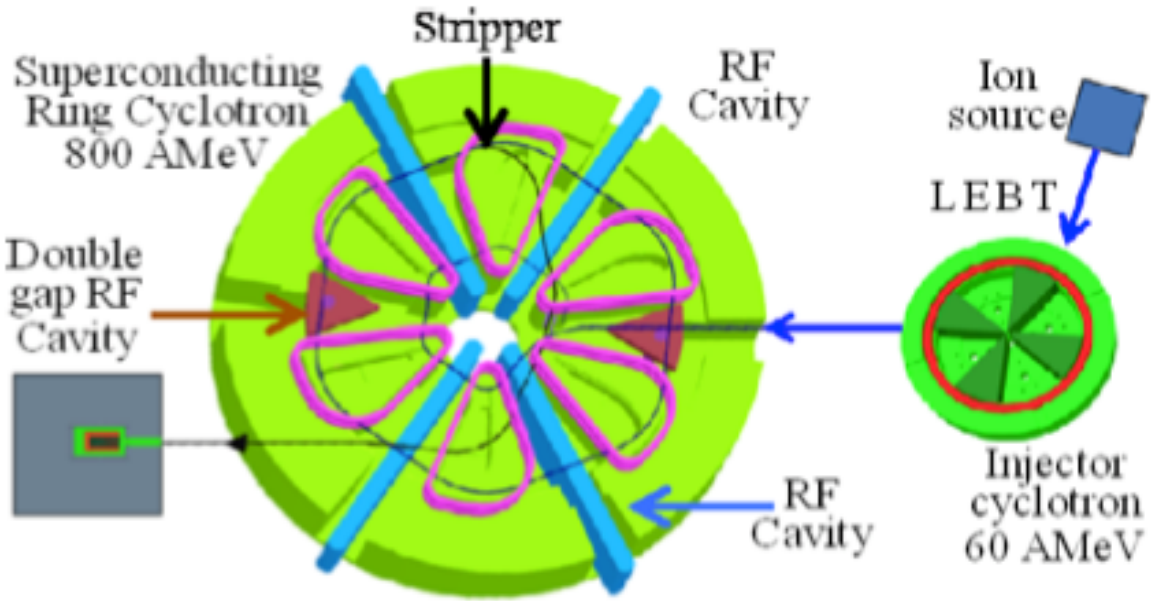
Texas A&M University



- 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
- Large turn separation allowing to insert SF beam transport channels made of Panofsky Qpoles (G=6T/m)

The Daeδalus two-stages H2+ 800 MeV/n Cyclotron

- Catania group Design: L.Calabretta et al.,www.jacow.org, EPAC 2000, p. 918
- A.Calanna et al., The Cyclotron complex for the Daedalus experiment, Proc. Of Cyclotrons 2013, Vancouver.



Magnet: 6 Sectors superconducting coils (Riken type)
RF: 4 Single gap RF Cavities (PSI Type)+2 double gap cavities
Extraction: **stripping of H2+**

AIMA
Accelerators for Industrial and Medical Applications

Single Stage Cyclotron Driver (S2CD™) based on the Reverse valley B-field

Option **A**: 600 MeV-10 mA protons

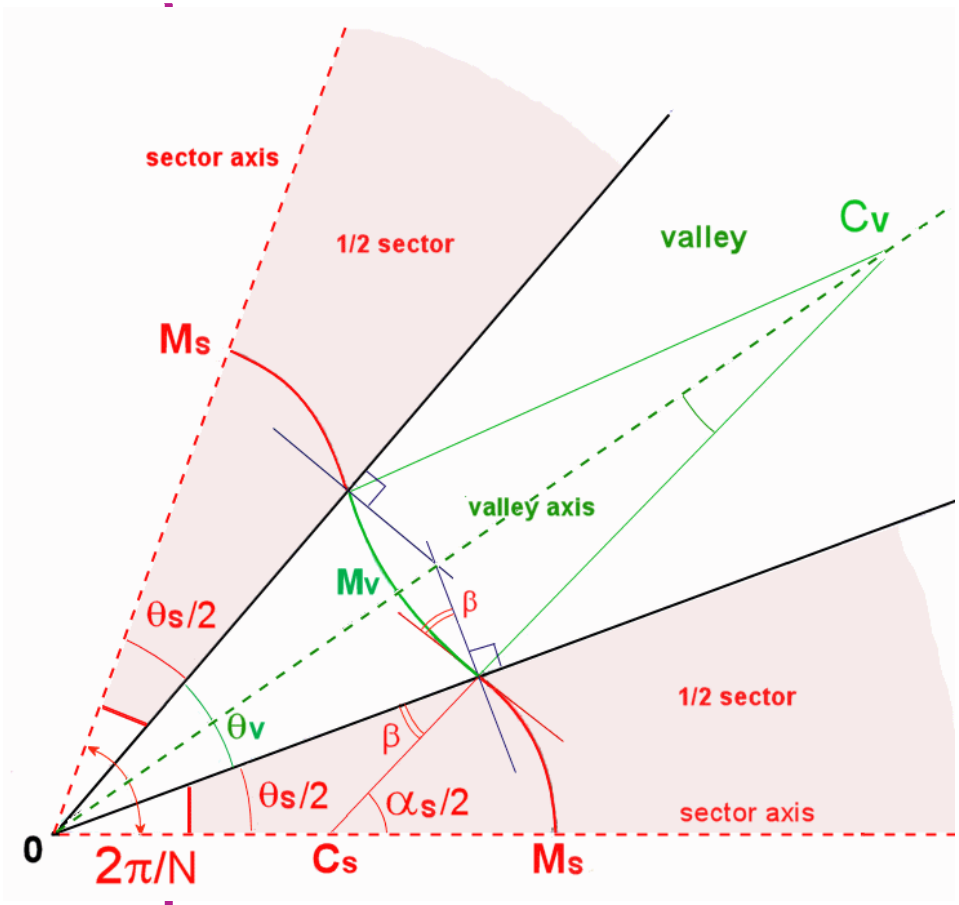
Option **B**: 1600 MeV-5 mA H2+ → 800 MeV-10 mA protons

The reverse valley bends Cyclotron

Proceedings of CYCLOTRONS 2010, Lanzhou, China THA1CCO04

CYCLOTRON AND FFAG STUDIES USING CYCLOTRON CODES

M.K. Craddock*, University of British Columbia and TRIUMF#,
Y.-N. Rao, TRIUMF, Vancouver, B.C., Canada



isochronism:

> positive radial gradient of <B>

> strong vertical defocusing:

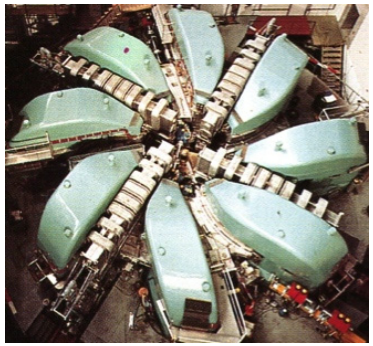
$$\Delta\nu_z^2 = -(\gamma^2-1) = -\,(d\langle B\rangle/dr)r/\langle B\rangle$$

> edge and spiral focusing

$$\nu_z^2 = -(\gamma^2-1)+F^2(1+2\tan^2\zeta)$$

F^2= Field Flutter = $(\langle B^2\rangle-\langle B\rangle^2)/\langle B\rangle^2$

ζ= spiral angle of the sector



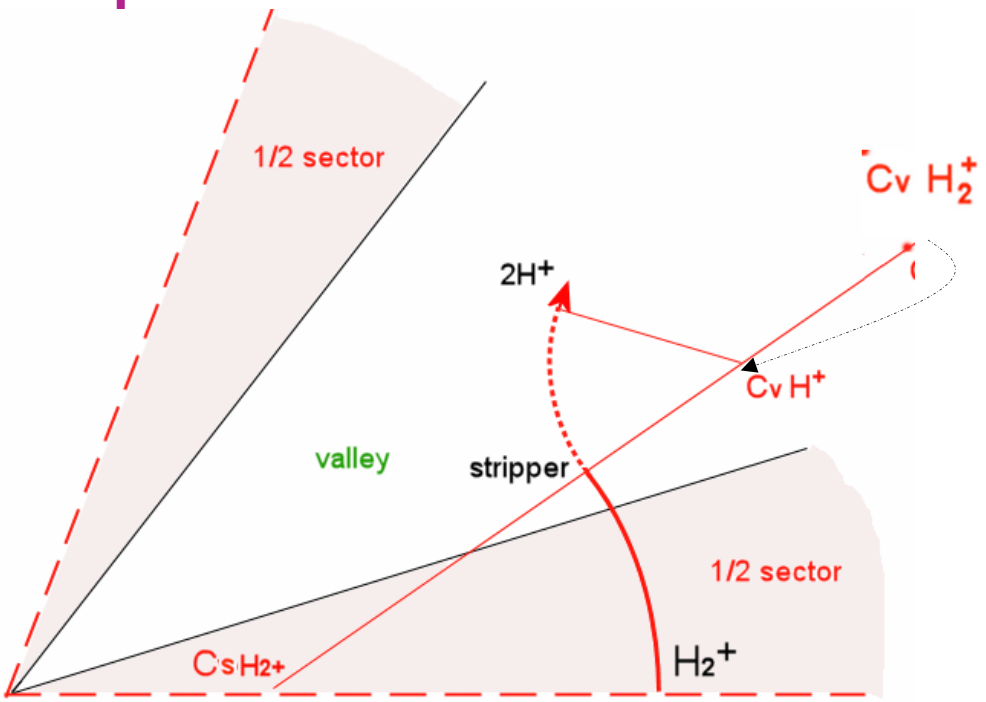
2-A separated sector with reverse valley B:
→ Stronger Flutter ➔ No Spiral needed

The reverse valley bends Cyclotron

Proceedings of CYCLOTRONS 2010, Lanzhou, China THA1CCO04

CYCLOTRON AND FFAG STUDIES USING CYCLOTRON CODES

M.K. Craddock*, University of British Columbia and TRIUMF[#],
Y.-N. Rao, TRIUMF, Vancouver, B.C., Canada



isochronism:

> positive radial gradient of <B>

> strong vertical defocusing:

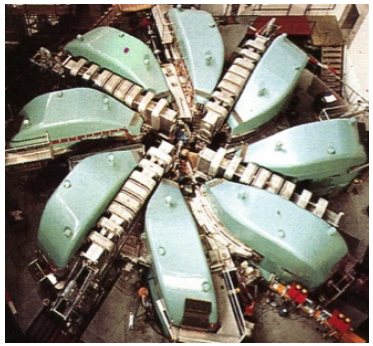
$$\Delta\nu_z^2 = -(\gamma^2-1) = -\,(d\langle B\rangle/dr)r/\langle B\rangle$$

> edge and spiral focusing

$$\nu_z^2 = -(\gamma^2-1)+F^2(1+2\tan^2\zeta)$$

F^2= Field Flutter = $(\langle B^2\rangle-\langle B\rangle^2)/\langle B\rangle^2$

ζ= spiral angle of the sector



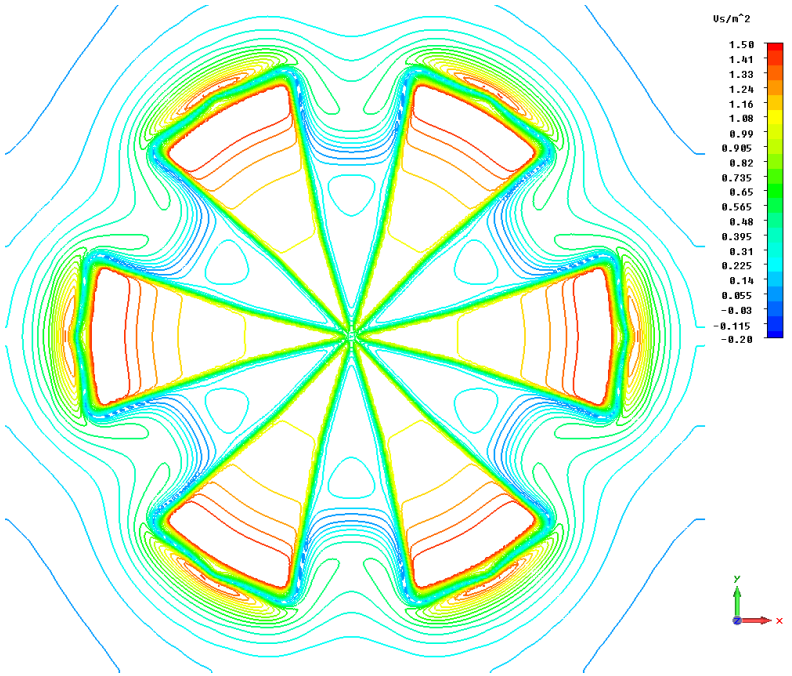
2-A separated sector with reverse valley B:
→ Stronger Flutter ➔ No Spiral needed

Proton Extraction is more simple

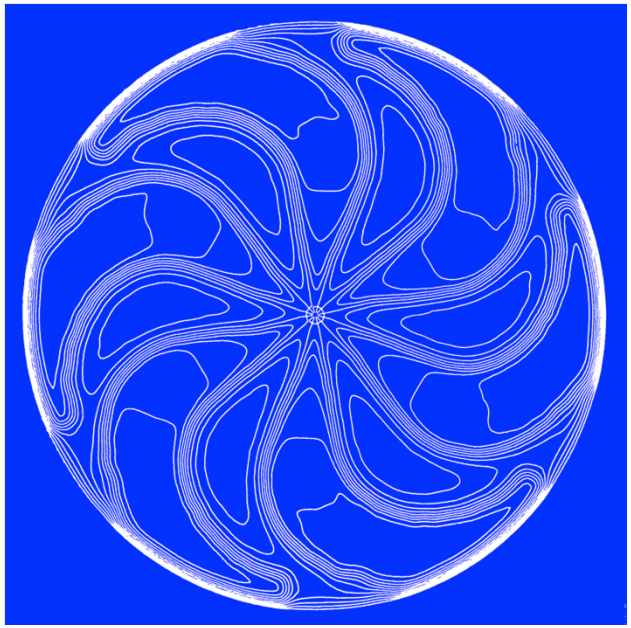
- by stripping of H2+ > very short !
- by a bump, i.e. « Septum free extraction »

Single stage Cyclotrons Magnetic Fields

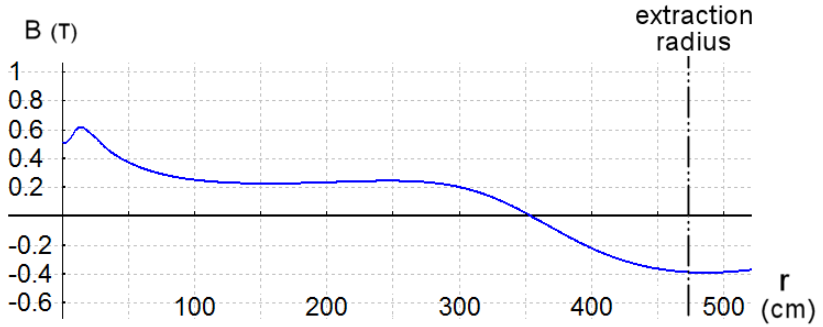
S2CD-600 MeV H+
With reverse Bv field



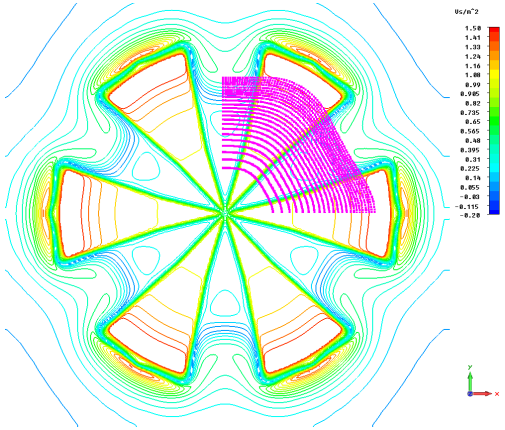
TRIUMF-520 MeV H-

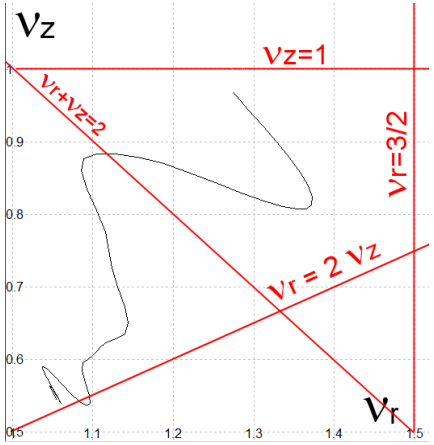


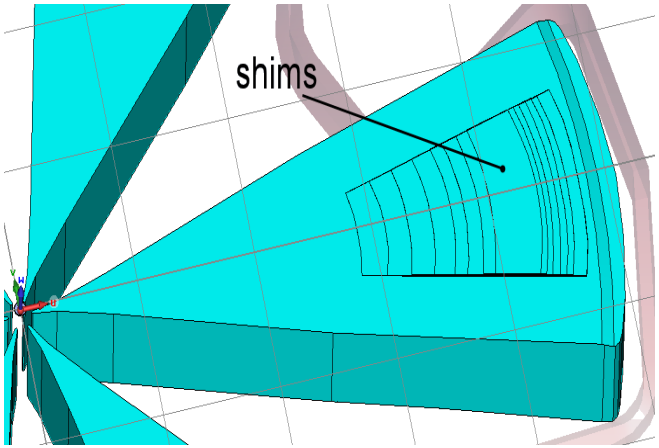
B on the valley axis

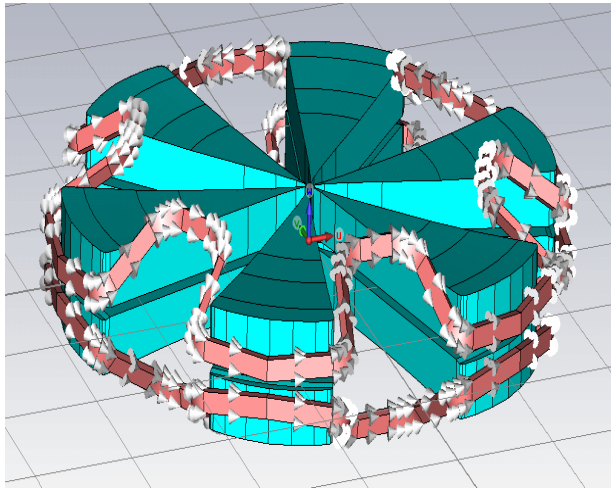


The 600 MeV proton S2CD









> Large complex Coils: 1.1 MAturns/coil

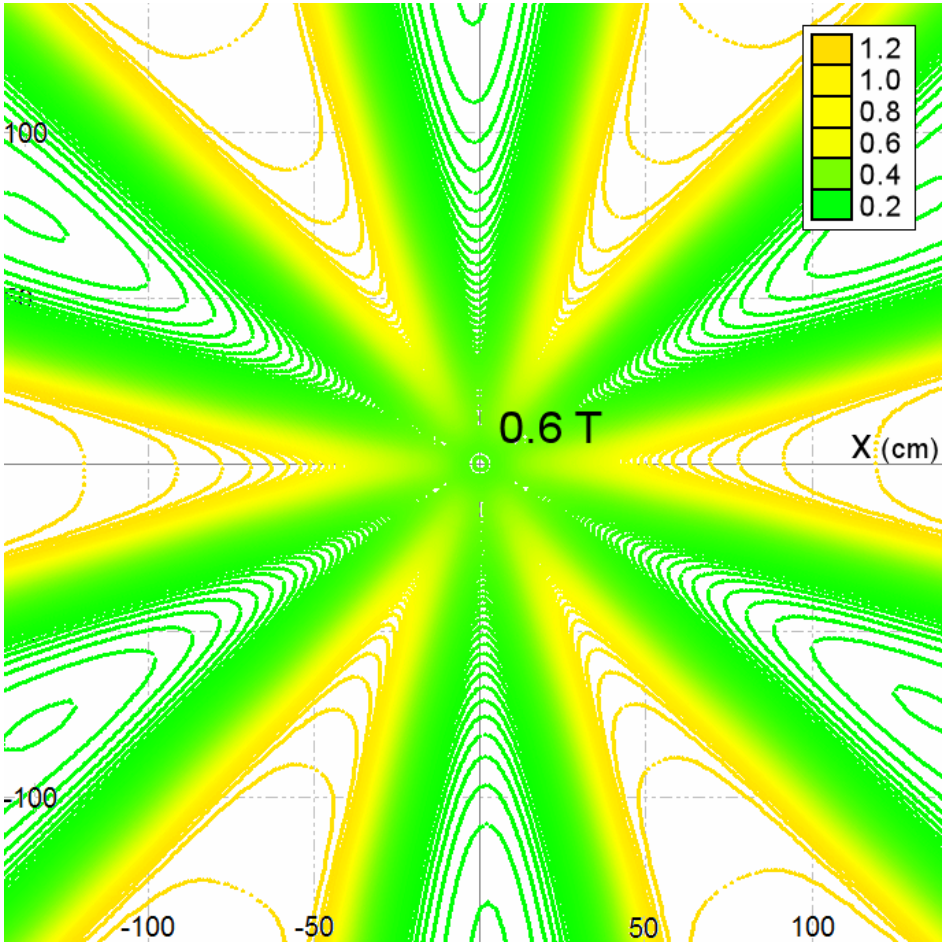
. Rmin: 3.6 m Rmax: 5.1m

. Total length ~48m

. Superconducting coil: Section: 130 mm * 280 mm Current density 31 A/mm²

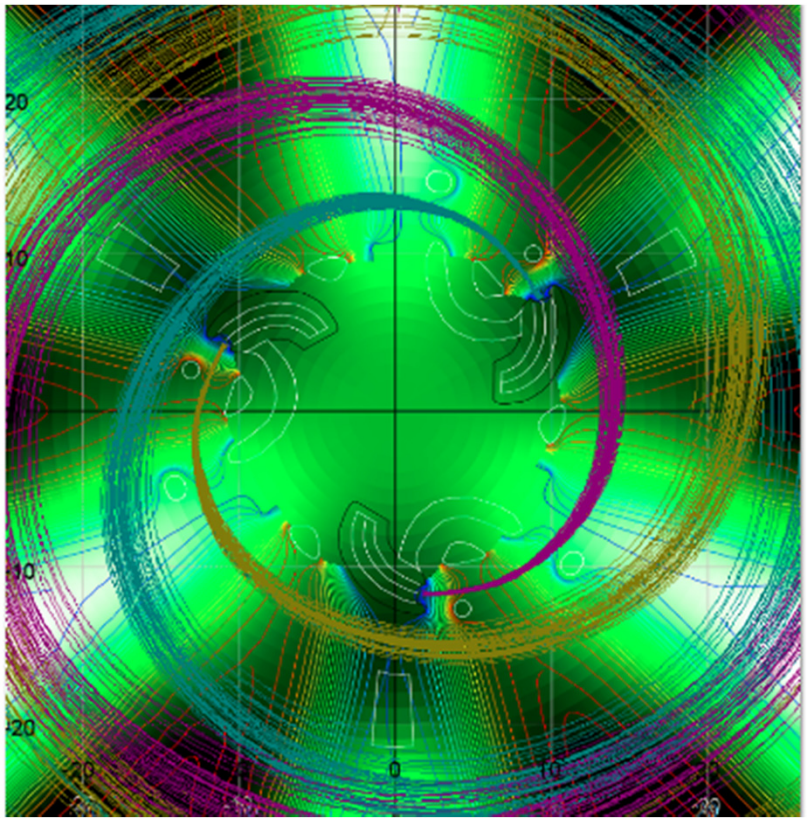
. Water cooled Copper coil: Section 220* 470 mm Current density 10 A/mm²

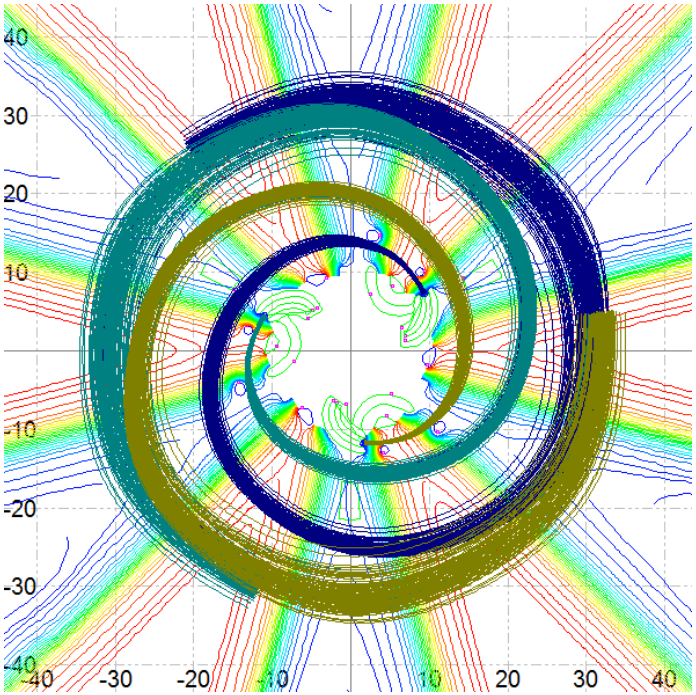
Triple injection central region



Triple injection central region

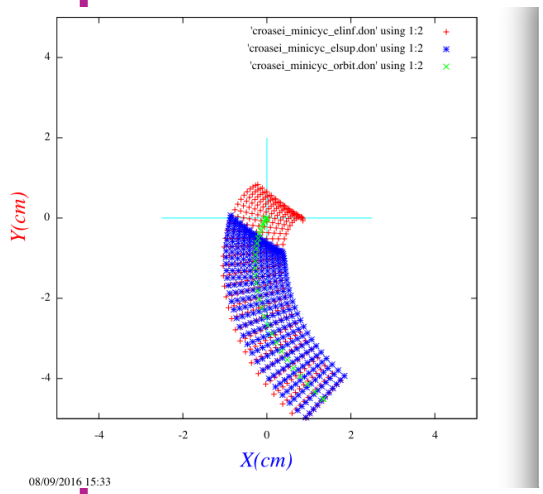
major advantage: low B-field in the central region
> 3 axial injections
➔An injector cyclotron is not needed anymore !



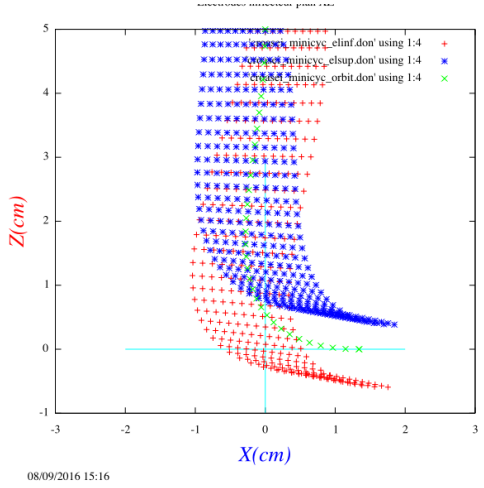


40° of phase acceptance
3 separated beams up to 1.8 MeV

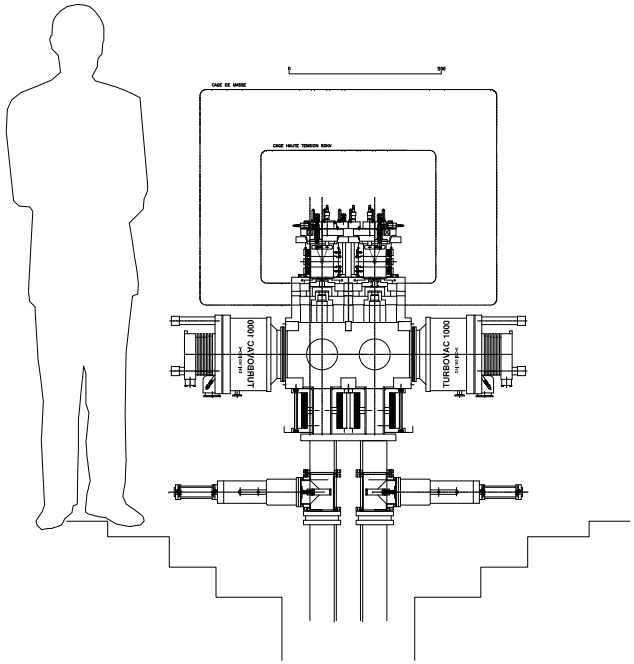
A single HV Platform for 3 Ion sources feeding 3 axial injections with spiral inflectors



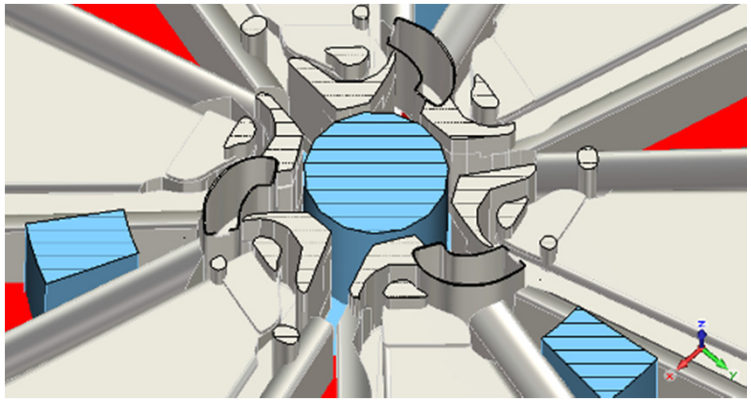
Median plane



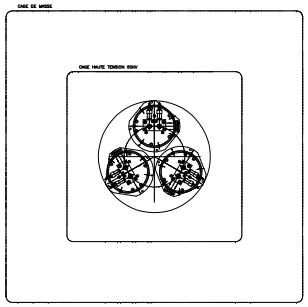
Vertical plane



E_{inj}= 60 KeV
E=20 KV/cm
k=0.6
k'=-0.15

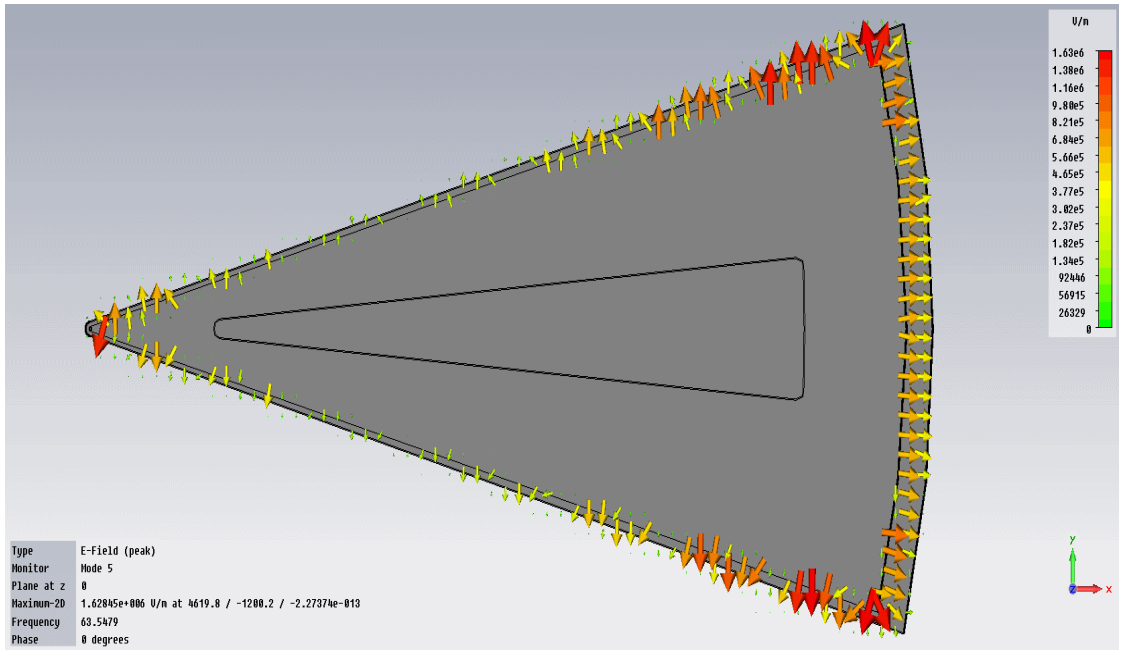


The crowded Central region

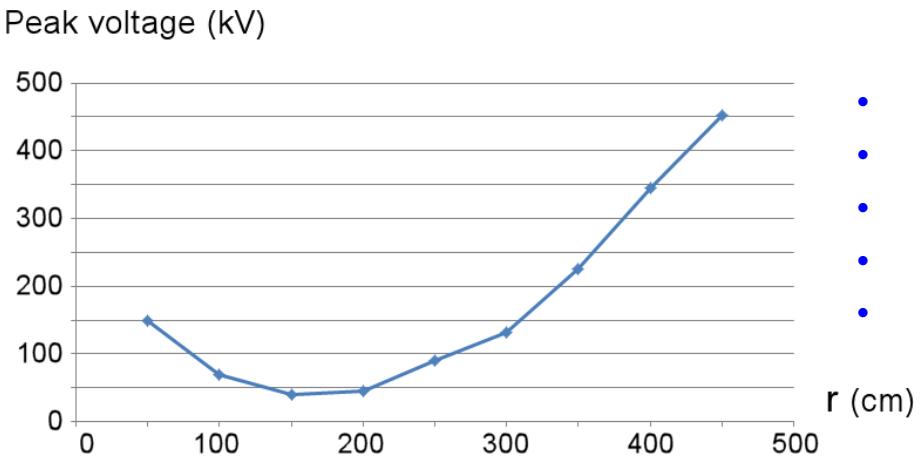


The 60 KV platform

RF Delta double gap tapered walls cavities

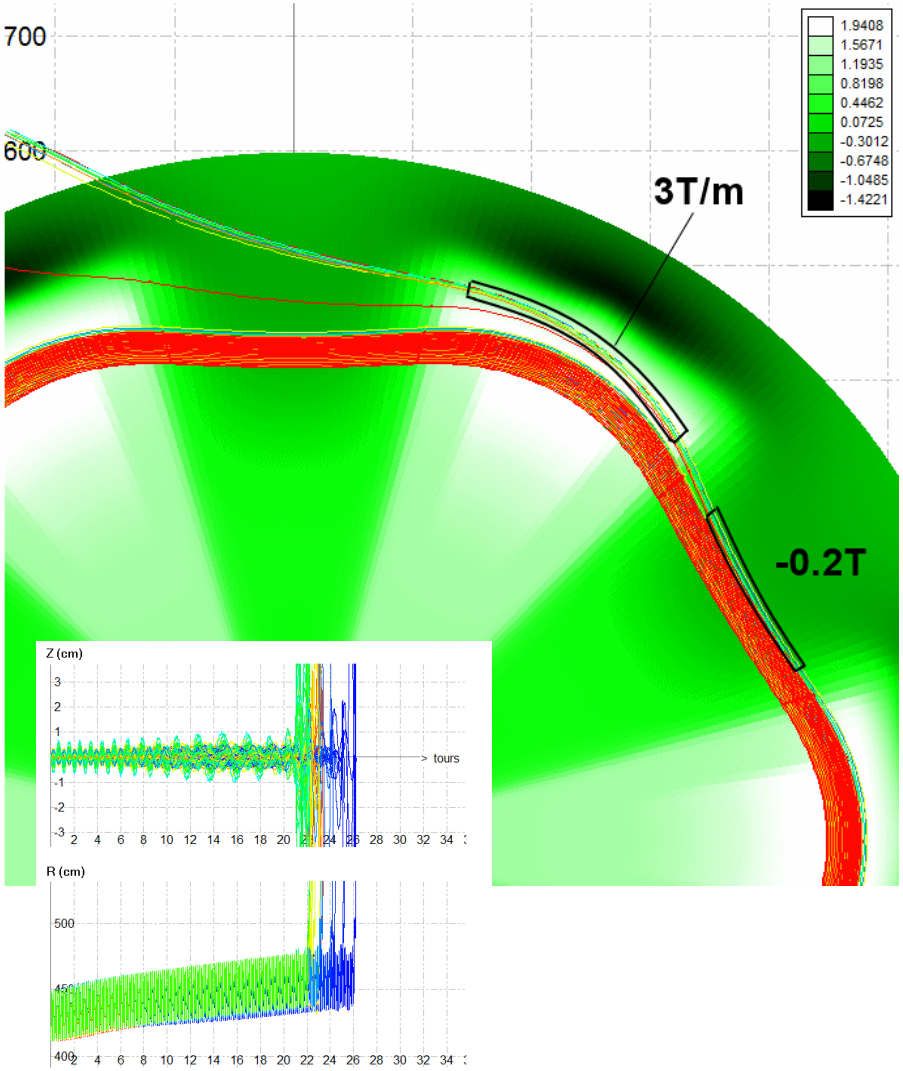


From CST



- 6 cavities at 49 MHz (Option H+)
- 1000 KW beam power /cav + 350 KW losses /cav
- 2 RF coupling loop/window
- 2 amplifiers (electron tubes)/cavity
- Large stem allows to install pumping

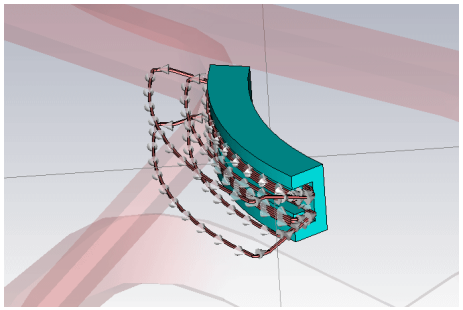
The septum free Extraction (H+)



2 channels:

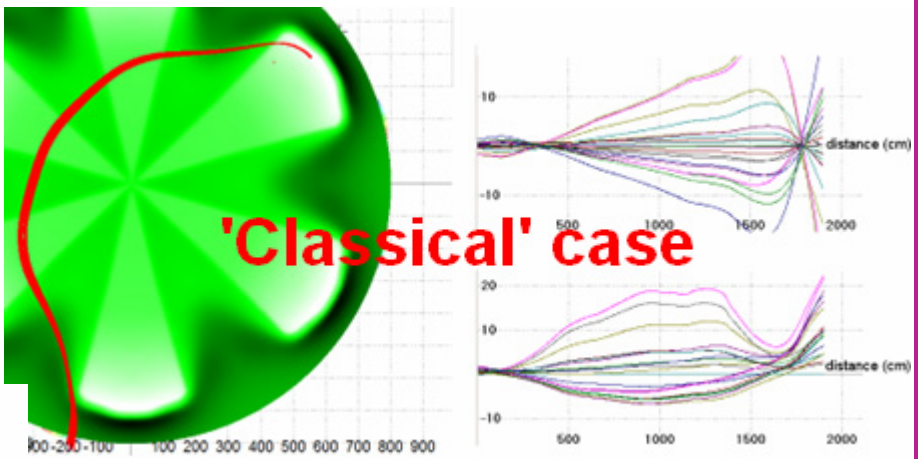
1st) Bump Channel: -2 kG to increase the -2 kG valley field

2nd) Foc. Channel: + 3T/m in the sector field.

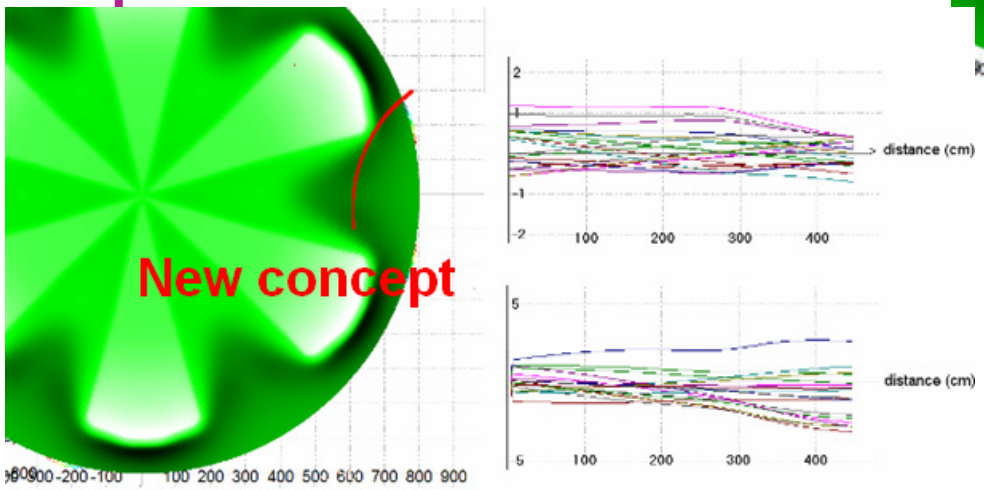


H2+ Extraction

short trajectory, no focusing elements, no complexity



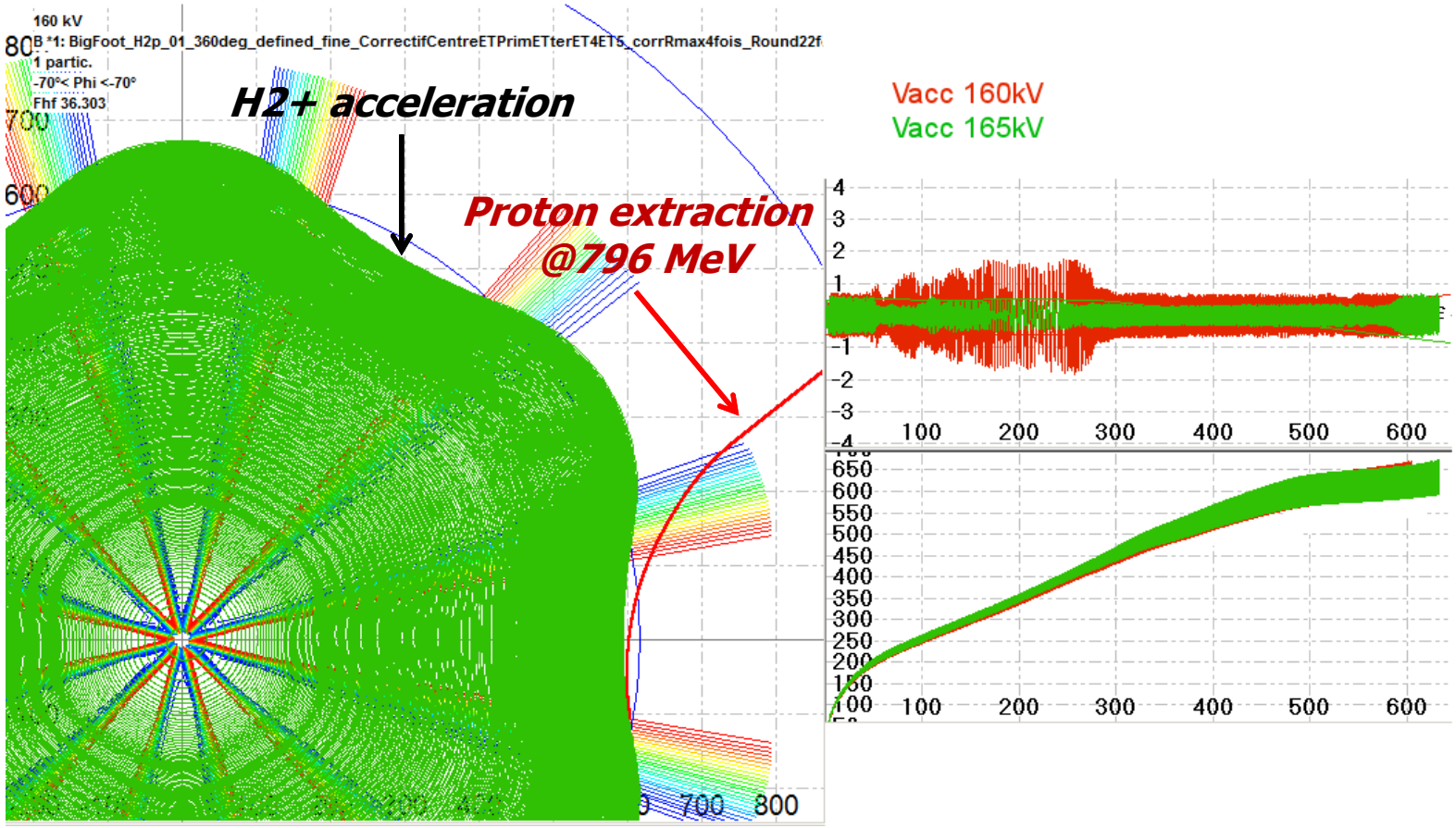
Initial condition:
5mm vertical amplitude @ 155MeV



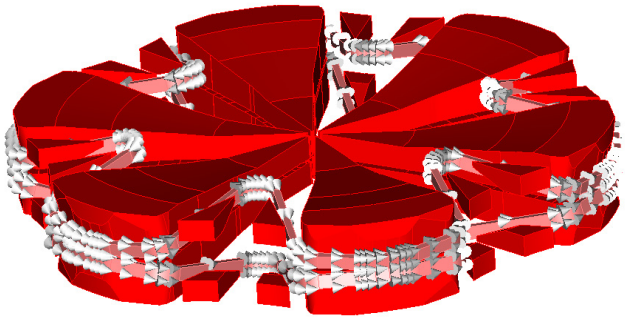
Shorter trajectory if the stripping foil is located in a valley: leads to a smaller extracted beam

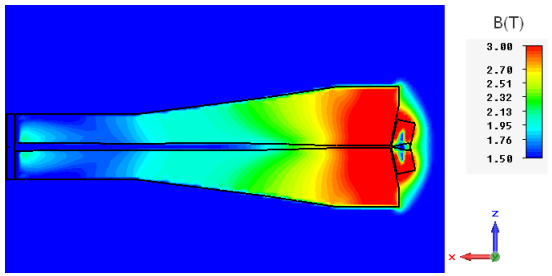
H2+ Extraction

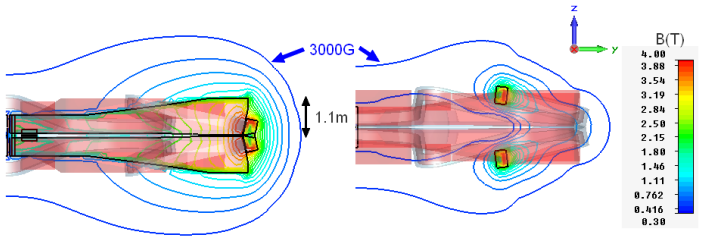
short trajectory, no focusing elements, no complexity

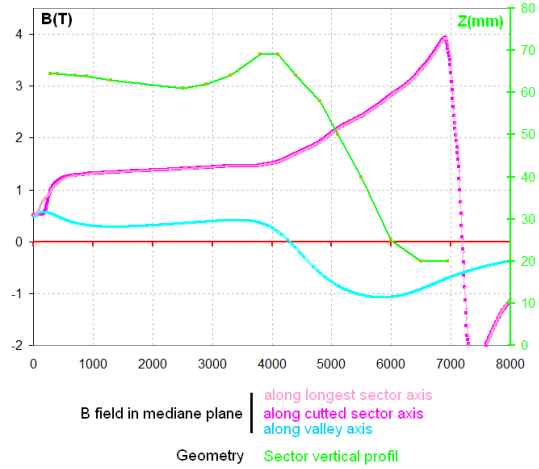


The 1600 MeV H2+ option









> 6 straight hill sectors (14 tons)
> 12 small valley sectors

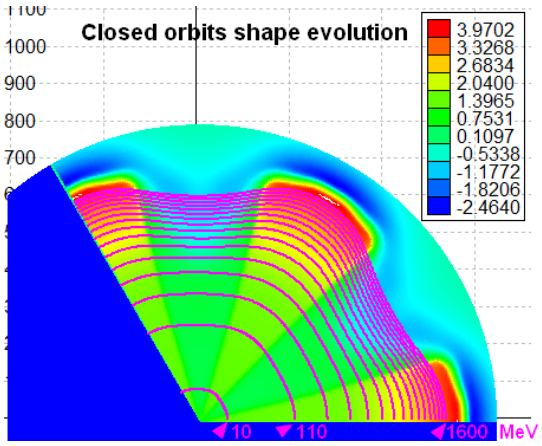
> Superconducting Coils

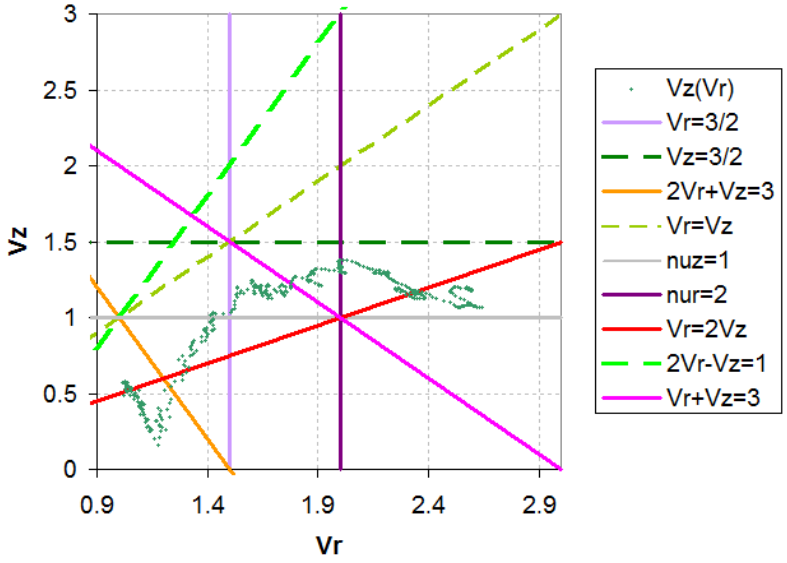
. Rmin: 4.2m Rmax: 7.1m

.Total length ~50m

.Section: 160 mm * 310mm

.Current density 55 A/mm²





Conclusions

Critical Issues of Single Stage designs

1-Large superconducting coils :

- Mechanical design of a complex shape with bends
- Possibility to use MgB2 for a cryo-free cooling system ?

=> Tests and prototypes are needed

2-High power RF cavity design to handle 1.4 (H+)-1.6(H2+) Mwatt :

- 2 RF Windows + 1 Amplifier/window
- relation between cavity & extraction system

3-Multi Injection :

- a single HV platform to house 3 ion sources is being investigated

4- H2+ acceleration :

- interaction with residual gas: High vacuum is needed (cf. Daedalus)
- Dissociation of the vibrational states producing high energy protons (according to experience, filament-based multicusp ion sources could be more relevant)
- stripping foil lifetime: 500 mA.hours outstanding performance achieved at TRIUMF with oriented pyrolic Graphite (courtesy of Yuri Bylinskii)

- ***Single stage accelerator***
  - Compact system - low construction budget and Low operational cost
  - Less components than traditional solutions → high reliability
  - No transport / no matching issues between stages

- ***3 sources + axial injection lines***
  - redundancy
  - reliability
  - Intensity Flexibility:
    - 8 mA protons>4mA H2+: 2 Ion sources on + 1 Ion source in Stand-by
    - 12 mA protons>6mA H2+: 3 Ion sources on

- ***Simplified Extraction system*** : No Septum required
  - Increasing reliability
  - less activation => easier maintenance

A single stage 600MeV H+ or 1600 MeV H2+ cyclotron with Reverse Valley Field: a good candidate for an industrial ADS demonstrator.

AIMA

Accelerators for Industrial and Medical Applications

Thank you for your attention