Single Stage Cyclotron for an industrial ADS demonstrator

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

** Partner in the CYCLADS Proposal*

Eucard2 Meeting, CERN February 8th 2017

The requirements for an industrial 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)

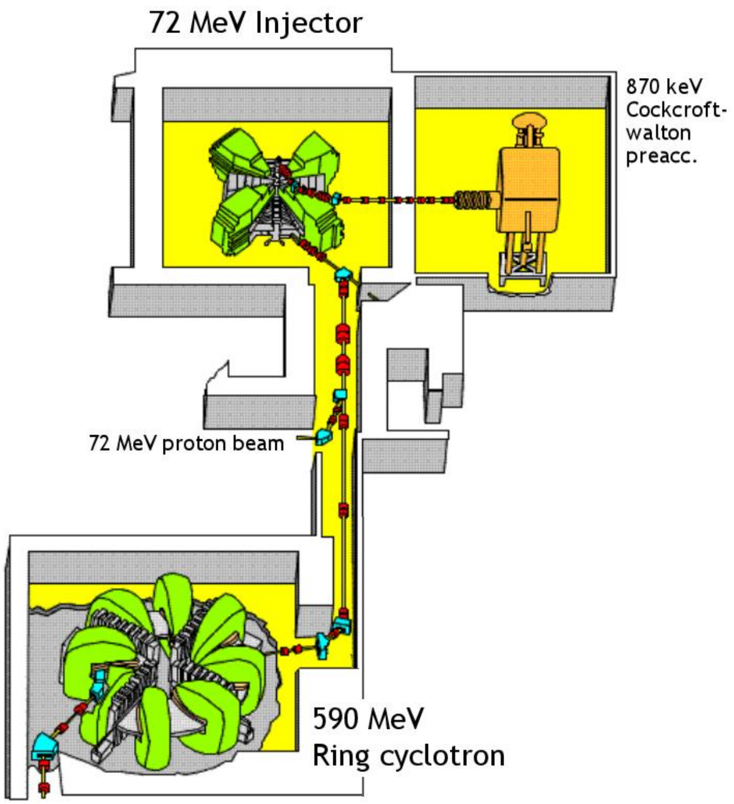
-Optimized Energy efficiency: $\eta = P_{beam}/P_{grid}$

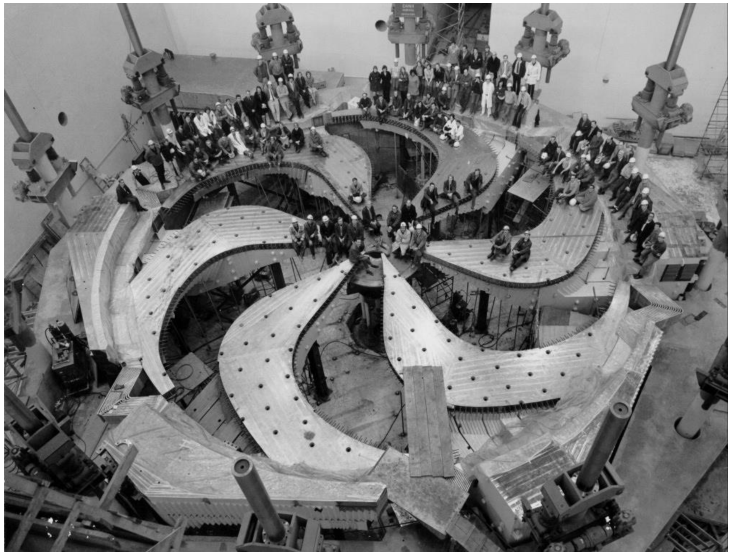
-Costs.

High intensity Cyclotrons:
The lessons from the pioneers:

PSI – H^+ 590 MeV
Multi stage cyclotron based on single turn extraction

TRIUMF – H^- 520 MeV
Single stage cyclotron based on stripping extraction





1) PSI: Single turn extraction

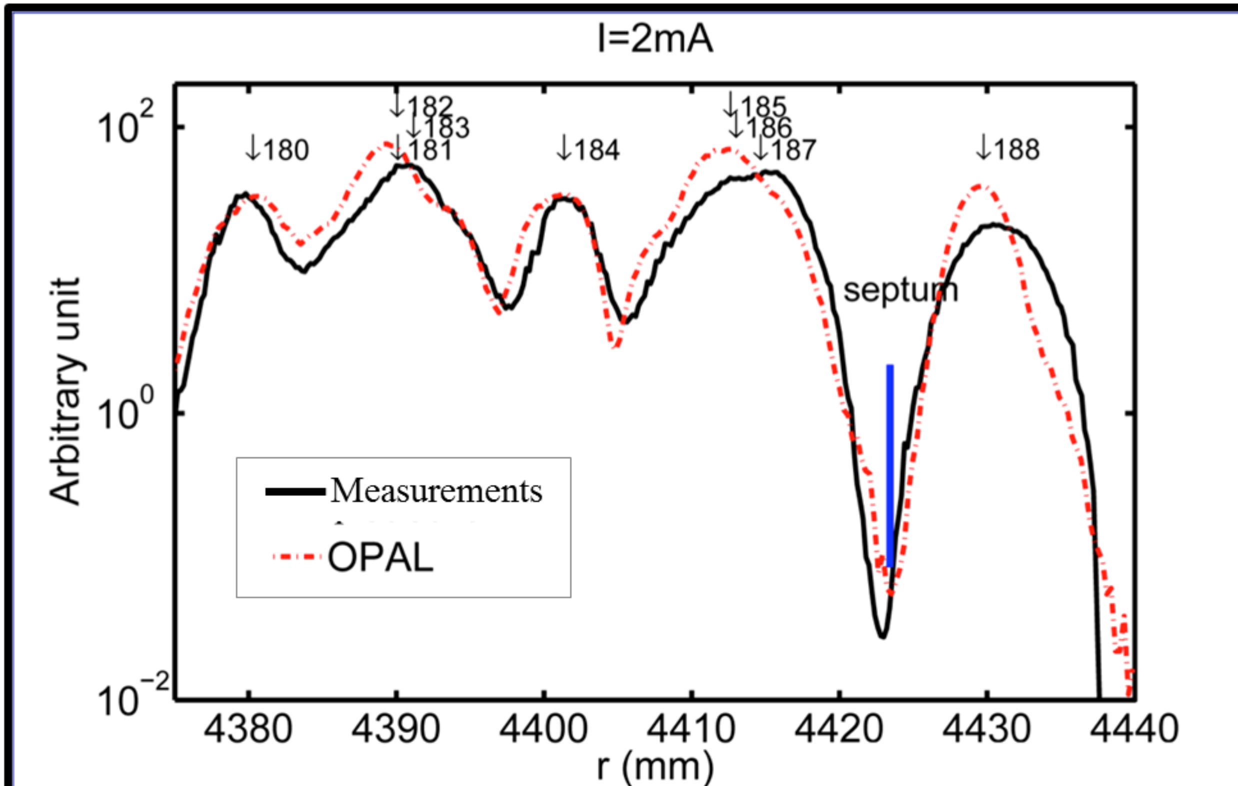
Excellent agreement simulations/measurements

> Increasing the separation δ between turns

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

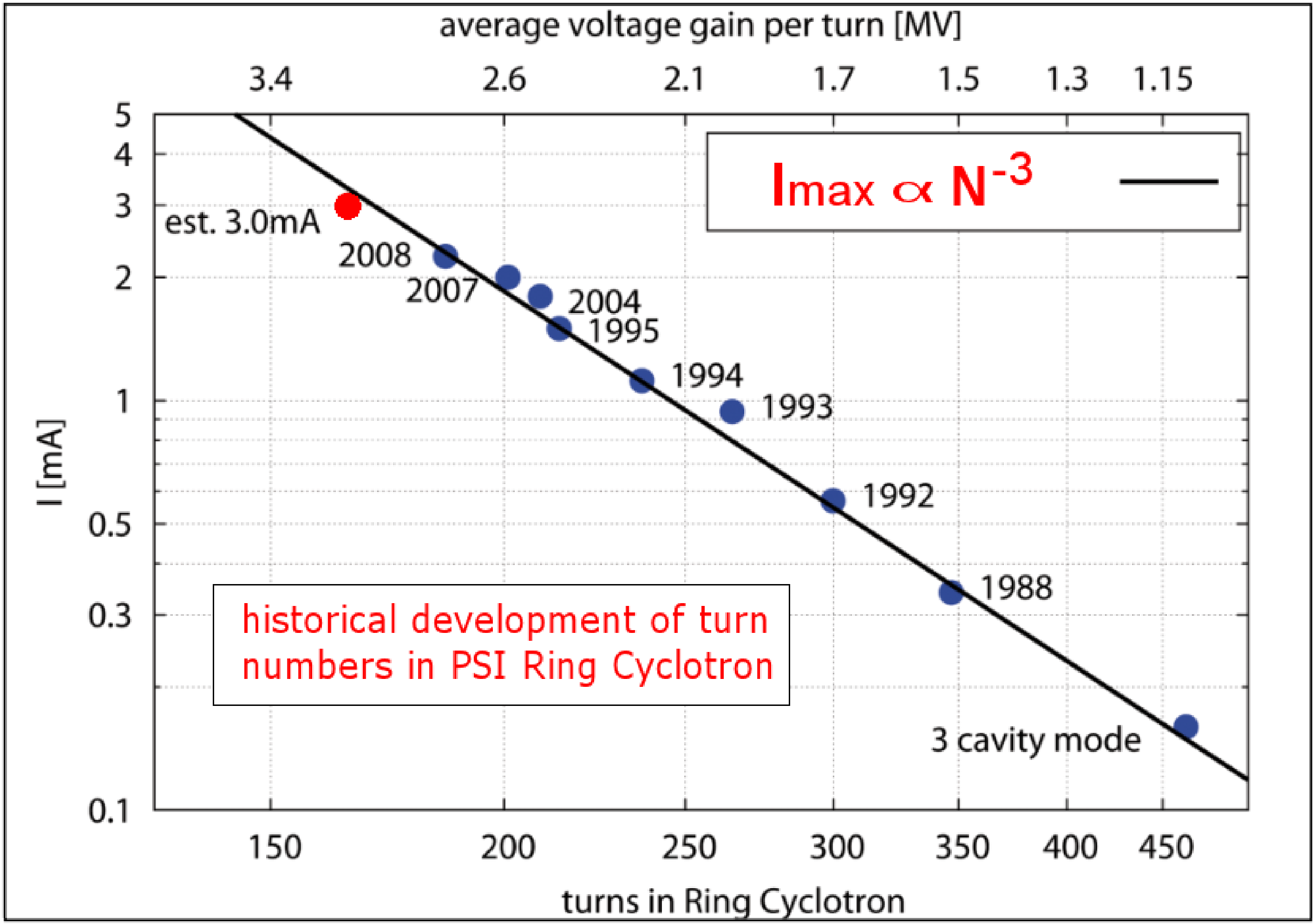
> Reducing the number of turns N with

High power new RF copper cavities.



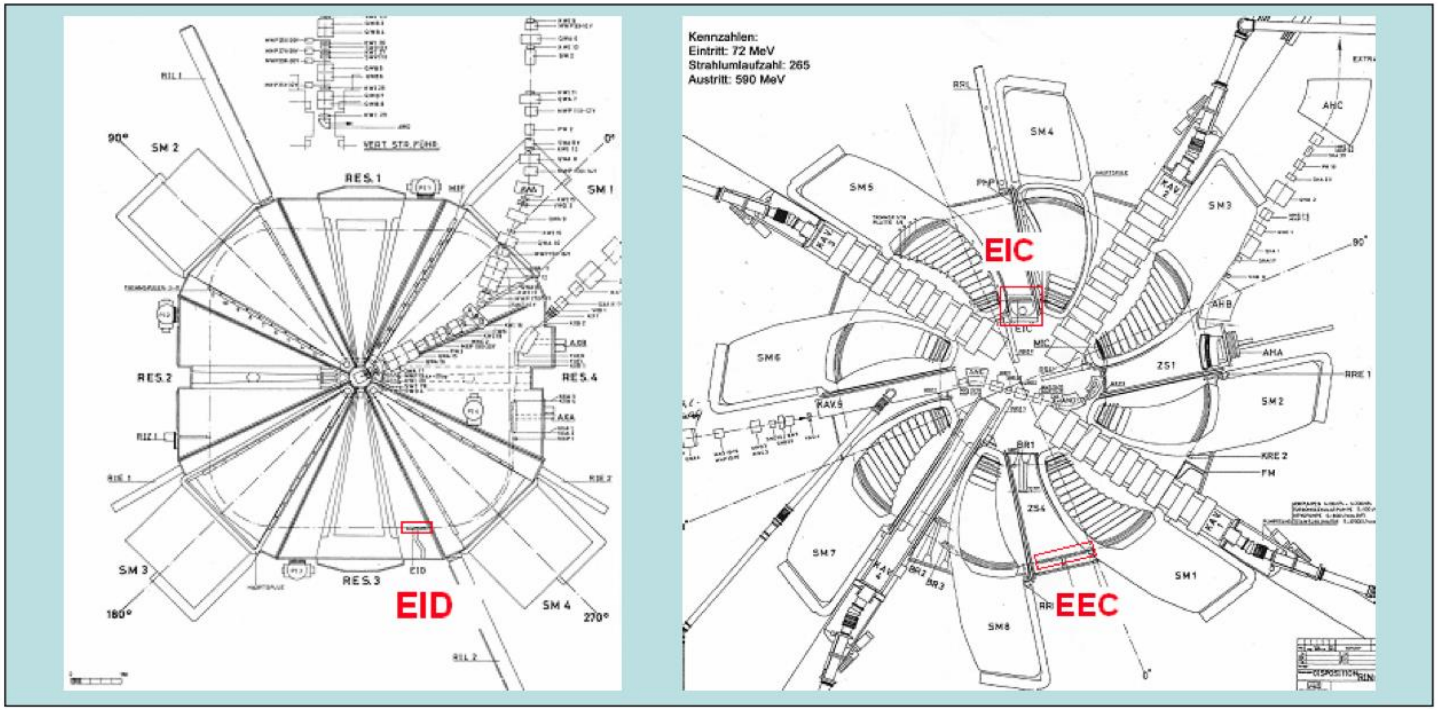
[Y.J.Bi (PSI & Tsinghua Univ.), A. Adelmann]

The successful Werner Joho law for intensity !



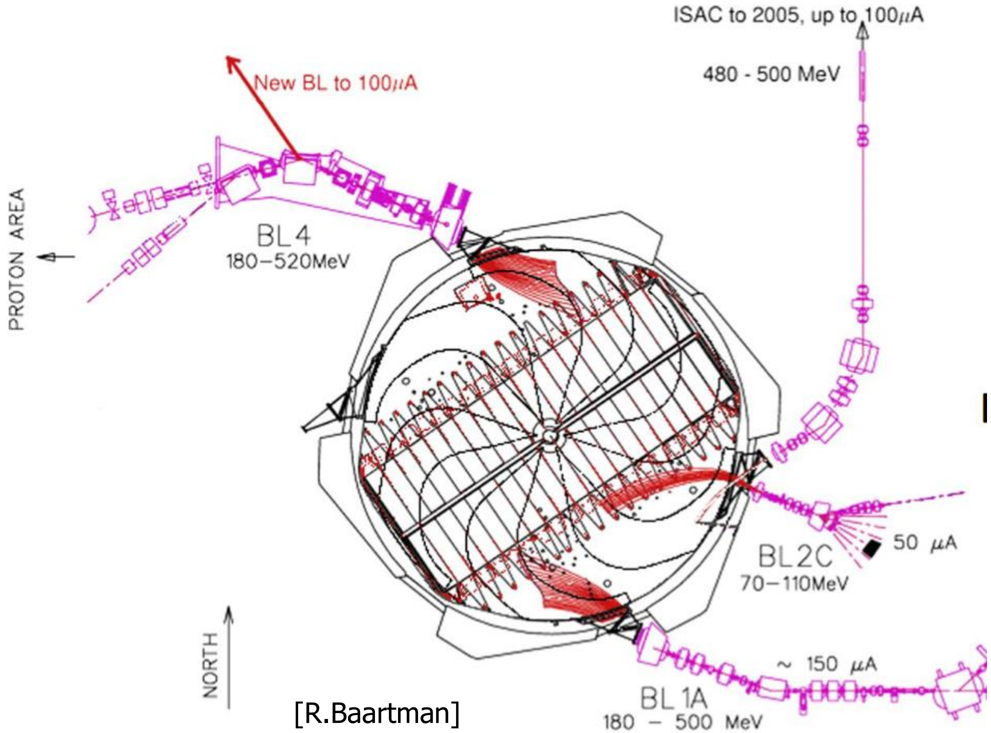
The injection/extraction devices of the multi-stages solution

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



[R.Baartman]

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

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

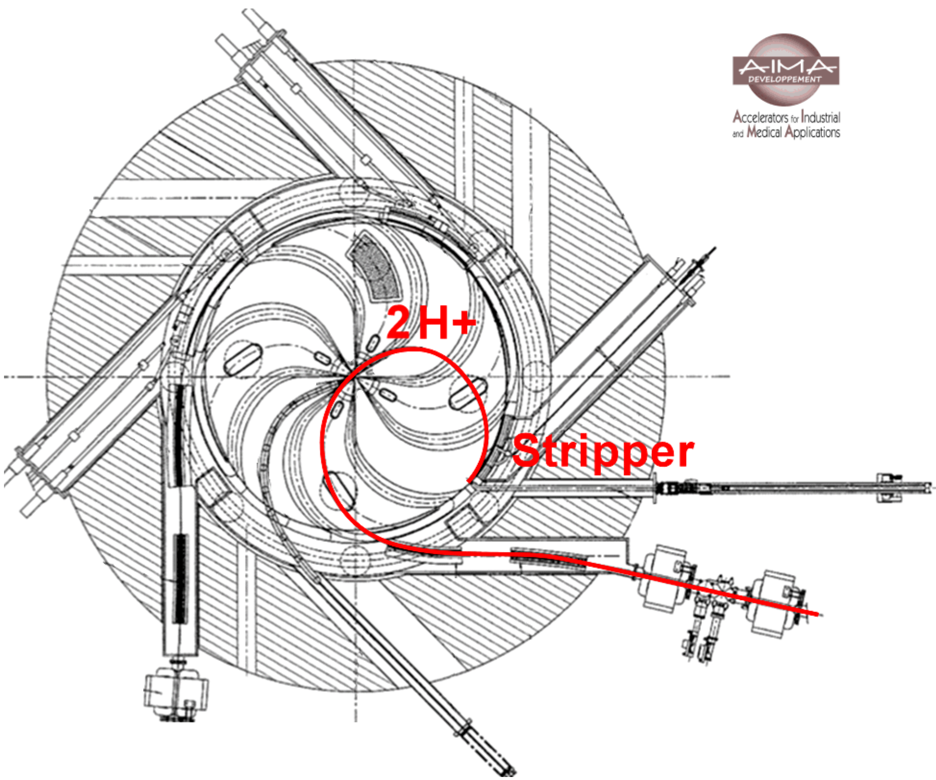
Well known method (low energy cyclotrons):
Drawback: The relativistic electromagnetic stripping of H- (0.754 eV)
➔ For 520 MeV, Bmax in the sectors 6 kGauss ➔ Large machine for 600 MeV

H2+ acceleration and inwards extraction of H+ by stripping

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

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

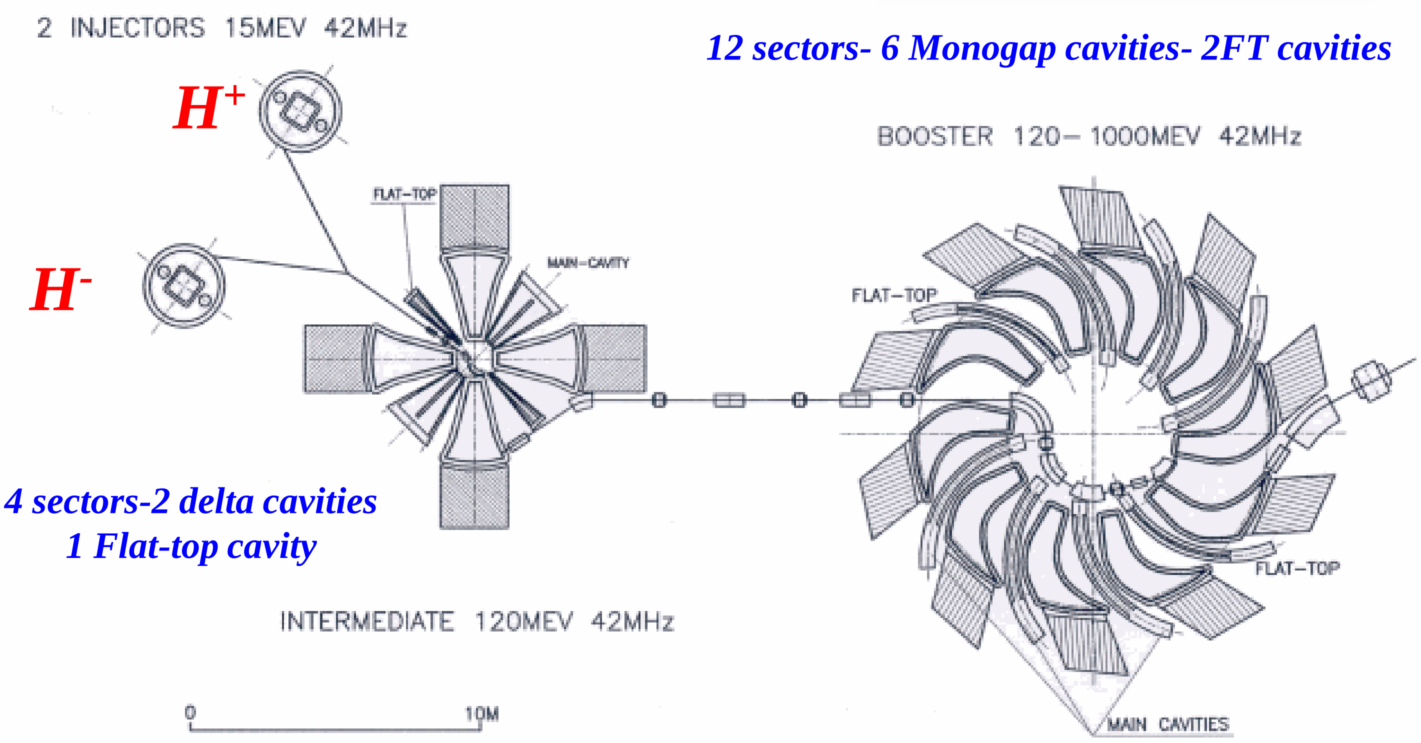


e.g. Trade driver proposal (ENEA - AIMA)
to deliver 2mA-110 MeV protons
by stripping of 1mA, 220 MeV H2+

Other examples of high power Cyclotrons:

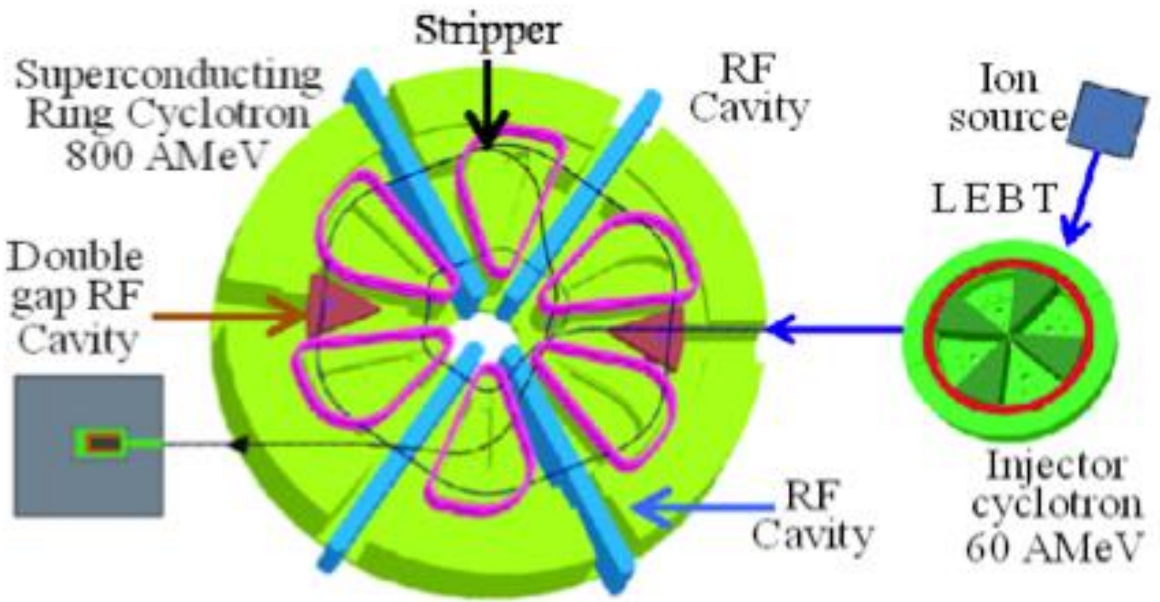
1995: Inspired by PSI the early proposal for driving the Energy Amplifier with a 1 GeV 3 stages Cyclotron

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



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+**

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

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

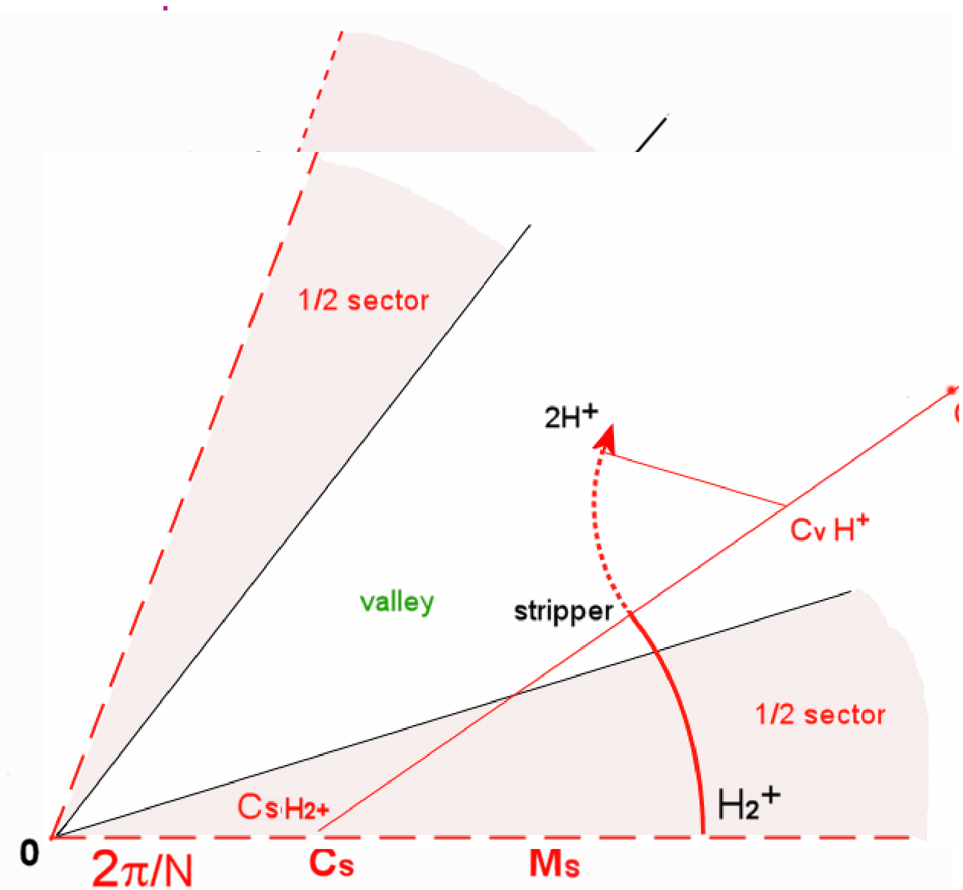
Option **B**: 1600 MeV-5 mA H2+ → 800 MeV-10 mA protons

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:

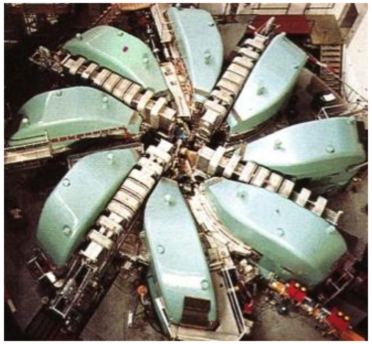
$$\Delta\nu_z^2 = -(\gamma^2-1) = -(d\langle B\rangle/dr)r/\langle B\rangle$$

> 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:

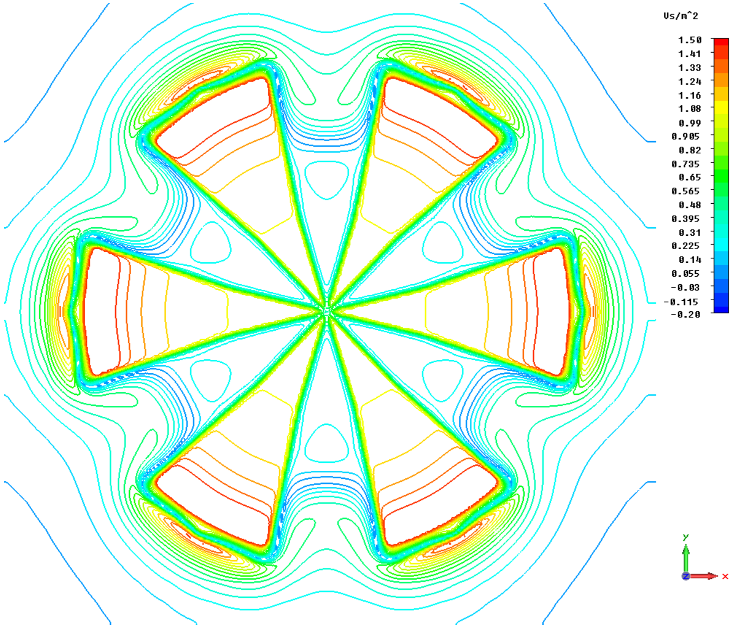
→ **Stronger Flutter → No Spiral needed**

Proton Extraction is more simple

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

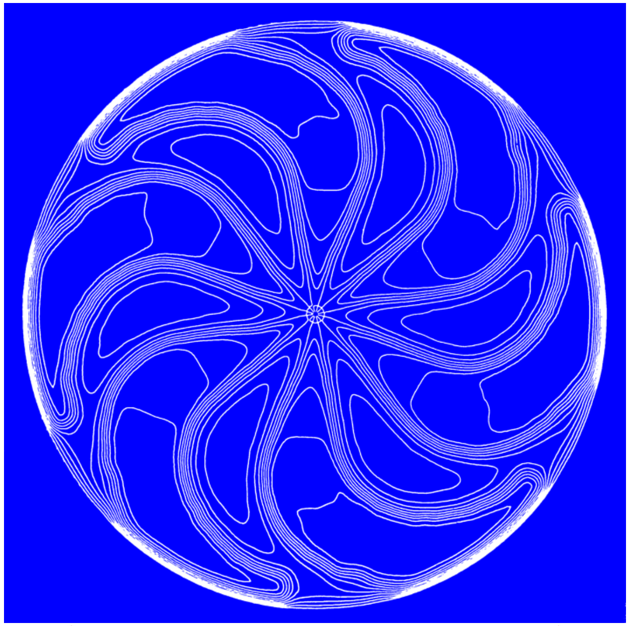
Single stage Cyclotrons Magnetic Fields

S2CD-600 MeV H+
With reverse Bv field



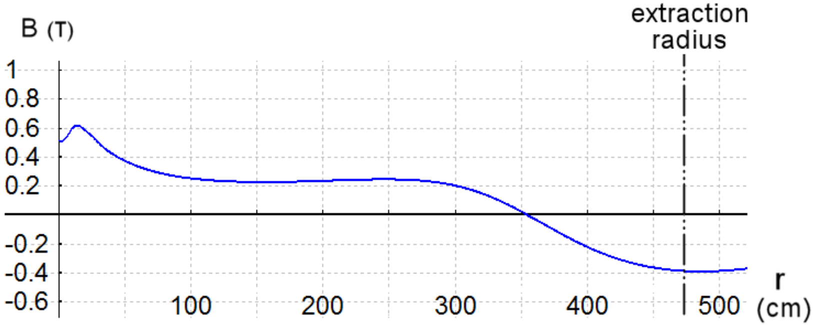
10m

TRIUMF-520 MeV H-

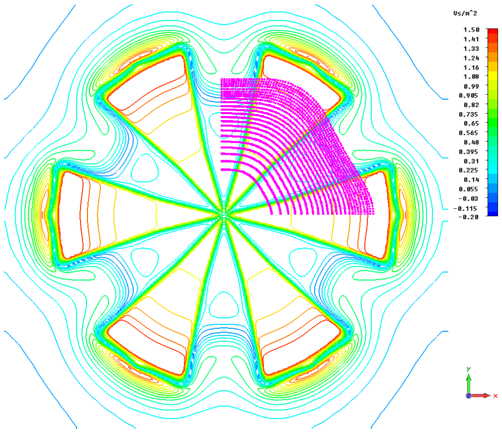


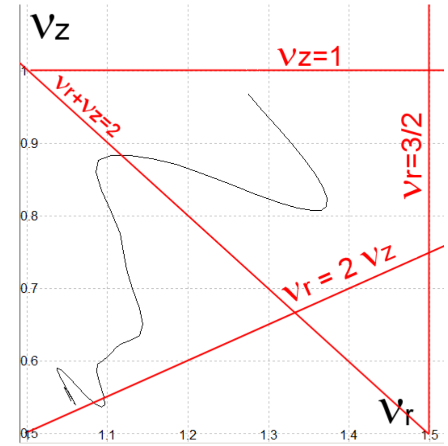
15m

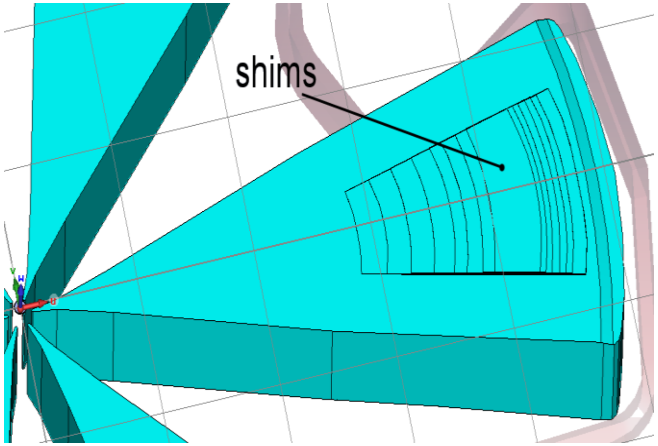
B on the valley axis

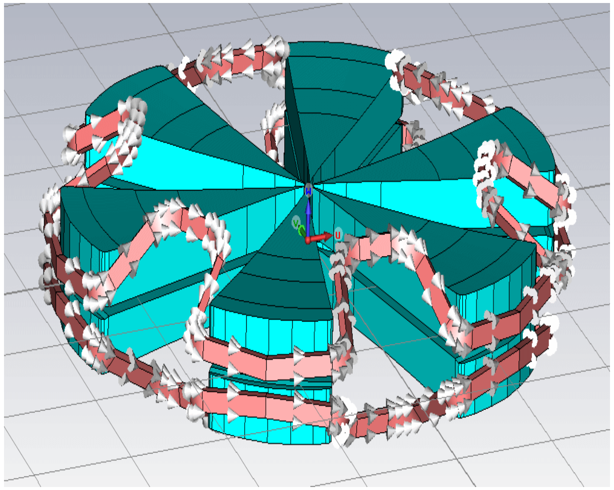


The 600 MeV proton S2CD









> 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

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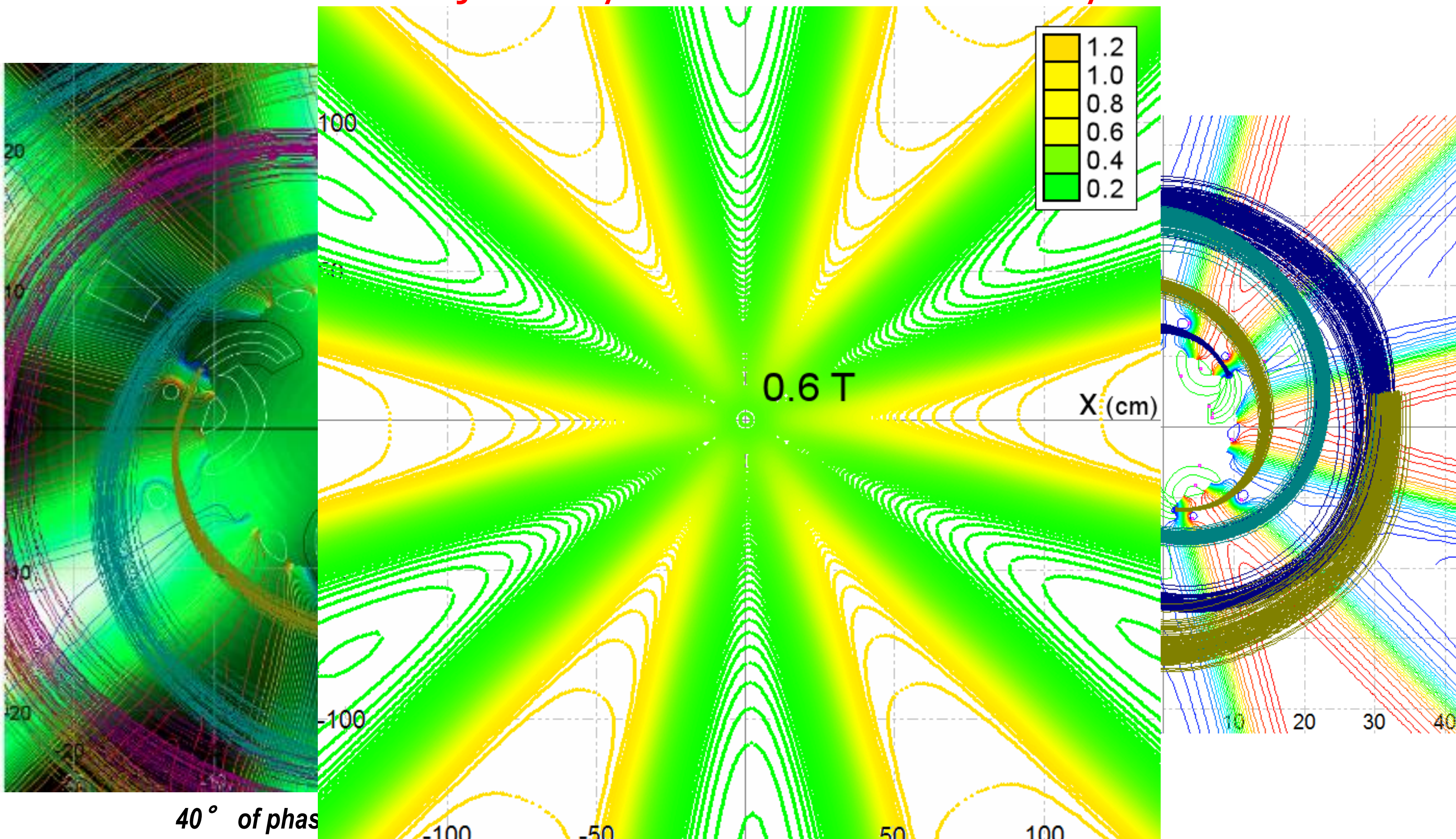
Triple injection central region

major advantage: low B-field in the central region

> 3 axial injections

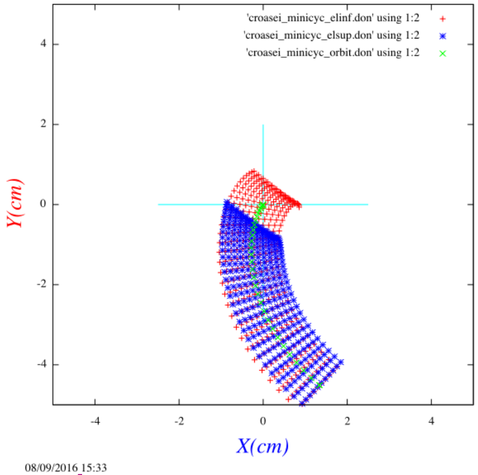
➔An injector cyclotron is not needed anymore !

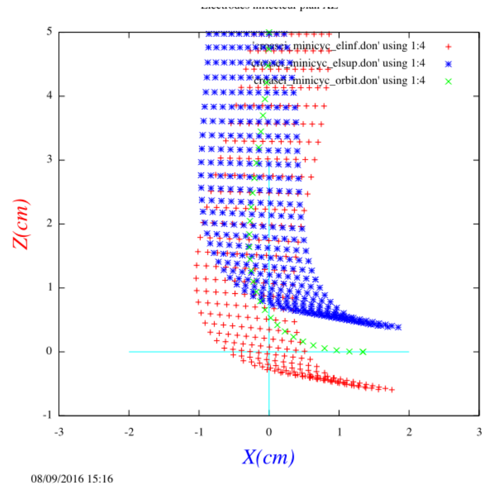


40° of phas

3 separated beams up to 1.8 MeV

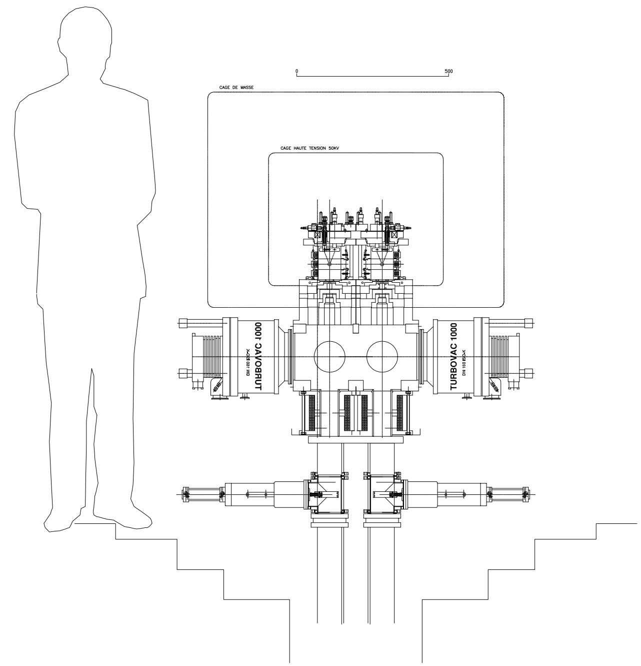
A single HV Platform for 3 Ion sources feeding 3 axial injections with spiral inflectors



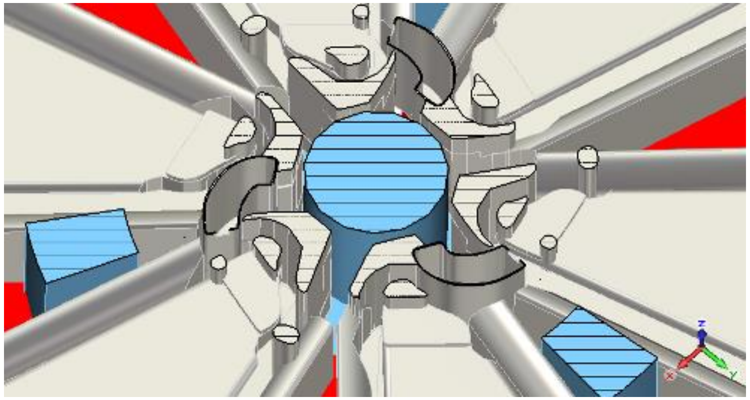


Median plane

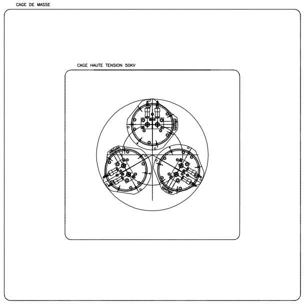
Vertical plane



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

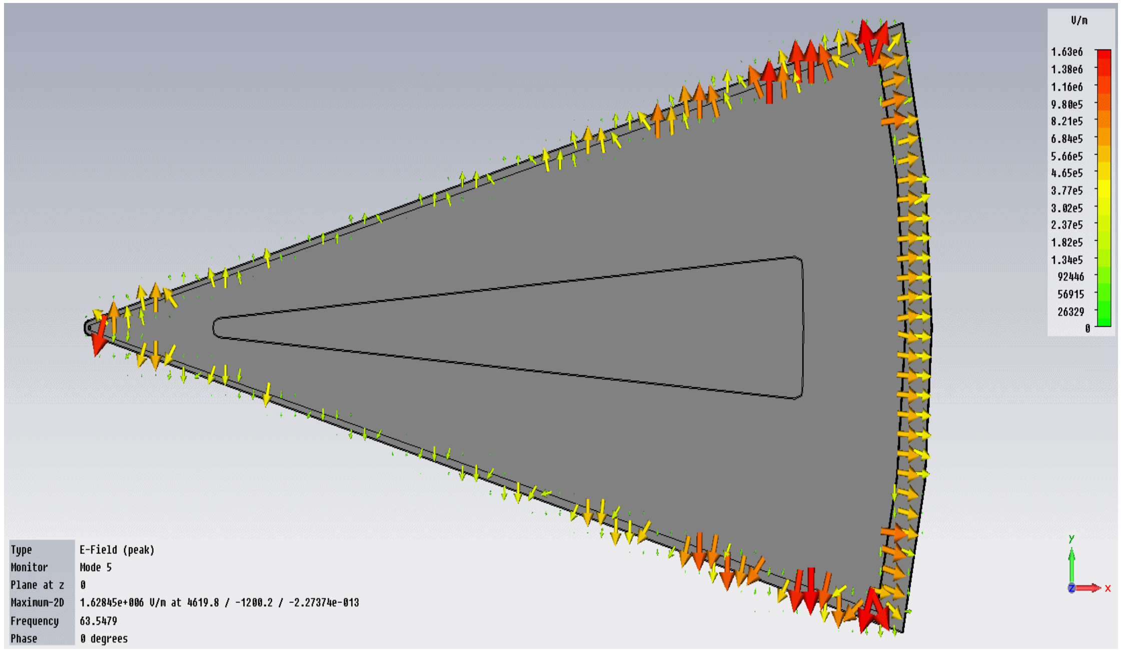


The crowded Central region

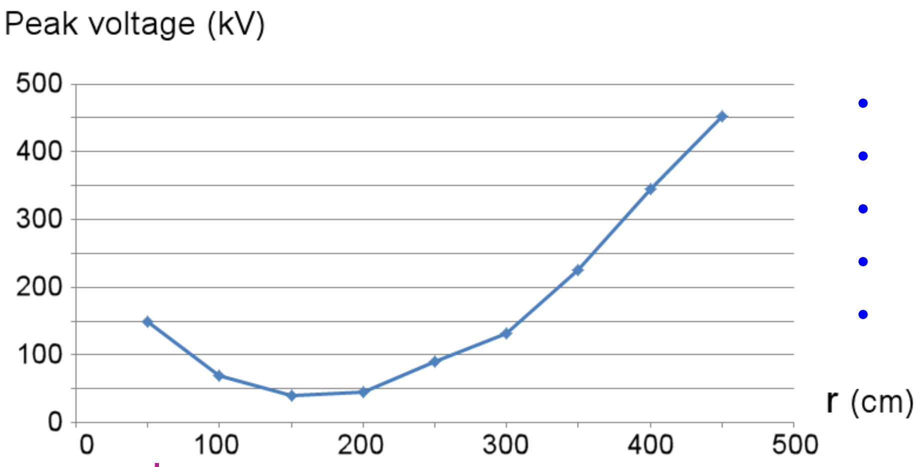


The 60 KV platform

RF Delta double gap tapered walls cavities

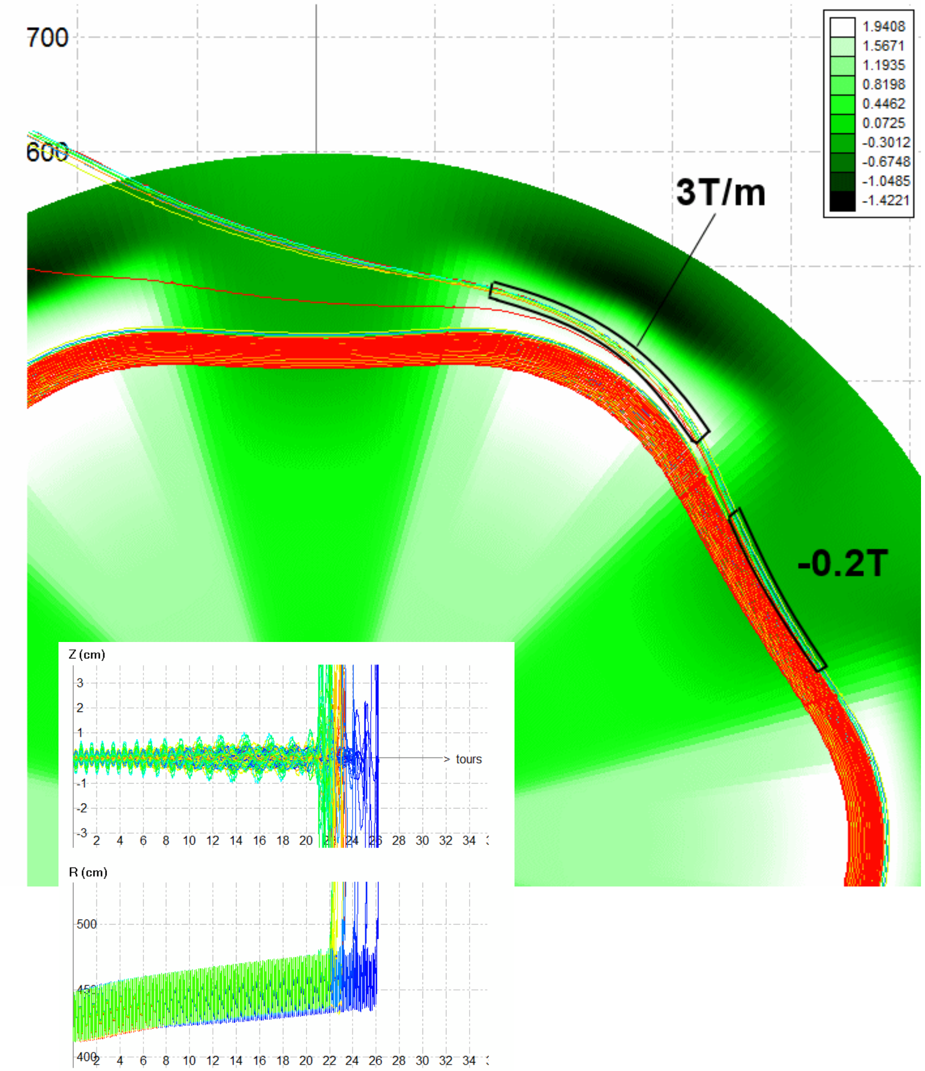


From CST



- 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

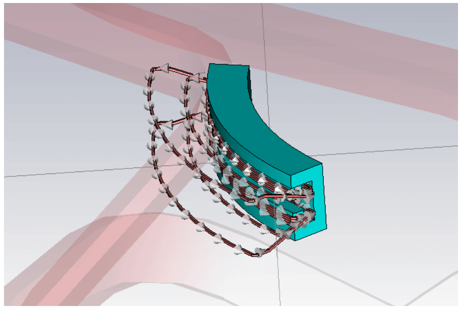
The septum free Extraction (H+)



2 channels:

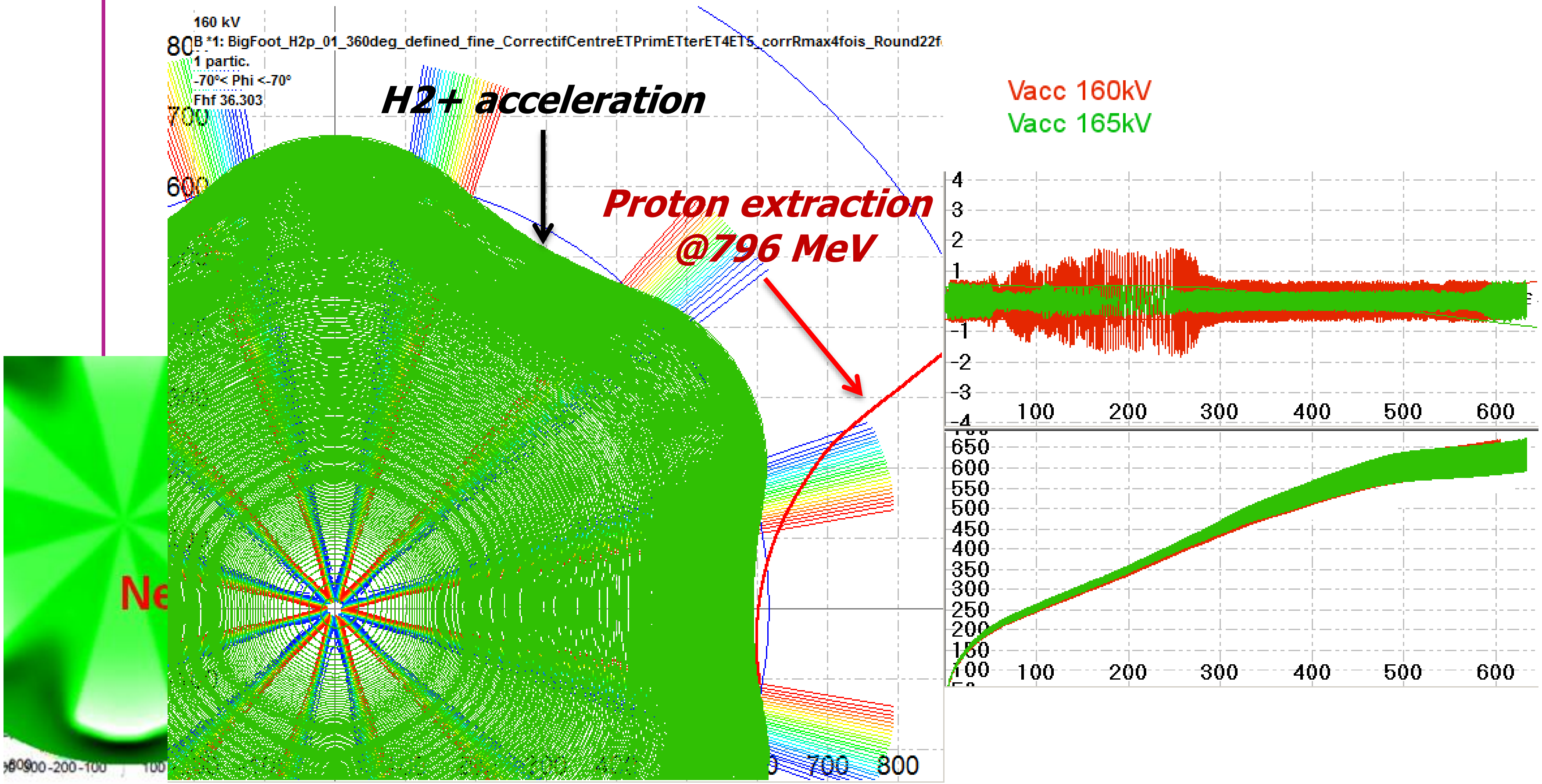
1st) Bump Channel: -2 kG to increase the -2 kG valley field

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

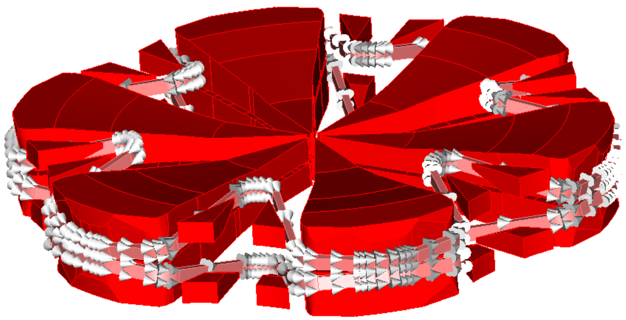


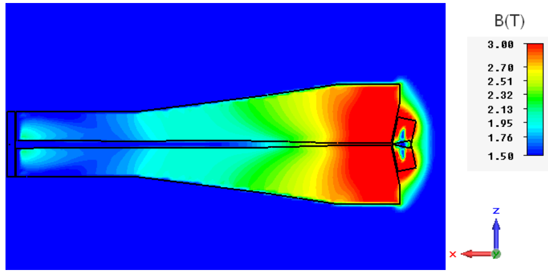
H2+ Extraction

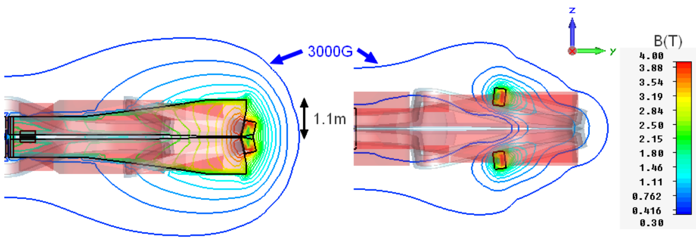
short trajectory, no focusing elements, no complexity

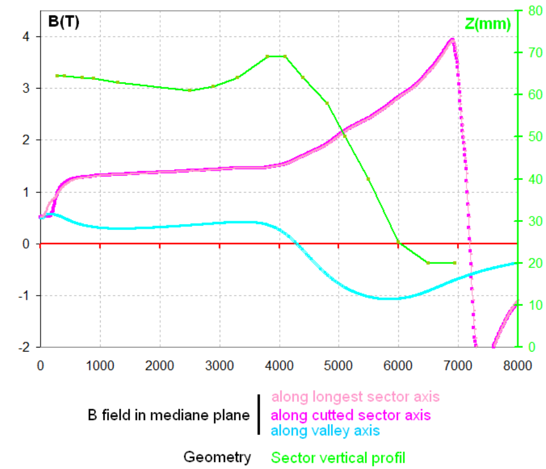


The 1600 MeV H2+ option



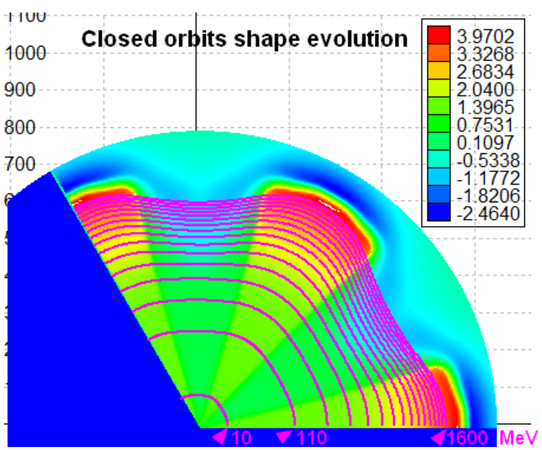


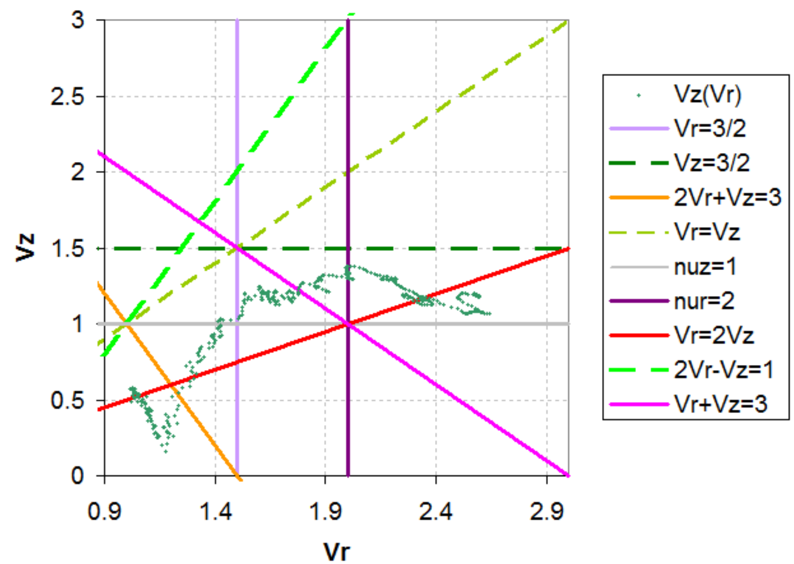




> 6 straight hill sectors (14 tons)
> 12 small valley sectors

> Superconducting Coils
. Rmin: 4.2m Rmax: 7.1m
.Total length ~50m
.Section: 160 mm * 310mm
.Current density 55 A/mm²





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Conclusions

Industrial constraints for ADS driver

1

Easy to maintain and repairable system

- Low beam losses in the different stages
- Low number of components
- Easy access to components (RF cavities, RF amplifiers, injection and extraction devices, ion sources…)

2

Easy to implement successive phases to raise up the beam power of the prototype

3

Beam stability: choice of Ion source with multiple injection systems (to reduce beam trips)

4

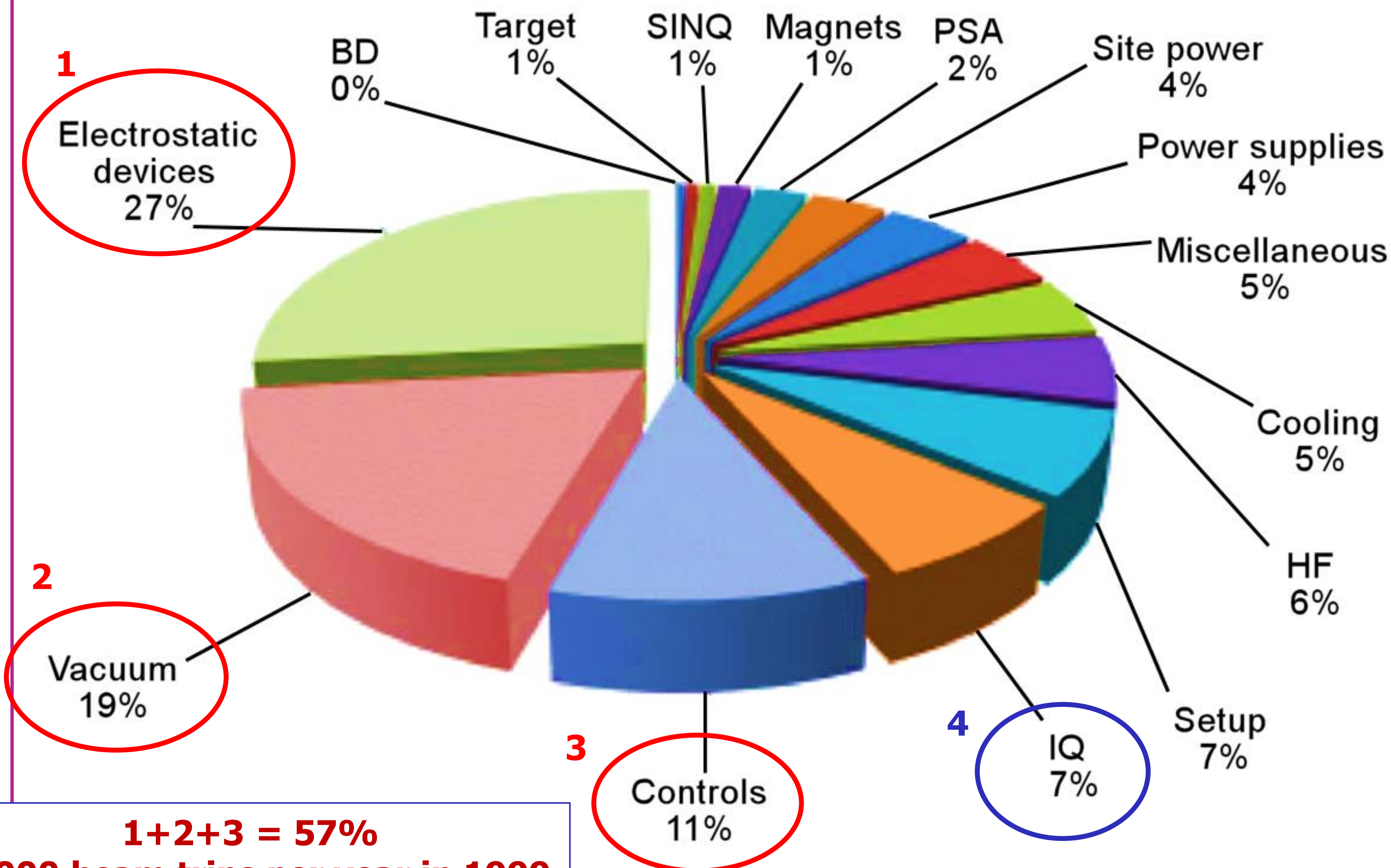
Investment and runing costs

5

Failures and repair rates of the competitors (Linacs and cyclotrons) should be carefully analysed with proven industrial methods (MTBF, …)

>> Single stage cyclotron is an attractive solution

The main causes of beam trips in a multi-stages cyclotron



1+2+3 = 57%
26000 beam trips per year in 1999

From M.Seidel PSI in 2009

Critical Issues of Single Stage designs

1-Large superconducting coils (role of the ASG partner in the CYCLADS Proposal):

- Mechanical design of a complex shape with bends
- Possibility to use MgB_2 for a cryo-free cooling system ?

=> Tests and prototypes are needed

2-High power RF cavity design to handle 1.4 (H^+)-1.6(H_2^+) Mwatt :

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

3-Multi Injection :

- a single HV platform to house 3 ion sources will be investigated

4-H_2^+ 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)

5- High intensity beam dynamics (role of the PSI partner in the CYCLADS Proposal):

Non linear beam dynamics models for halo characterization…

The pro of the single stage cyclotron solution (1)

- ***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

The pro of the single stage cyclotron solution (2)

Global yield could approach 31 % (e.g. H+ 600 MeV – 10 mA)

Driving Beam Power	6 MW
Total RF Power	16 MW
Total magnet Power	~1 MW
Triple injection Platform	~0.5 MW
Extraction channel	~0.5 MW
Anciliary equipts	~1 MW
Total Power	~19 MW
Estimated global yield	~ **31 %**

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

Thank you for your attention

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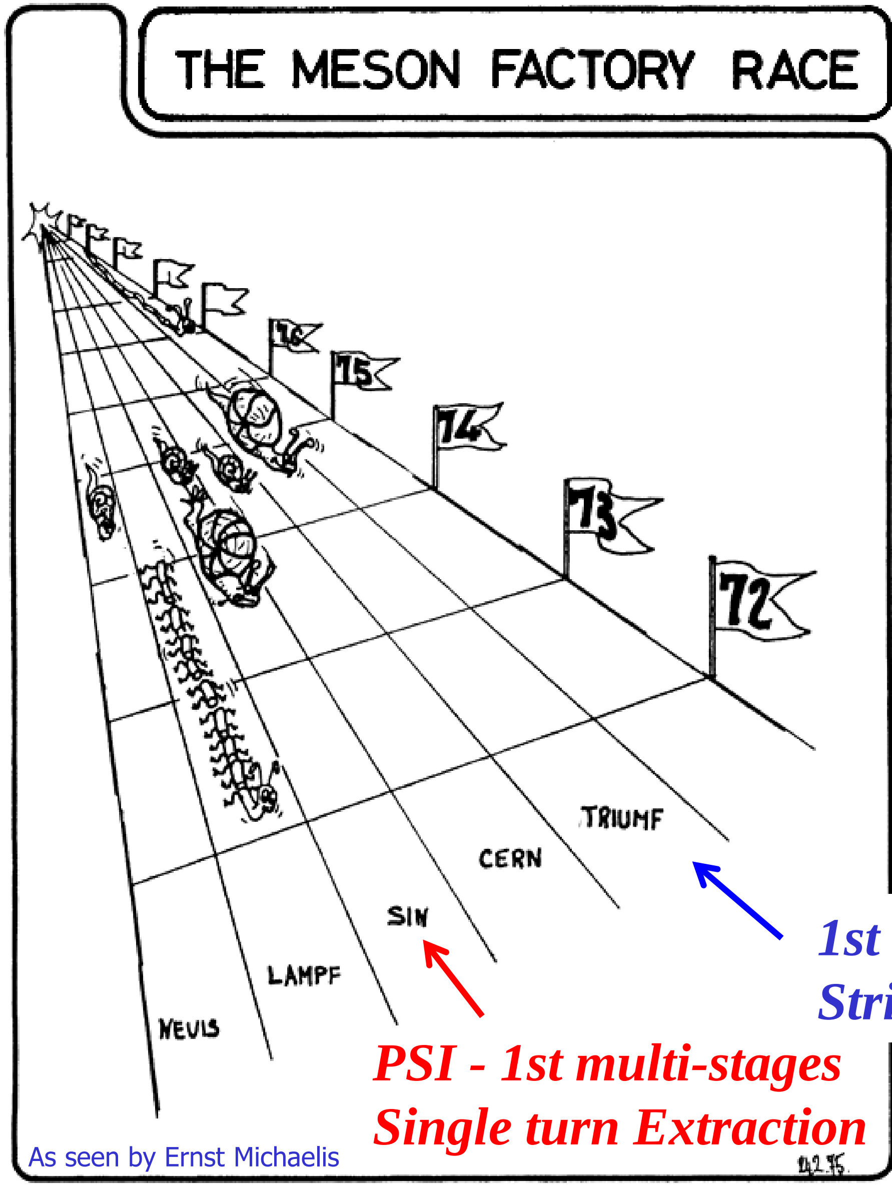
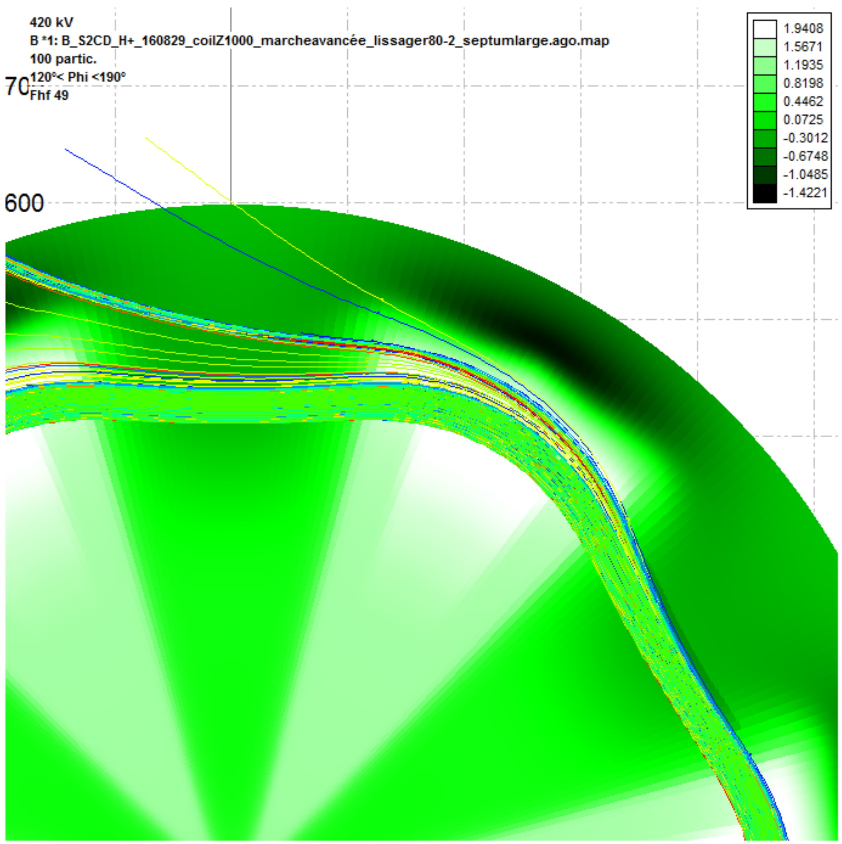


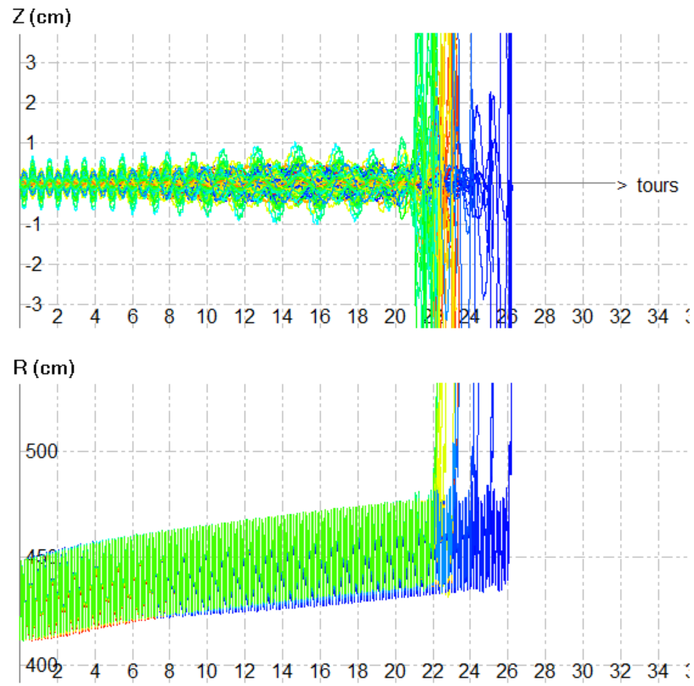
As seen by Ernst Michaelis

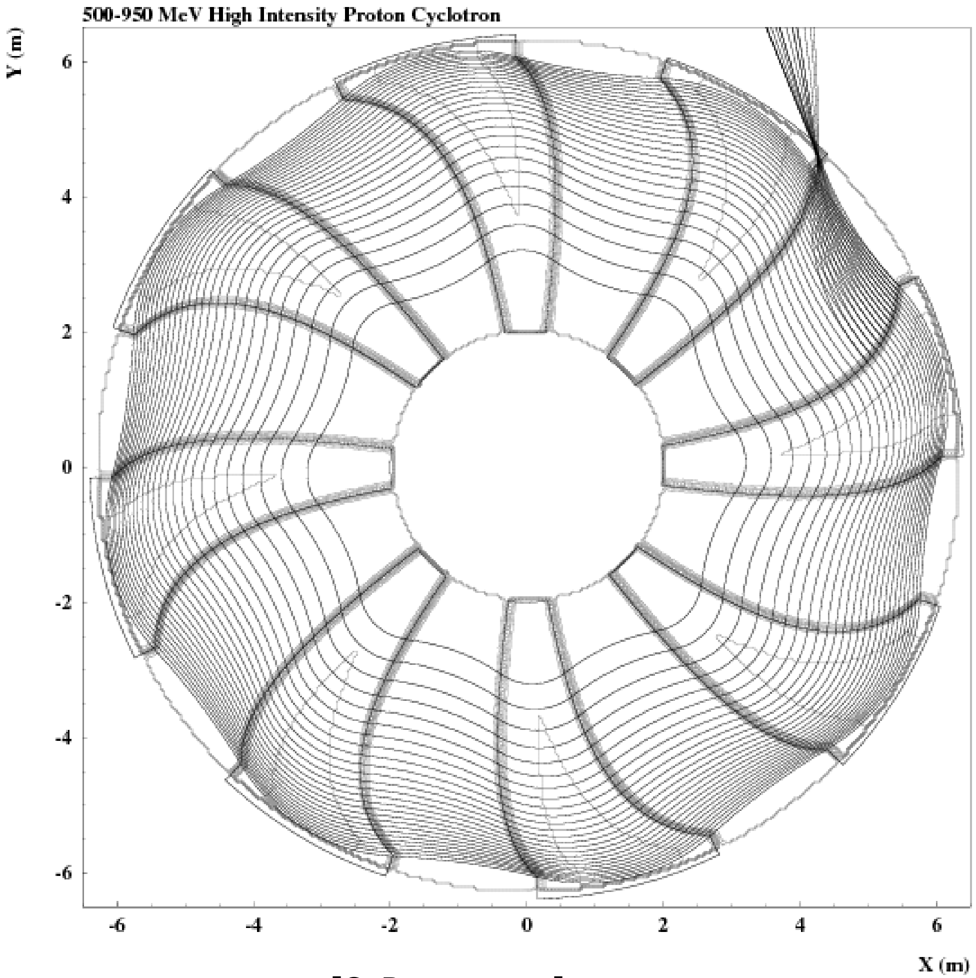
ICC 1975 in Zurich !

1st Single stage with Stripping Extraction of H^-

PSI - 1st multi-stages Single turn Extraction


420 kV
B *1: B_S2CD_H+_160829_coilZ1000_marcheavancée_lissager80-2_septumlarge.ago.map
100 partic.
120°< Phi <190°
Fhf 49
700
600
1.9408
1.5671
1.1935
0.8198
0.4462
0.0725
-0.3012
-0.6748
-1.0485
-1.4221

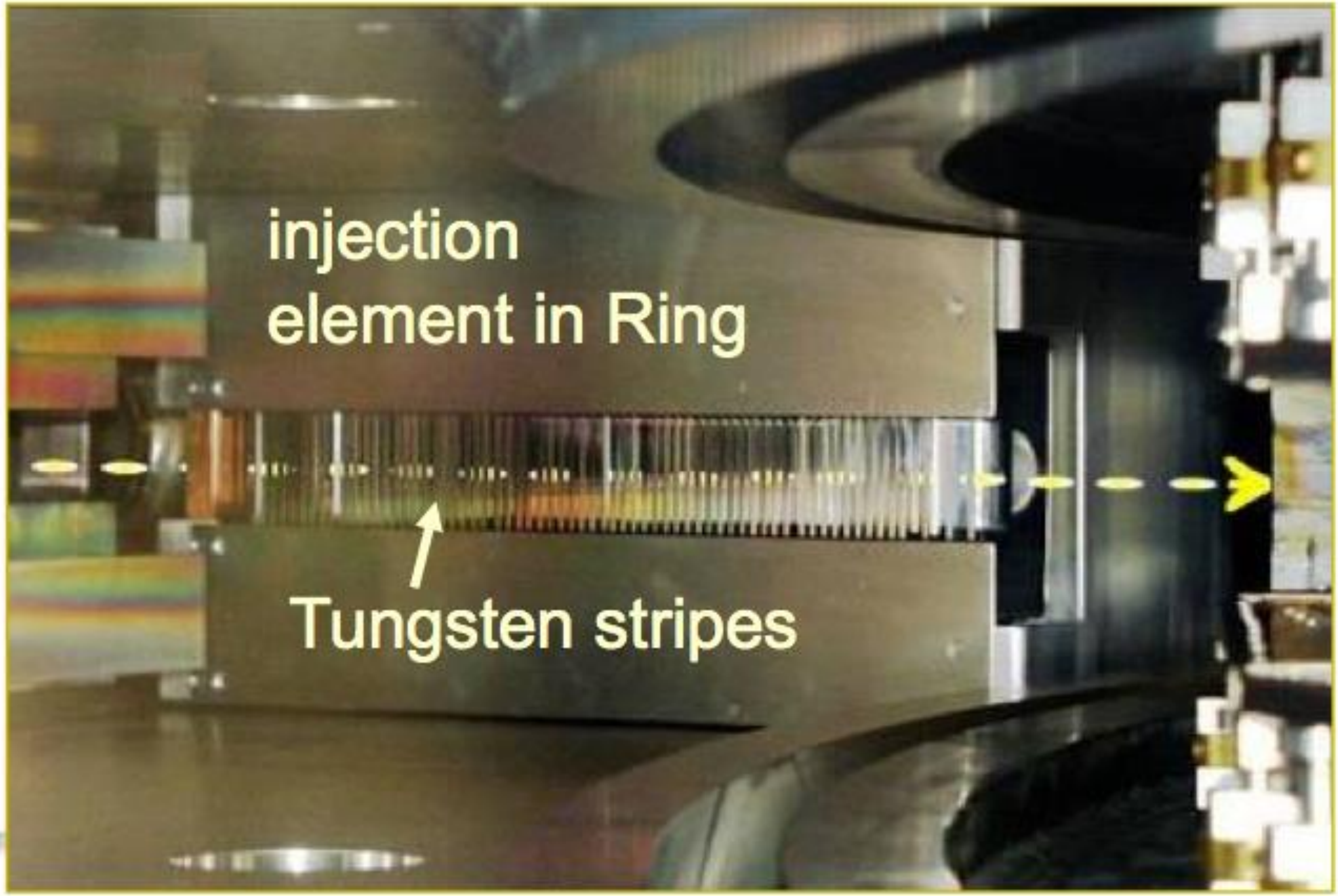

Z (cm)
3
2
1
-1
-2
-3
2 4 6 8 10 12 14 16 18 20 24 26 28 30 32 34
> tours
R (cm)
500
400
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34



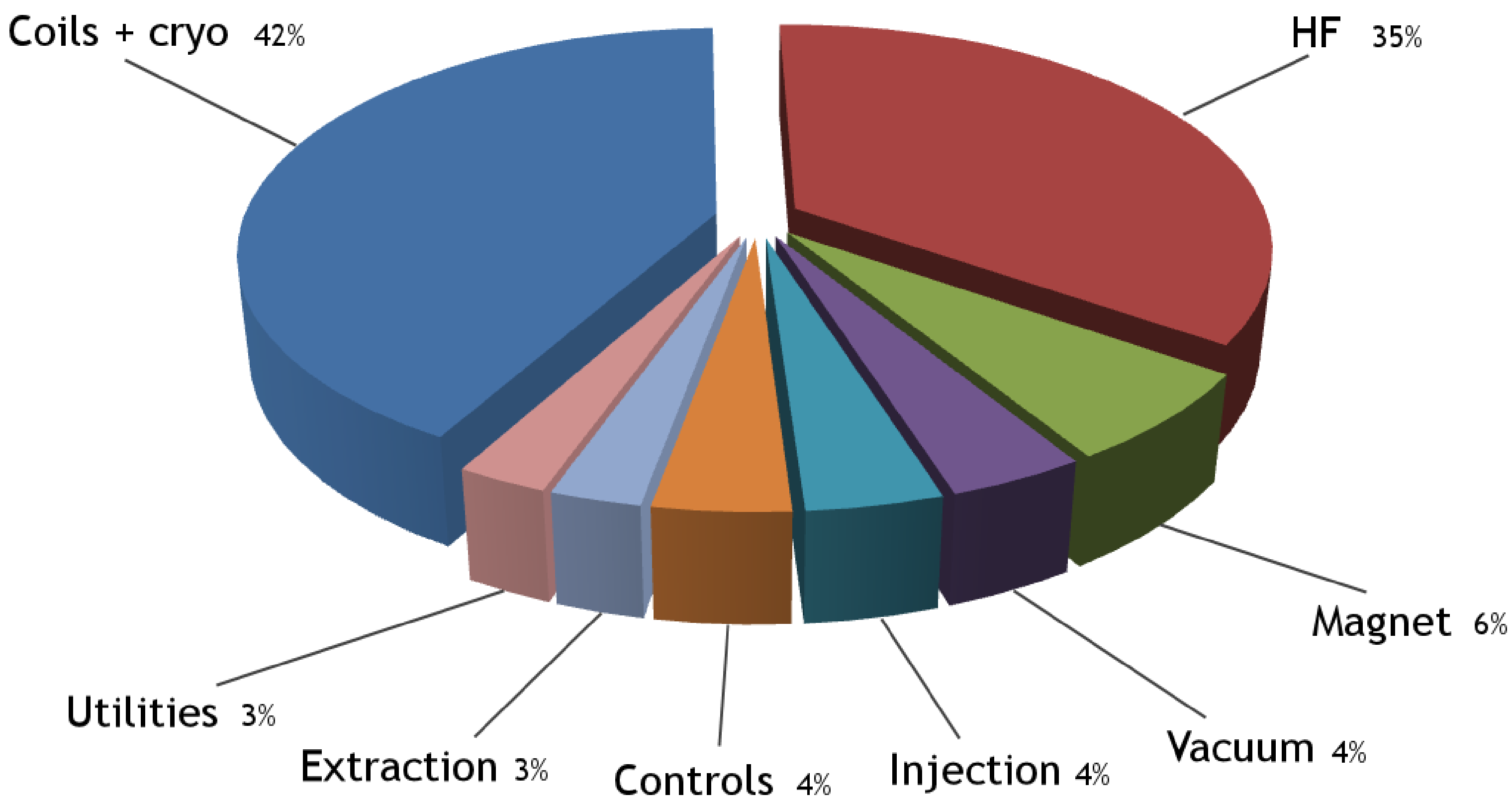
[C. Baumgarten]

The High-Tech injection/extraction electrostatic channels

Emax = 90 KV/cm



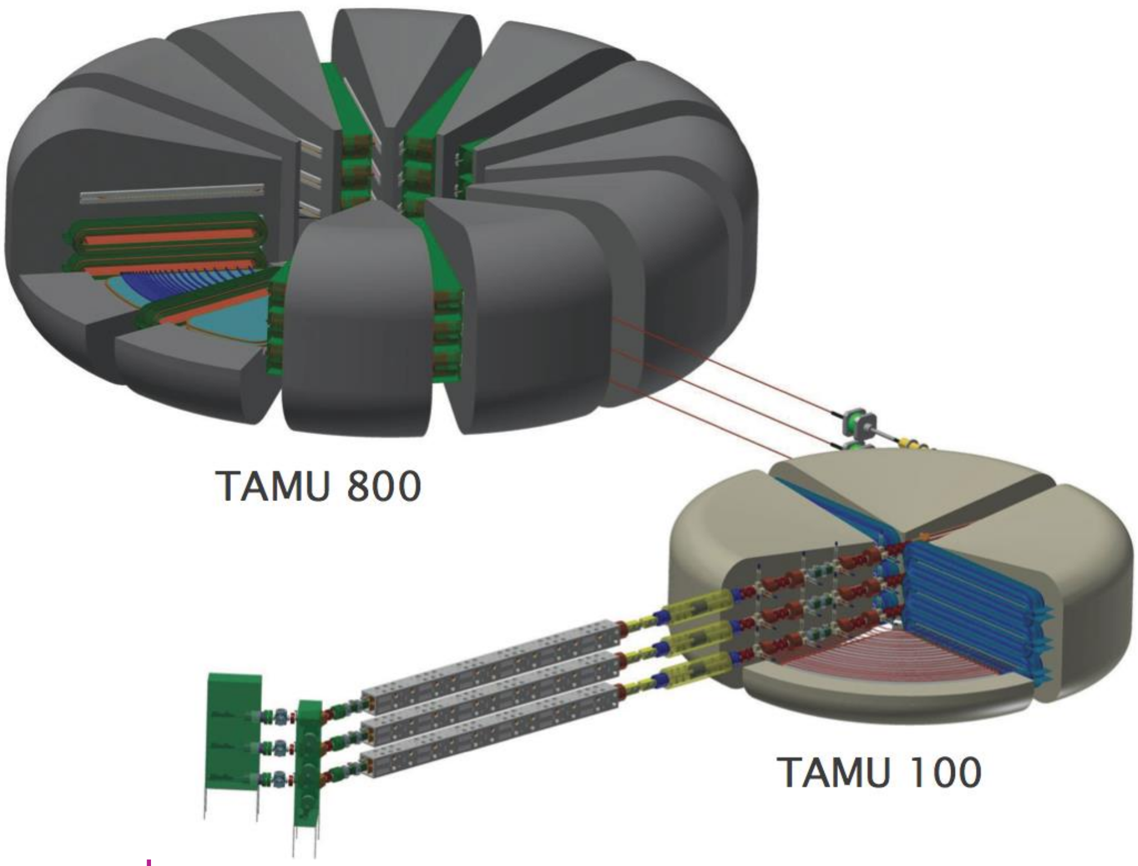
S2CD Equipment Costs



800 MeV Superconducting Strong-Focusing Cyclotron

High current proton driver for ADS

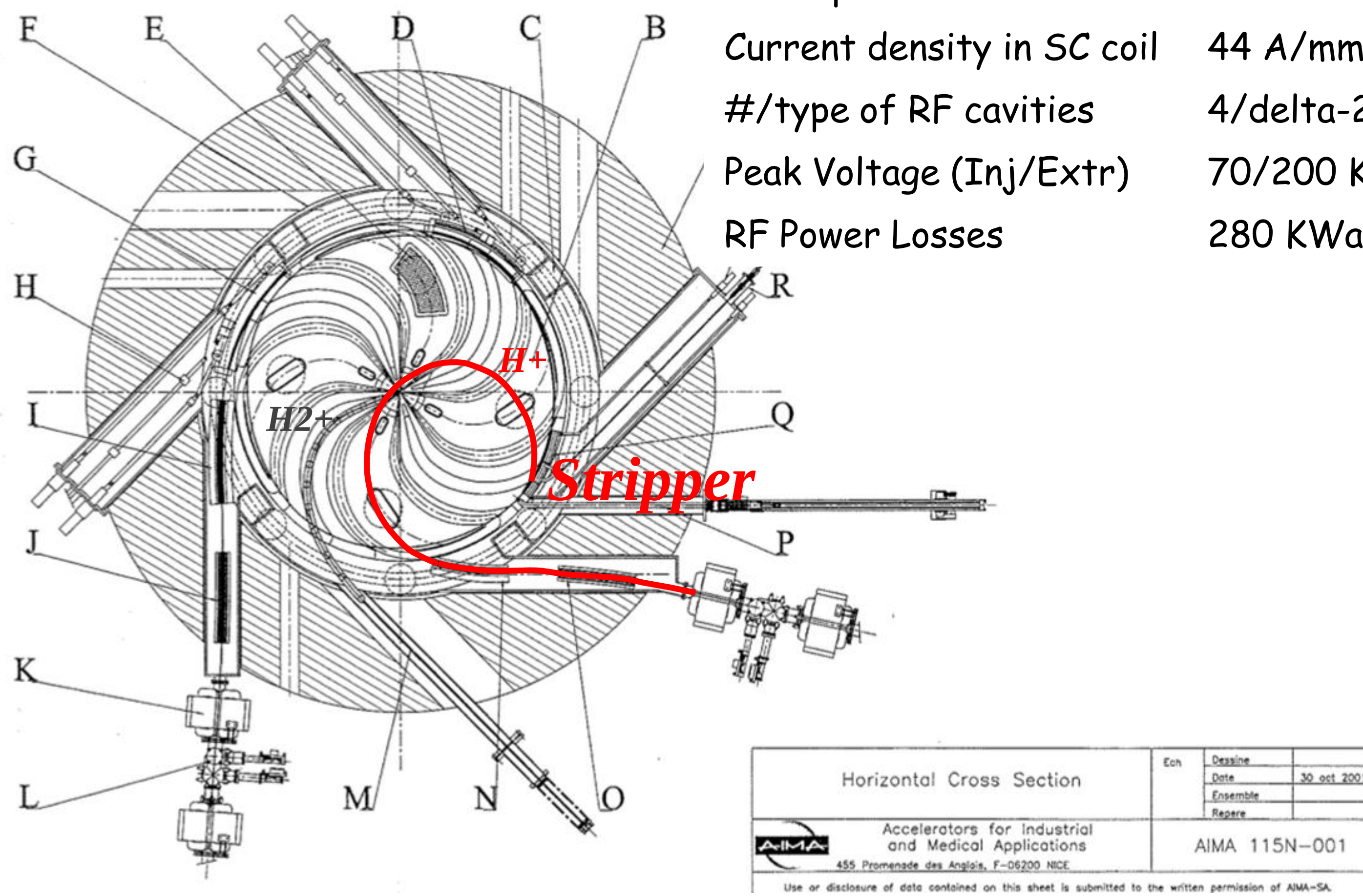
Texas A&M University



- 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 superconducting focusing beam transport channels made of Panofsky Qpoles (G=6T/m)

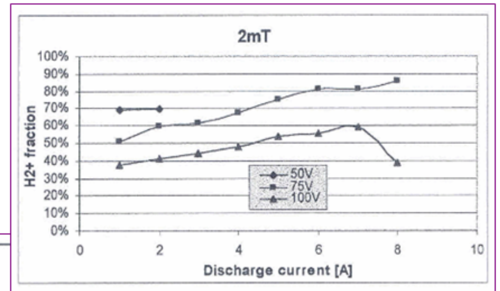
Median Plane view and principle of H2+ Extraction

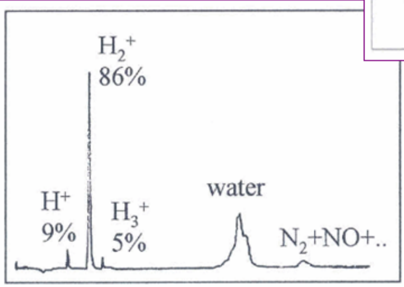
Max Energy (H2+/P)	**240/120 MeV**
Nominal Extr. Intensity	3 mA proton (1.5 mA H2+)
External diameter	4.4 m
# of spiral sectors	4
Current density in SC coil	44 A/mm2
#/type of RF cavities	4/delta-2 gaps
Peak Voltage (Inj/Extr)	70/200 KVolts
RF Power Losses	280 KWatt



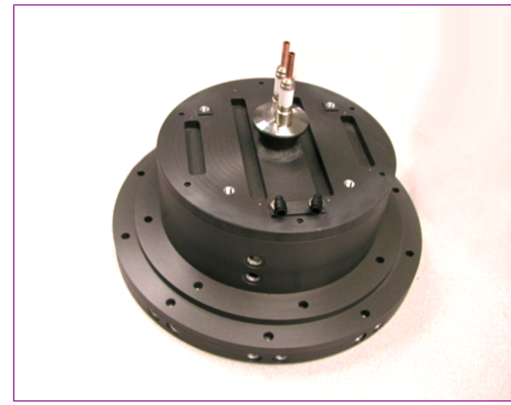
AIMA H2+

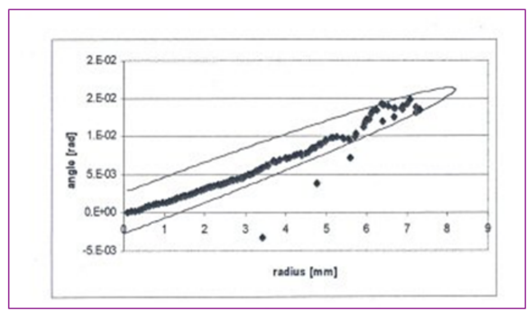
H_2^+ **fraction: 90%**





75V 8A discharge



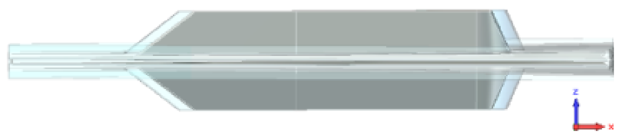


Normalized emittance (97%)
0.18 π mm.mrad

RF-delta double gap cavities

Peak Voltage versus radius

RF cavities H=6 / 36.3MHz



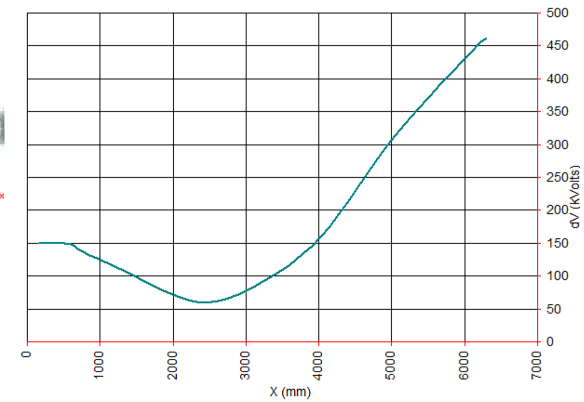
Must be inserted in the magnet

We need 1^{e}-8 mbar:

- pumping through the stem
- Possibility to use cryogenic panels inside the delta electrode

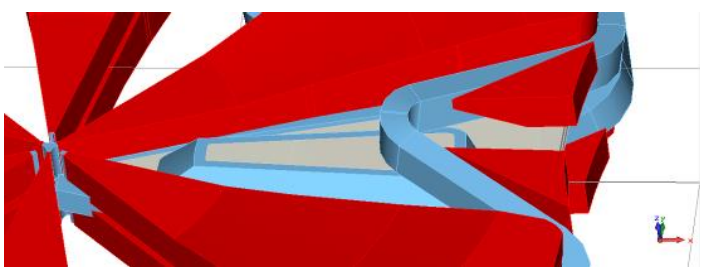
6 cavities, 12 accelerations / turn:

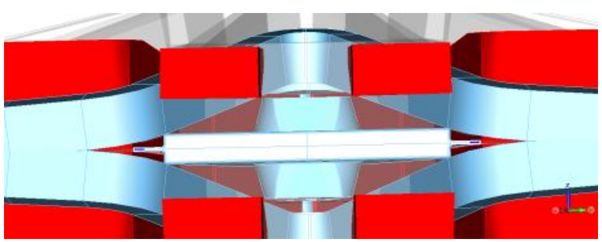
- Possibility to insert the stripper support through the stem

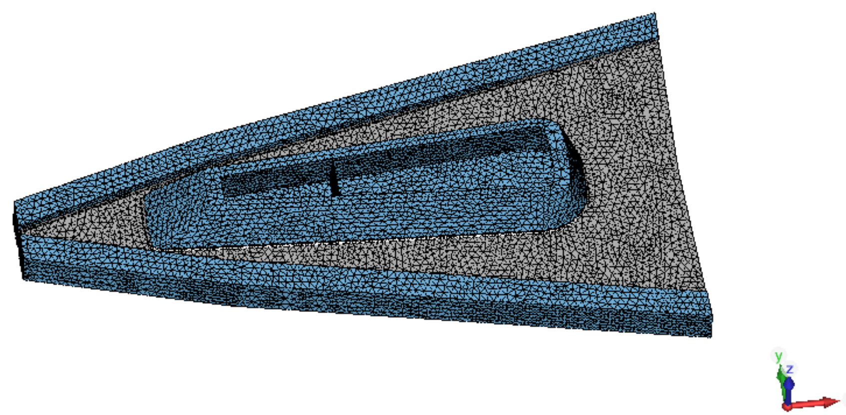


150 KV in the center up to 450 KV at extraction

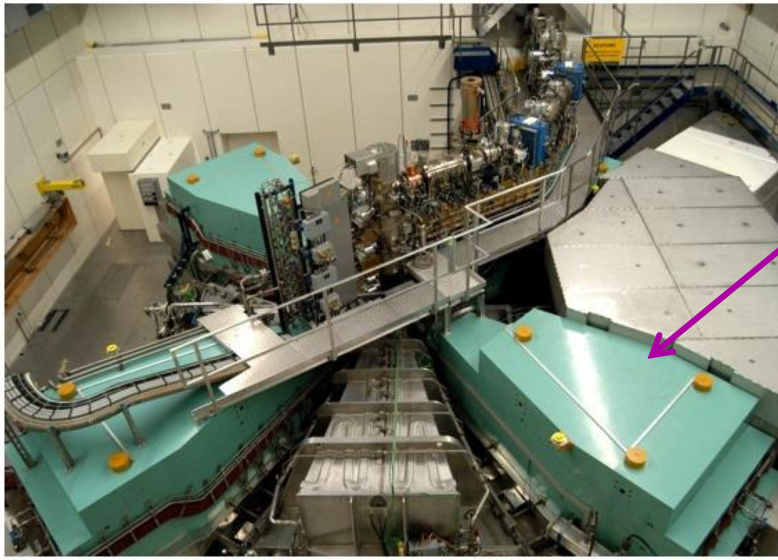
Q = 6200 ->Total losses 3MW





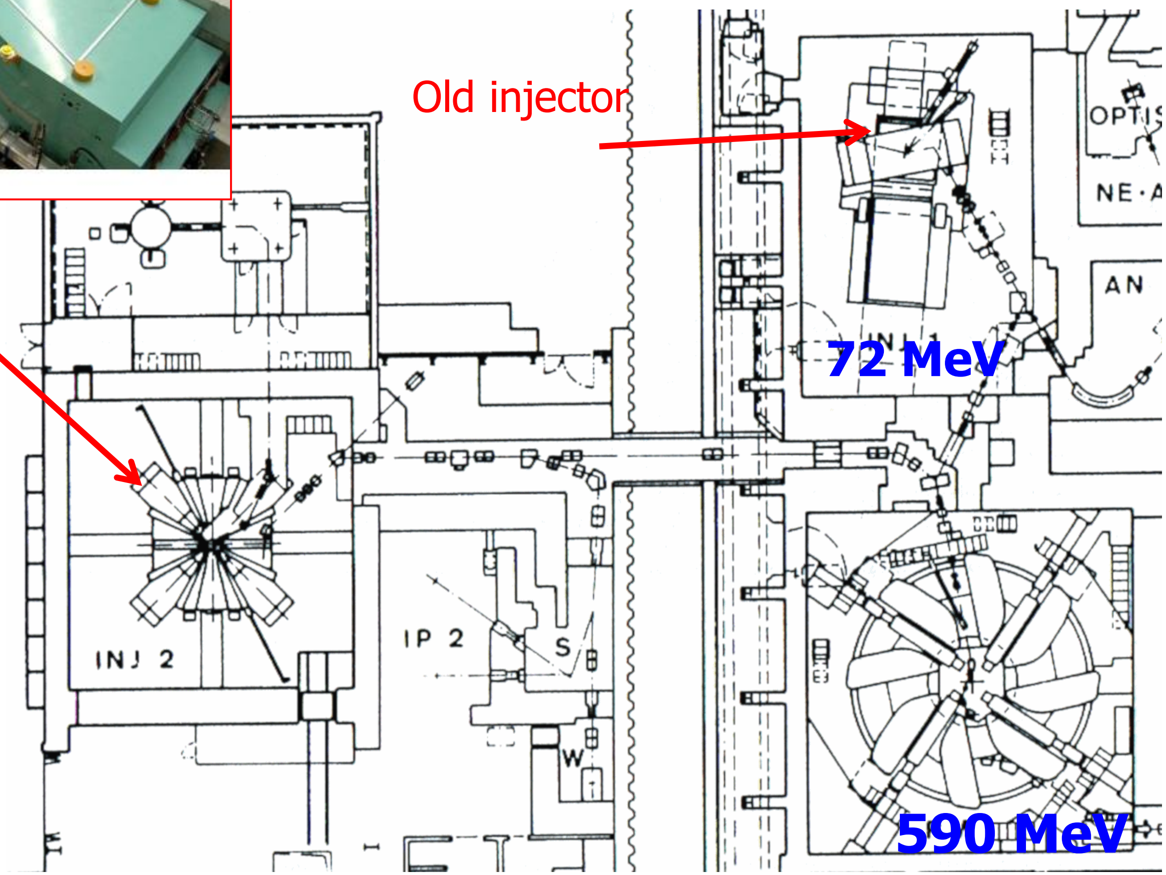


The PSI Layout



Injector 2 Cyclotron for 72 MeV proton beams.

1984: Towards Higher intensity
The new separate sectors Injector



AIMA DEVELOPPEMENT
Accelerators for Industrial and Medical Applications

Acknowledgements

In this review it was not possible to cover all the contributions to the ADS concept. Our attention was focused on what in our opinion are the most relevant technical developments and for sure we have failed to include the contributions of many scientists that have worked in this field. We apologize for being incomplete.

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