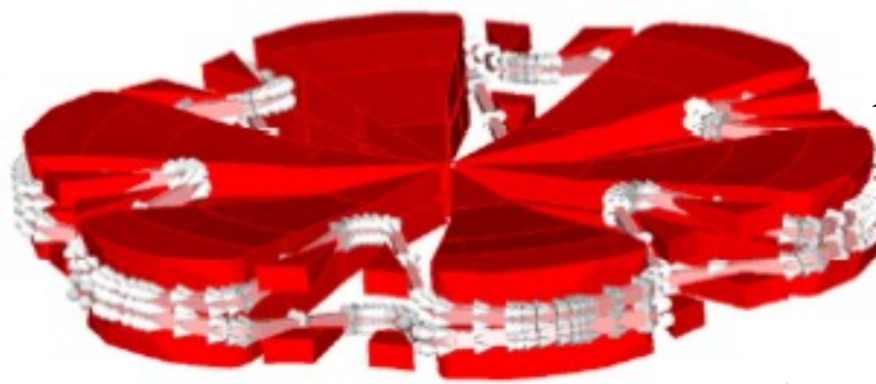
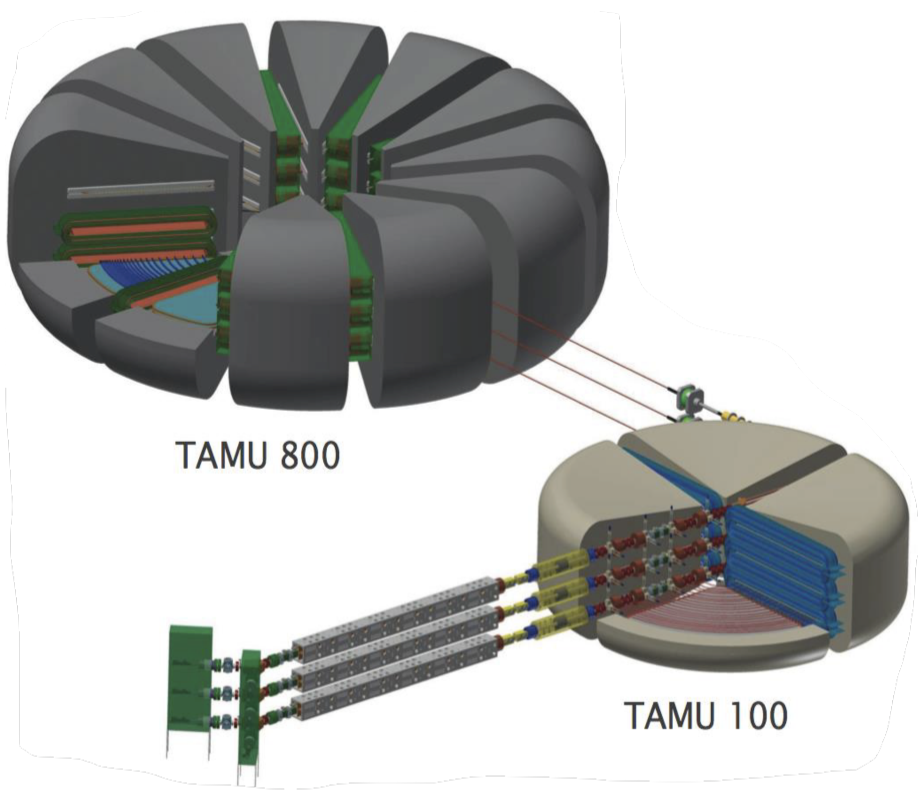
Limits of present cyclotron projects for ADS and future perspectives

A short review of high-power cyclotron projects proposed to drive ADS is presented. Their advantages and limits as drivers for ADS are discussed. The possible technical solutions and/or research needs to overcome these limits are also discussed.

By Luciano Calabretta, INFN



AIMA



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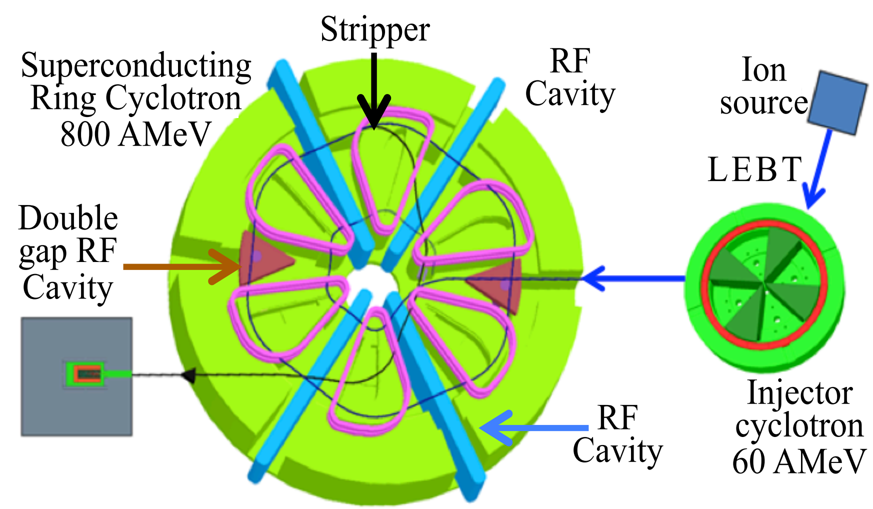


Workshop on High Power Cyclotrons/FFAs, 7-9 September 2021

The major request for ADS is the reliability of the beam!

The TAMU project (by P. McIntyre) plan to accelerate proton beam up to 800 MeV, and a set of 3 or 4 stacked cyclotrons are proposed to solve the reliability problem! **Good idea!**

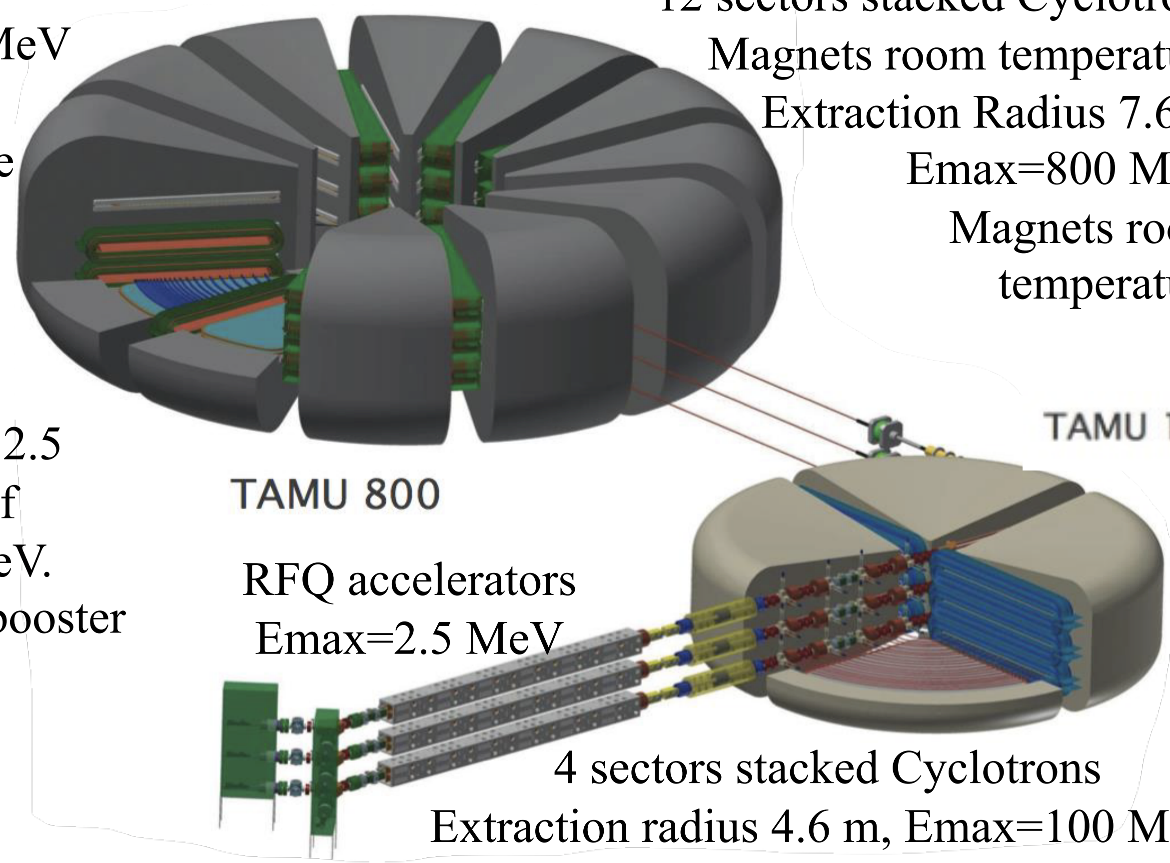
To achieve 10 MW with proton at 800 MeV a proton current of 12.5 mA is request!

- 3 staked cyclotrons need to accelerate up to 4.2 mA for each cyclotron;
- Or with 4 stacked cyclotrons the current is reduced to 3.2 mA.

A set of 3 or 4 RFQ are used to injects 2.5 MeV proton beam into the first stage of cyclotrons that accelerate up to 100 MeV. Then the beam is re-accelerate by the booster cyclotron up to 800 MeV!

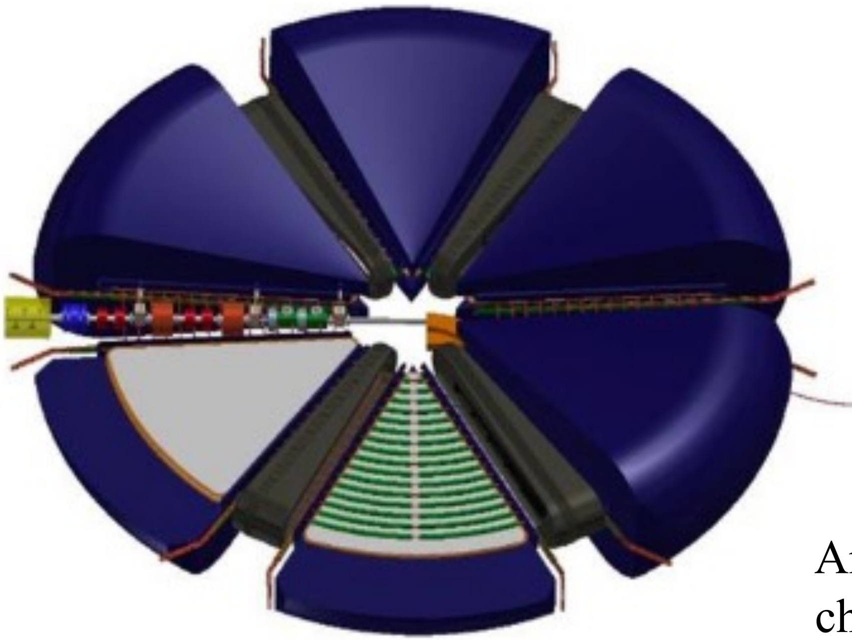
Texas A&M University
Ref. IPAC 2012, 2018

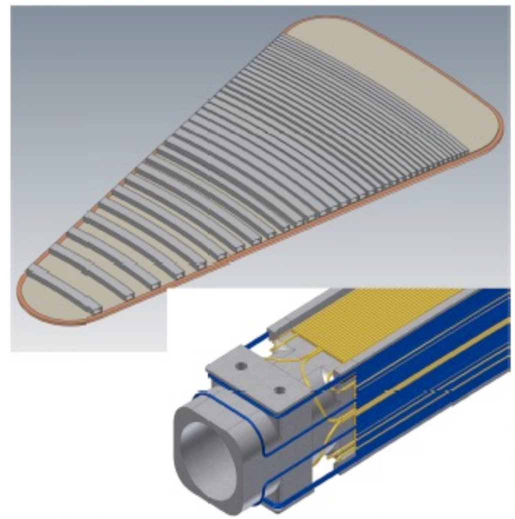
12 sectors stacked Cyclotrons
Magnets room temperature
Extraction Radius 7.6 m
Emax=800 MeV
Magnets room temperature



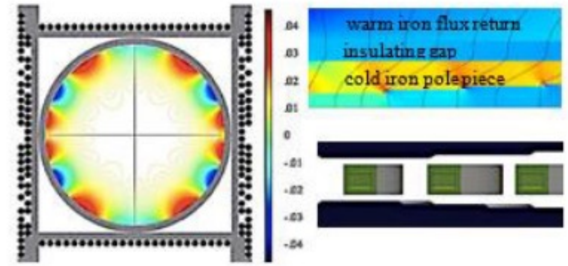
4 sectors stacked Cyclotrons
Extraction radius 4.6 m, Emax=100 MeV
Magnets room temperature

Main Features the TAMU project: Strong focusing cyclotrons and superconducting cavities.

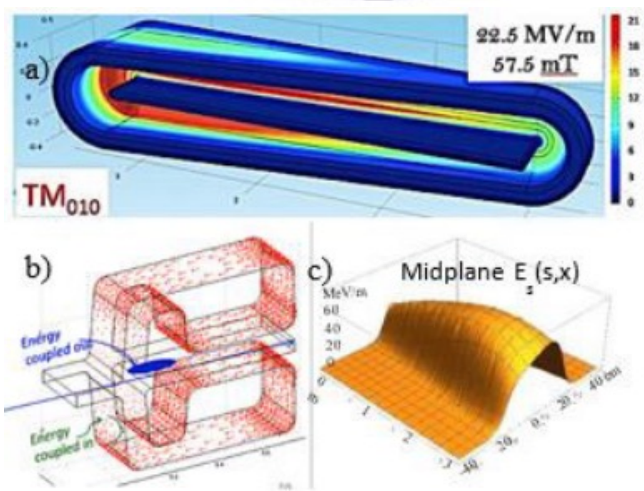




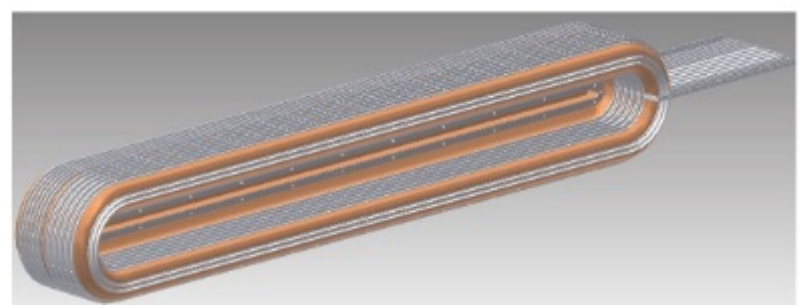
Array of 35 quadrupole focusing channels inside a sector (top) for each stacked cyclotron.



Detail of one QFC (bottom) with the single layer Panofsky quadrupole (gold) and window frame dipole windings (blue).



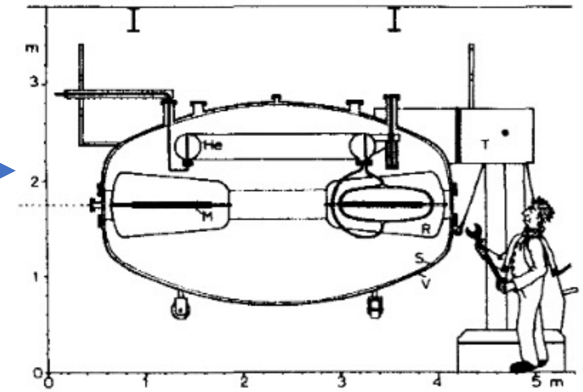
Superconducting cavity rf cavity, showing details of structure, location of couplers, midplane rf field.

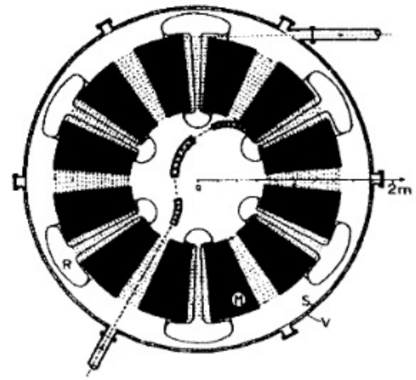


Parameters of the Two Cyclotrons

	TAMU 100		TAMU 800		
	inject	ex-tract	inject	ex-tract	
Energy	2.5	100	100	800	MeV
Orbit radius	0.66	4.6	3.8	7.6	m
Dipole field in sectors	1.5	.37	.98	.93	T
Beam aperture	4.6		4.6		cm
# rf cavities	2		10		
Frequency	100		100		MHz
rf harmonic	23		19		
# orbits	35		35		

Tritron project, U. Trinks at al., Int. Cyc. Conf. and Appl., 1998,
early proposal by F.M. Russell, Separated Orbit Cyclotron (SOC) NlM 23 (1963) 229





Problems:

-Tritron people spent more than one year to set the magnetic field to accelerate the beam along six turns, 75 channels (full machine 20 turns 240 channels), then the project was stopped;

-Tritron was a superconducting single layer cyclotron not 3 or 4 stacked room temperature cyclotrons **with further interaction among the different planes and the difficulty to have a symmetry plane for each cyclotron**!;

- if a superconducting cavity goes out the beam strikes the wall of the following magnetic channels and/or of superconducting cavities, with serious risk of permanent damages! It is not so clear that the RF cavities of one plane are independent from the other planes!

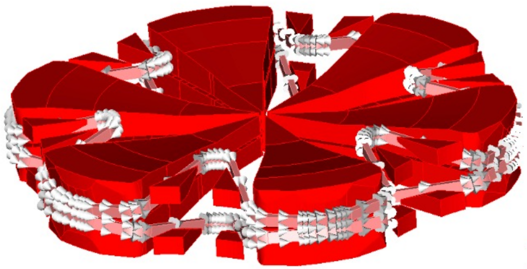
Magnetic field layout of the 1600 MeV H2+ design

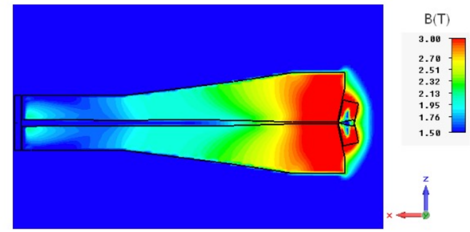
Positive items of AIMA design:

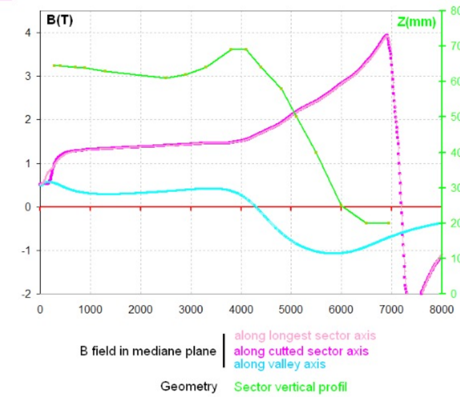
-Single stage machine with stripping extraction remove the problems of deflectors;

- Three ion sources inject three independent beams, to increase reliability;

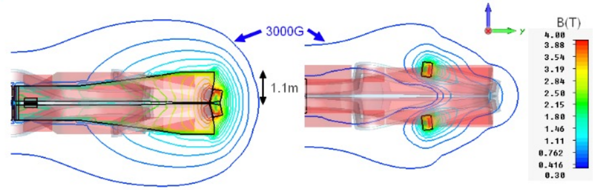
- Superconducting coil with enough reversal field in the valleys to increase the flutter (Vertical focusing) and simplify the extraction path.



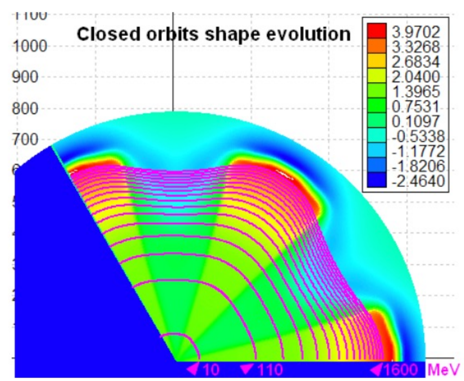


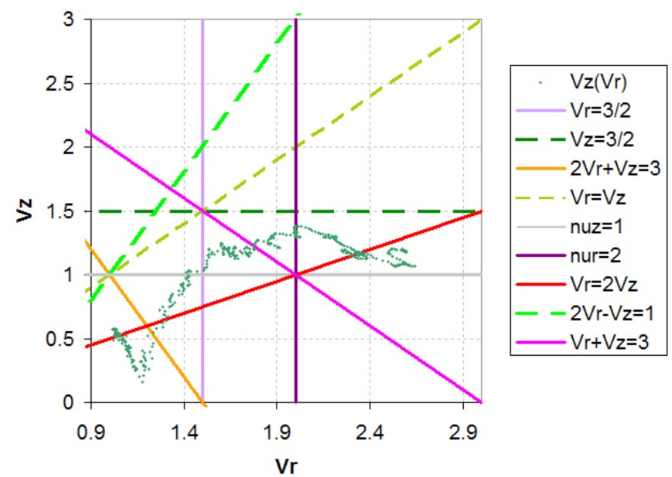


> 6 straight hill sectors (14 tons)
> 12 small valley sectors



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





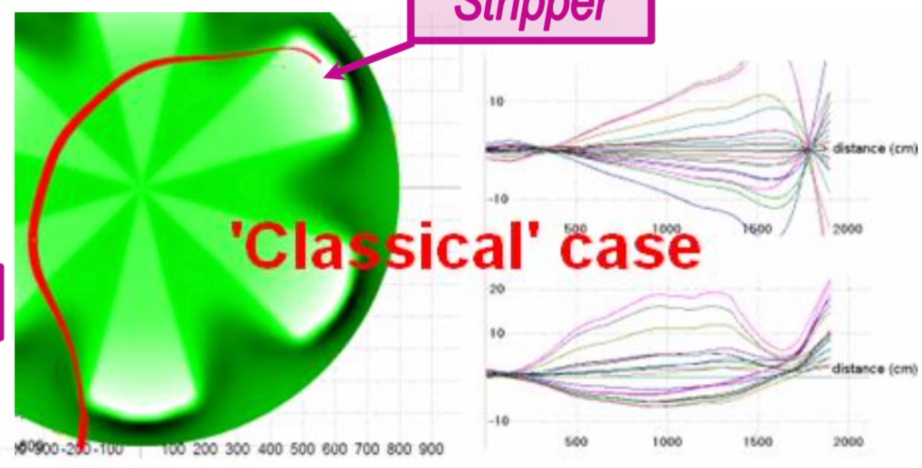
Return yokes could be added to reduce the coil stored energy (3 times lower than in a classical booster!)

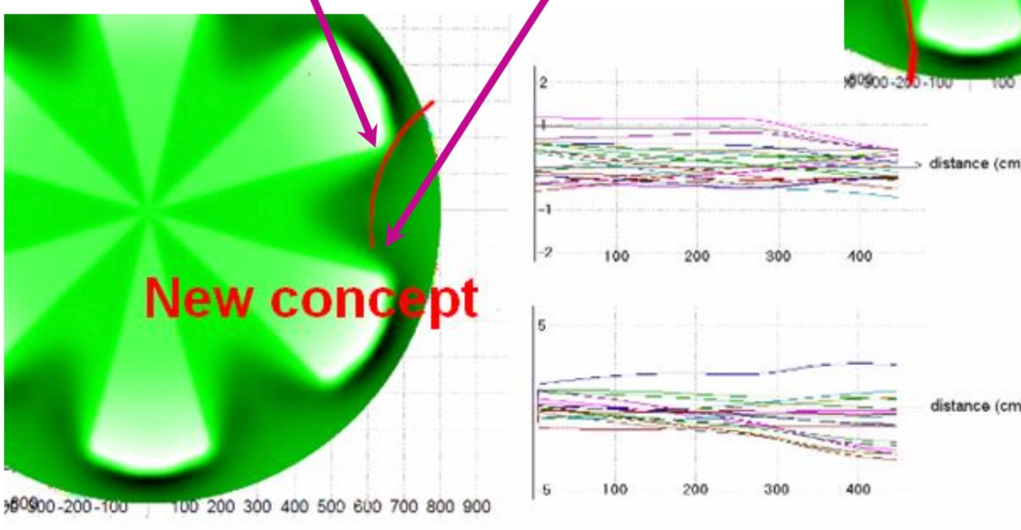
Extraction

New extraction concept for H2+ stripping: short trajectory, no focusing elements, no complexity

Short trajectory if stripping foil located in valley

Stripper





Initial condition:
5mm vertical amplitude @ 155MeV

ThEC13, CERN, Geneva, October 30 2013

AIMA
Accelerators for Industrial and Medical Applications

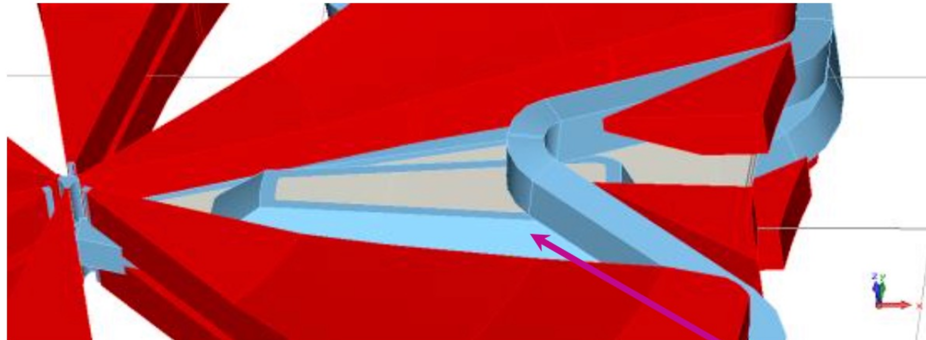
RF-delta double gap cavities

Critical items of AIMA design:

- Superconducting coil is too large and too complex;
- Magnetic field at center low, it is possible to achieve better solution, to be optimized;
- Investigate the optimum final energy, 800 MeV/n or higher?
- Maybe, a solution with 8 sectors is more reliable.

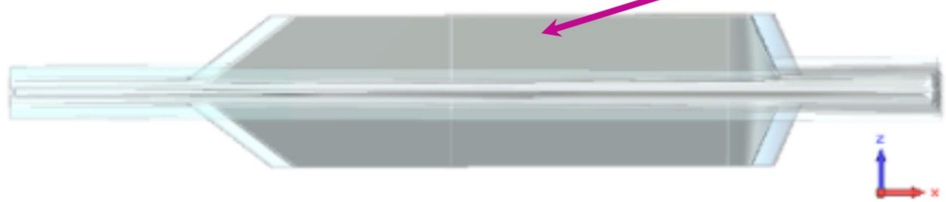
1600 MeV H2+ layout

RF cavities H=6 / 36.3MHz



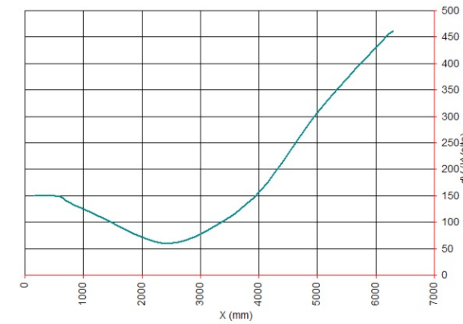
- *6 cavities inserted in the valleys (12 accelerations gaps / turn)*
- *Pumping through the stem*

Stem

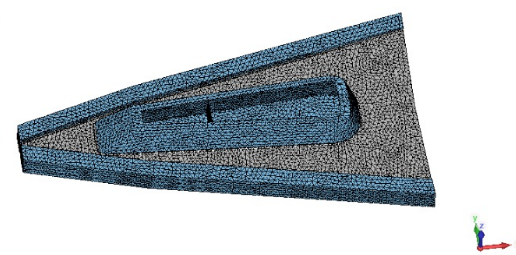


Vertical cross-section through the valley axis

Peak Voltage versus radius



- *150 kV in the center up to 450 kV at extraction*
- *Q = 6200 ->Total losses 3MW*



What happened if a RF cavity goes out? Maybe the beams continue to be accelerated and extracted. Maybe, the beam from one ion source is lost… to be investigated!

Pro e Cons of the single stage proposed by P. Mandrillon

Advantages:

- A single stage reduce the construction cost of the machine and of the building;
- The use of three ion source mitigate the performance request to the ion sources and mitigate also the problem of trips and of the ion source maintenance. Any kind of ion sources need a maintenance service one time per week or in best case one time per month.
- High reverse magnetic field in the valley simplify the beam extraction by stripper and increase the flutter and the vertical focusing. The sectors not need to be spiraled.

Cons:

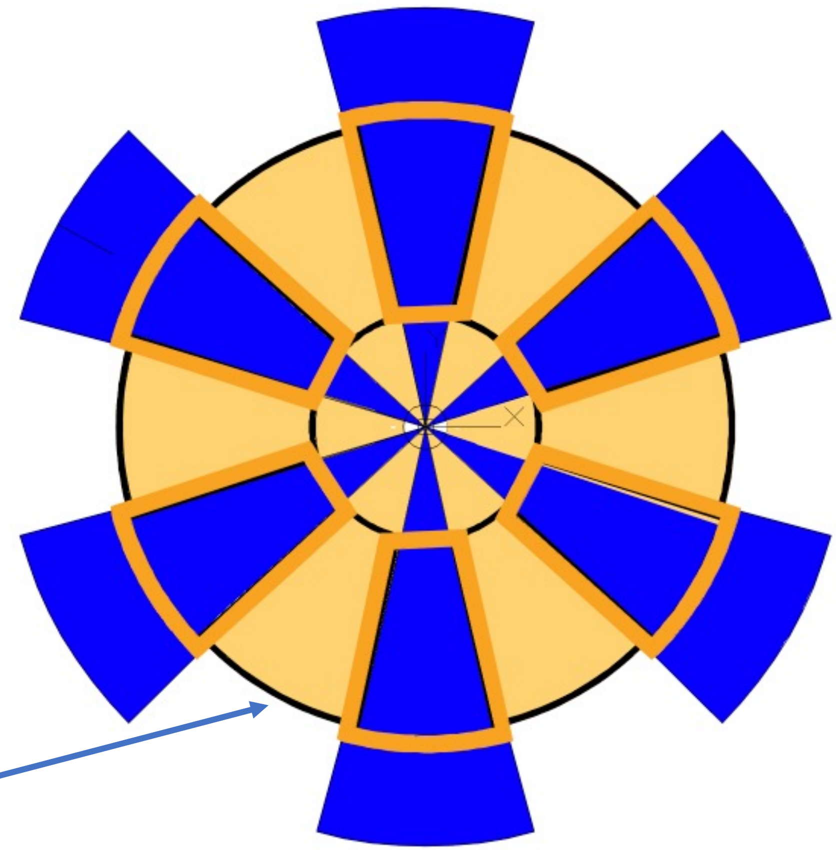
- The superconducting coils is very large and complicated. Alternative solution must be investigated.
- The Q value of the single stem of the cavities is not very high (6000), we could apply method of multi-stems to increase the Q value of the cavities up to 8500.
- Low central magnetic field (7.9 kGauss) → large pole size about 7 m. Probably related with the request to achieve three injection sources.
- **Beam losses due to the dissociation of the vibrational states of the H_2^+ molecul**e.

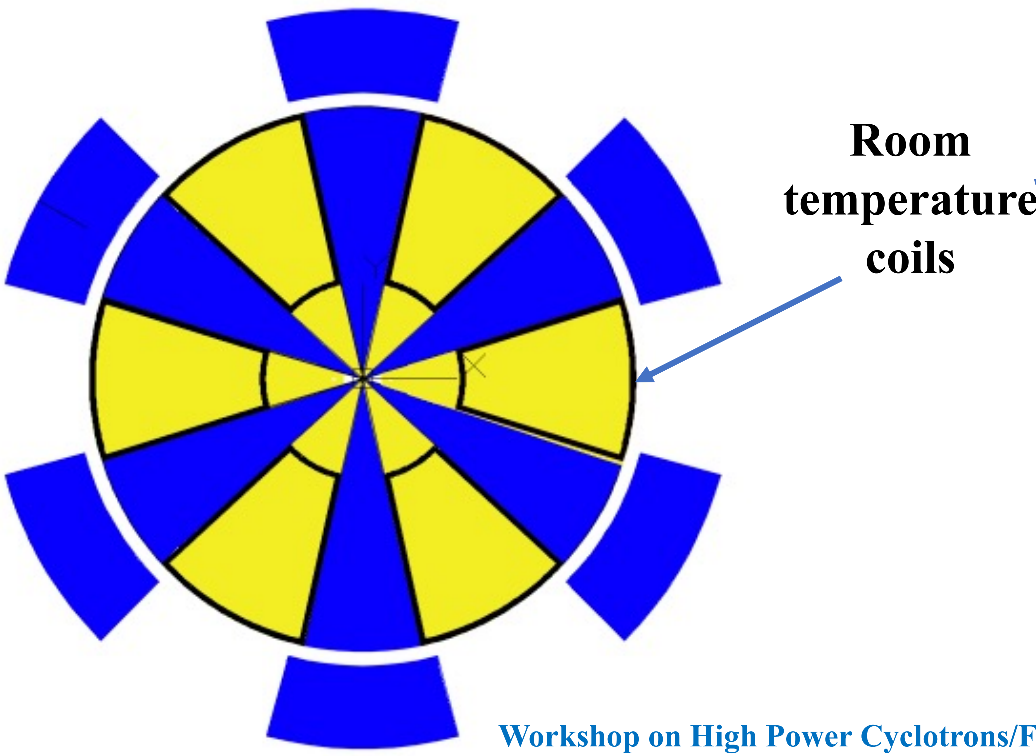
A possible alternative solution for a 6 sectors Cyclotron with simpler superconducting coils.

The main superconducting coils (orange color) are not parallel but tilted respect to the median plane.

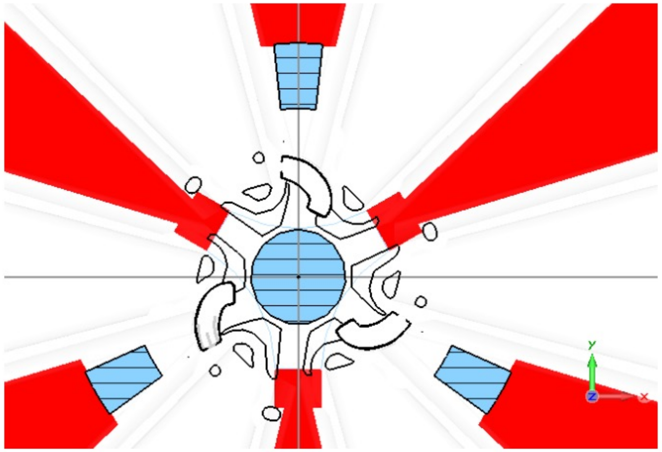
The **black lines** are additional coils placed in the valleys at room temperature, useful to produce a magnetic field with reverse polarity, to increase the flutter and the axial focusing of this cyclotron.

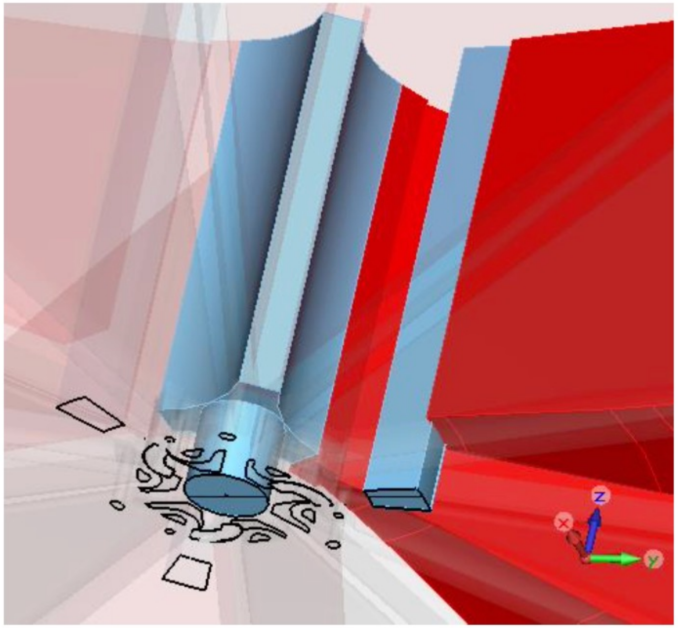
The iron sectors are in Blue, while the superconducting coils are in orange, the RF cavities are in yellow.



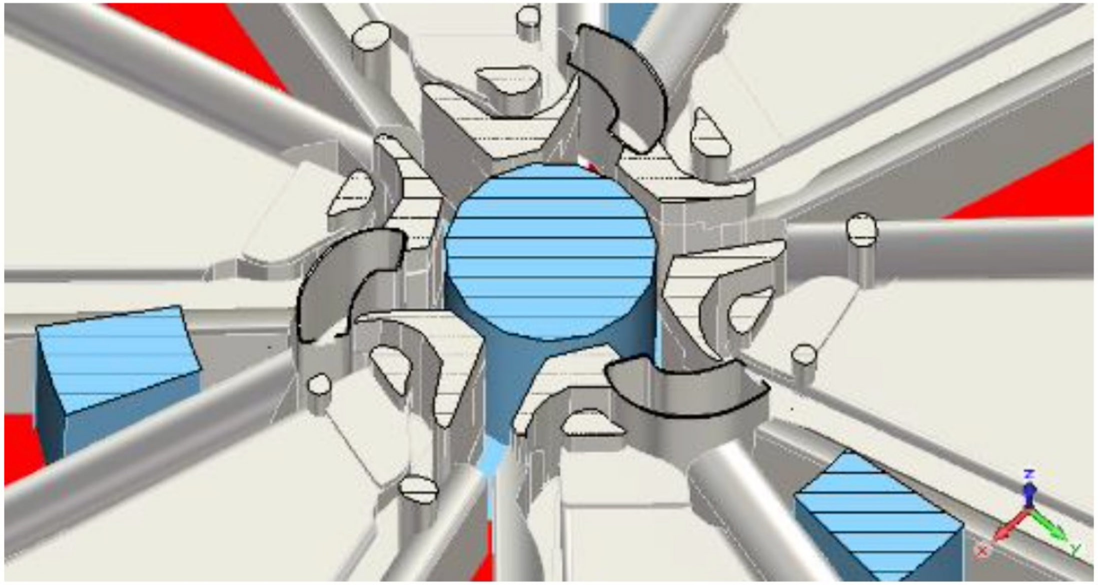


Central region for H2+ multi-injection





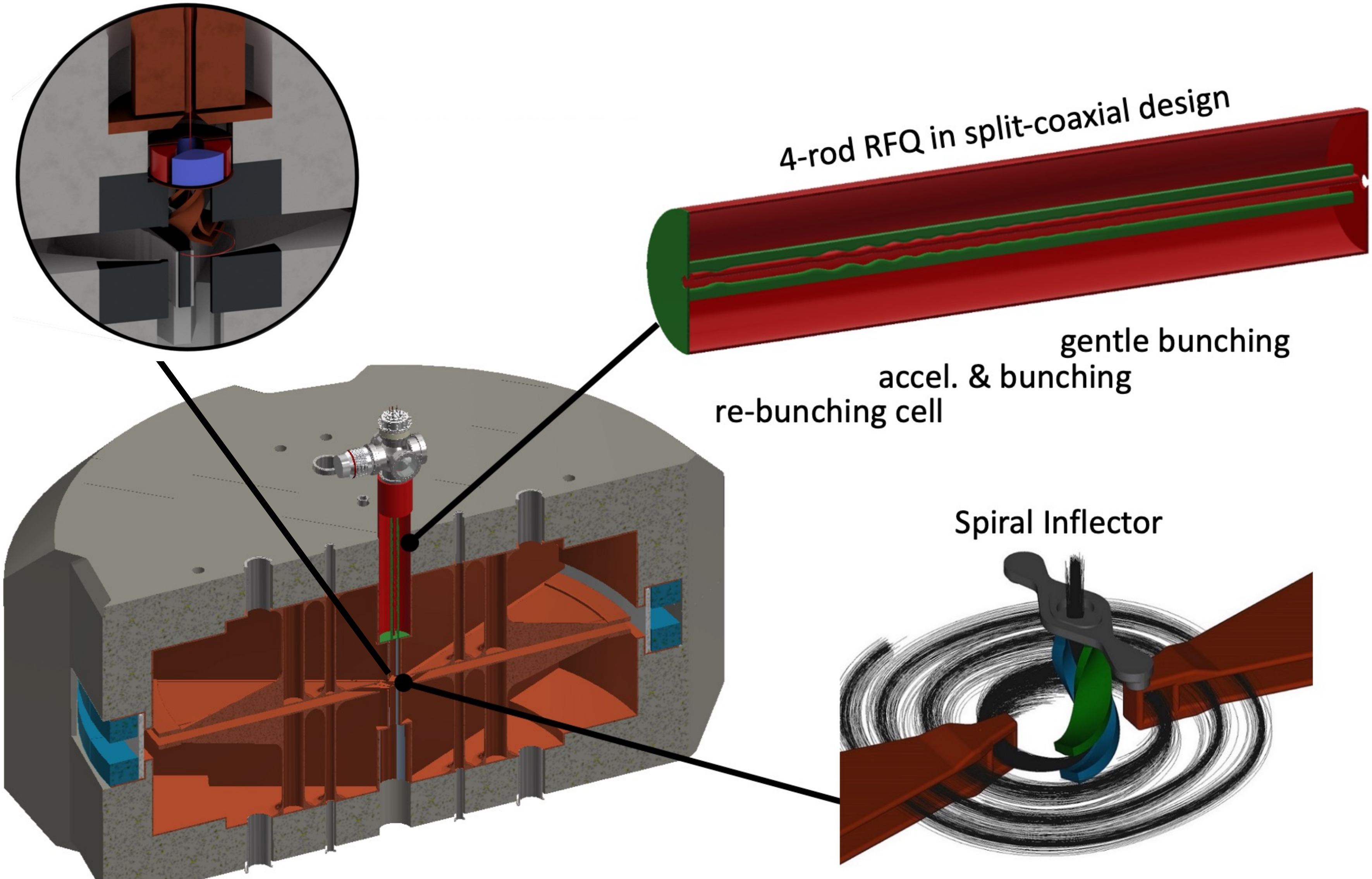
60 KVolts injection HV
Axial injection Line
Electrostatic spiral inflector E=18KV/cm



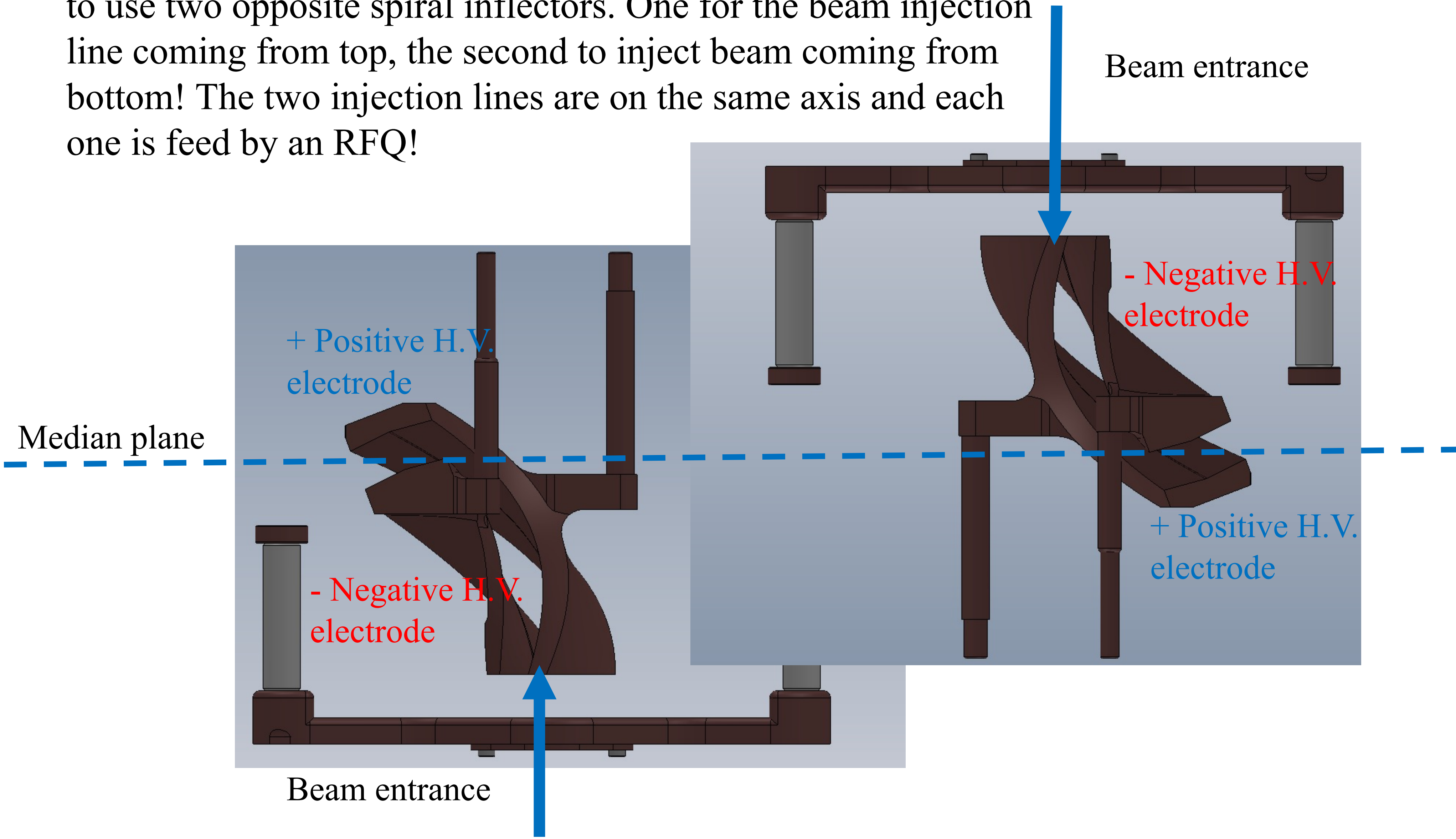
This solution do not allow for installation of RFQ or to inject at higher energy!

IsoDAR Cyclotron

LEBT - Inflection



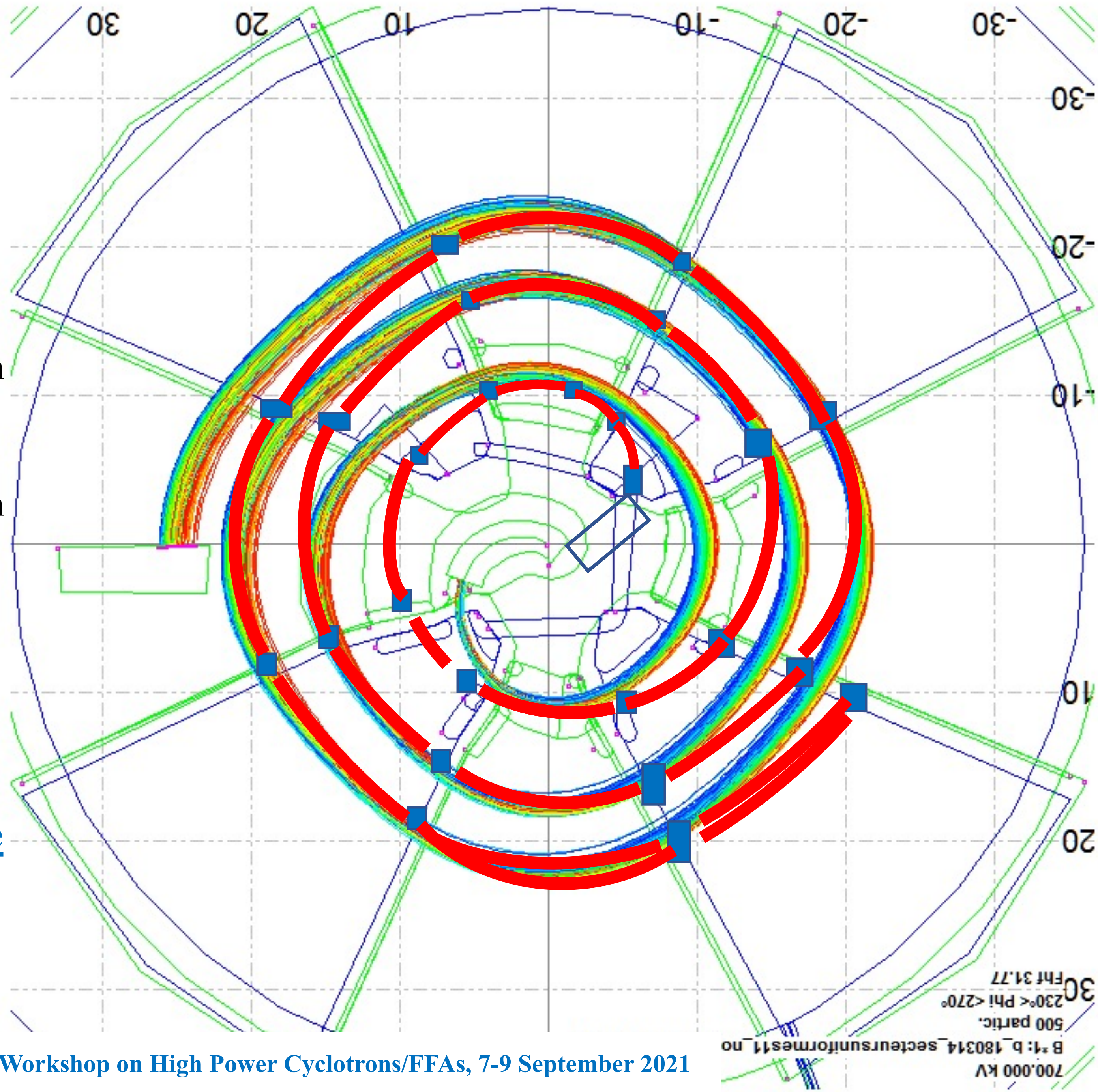
As alternative solution to the AIMA three ion source we suggest to use two opposite spiral inflectors. One for the beam injection line coming from top, the second to inject beam coming from bottom! The two injection lines are on the same axis and each one is feed by an RFQ!



Central region for IsoDAR cyclotron, designed by Matthieu Conjat (AIMA) but rotate of 180° (second inflector) + the blue marker and the red arcs of the trajectories coming out from the first inflector.

Of course, the central region has to be modified to leave hole for the two set of trajectories!

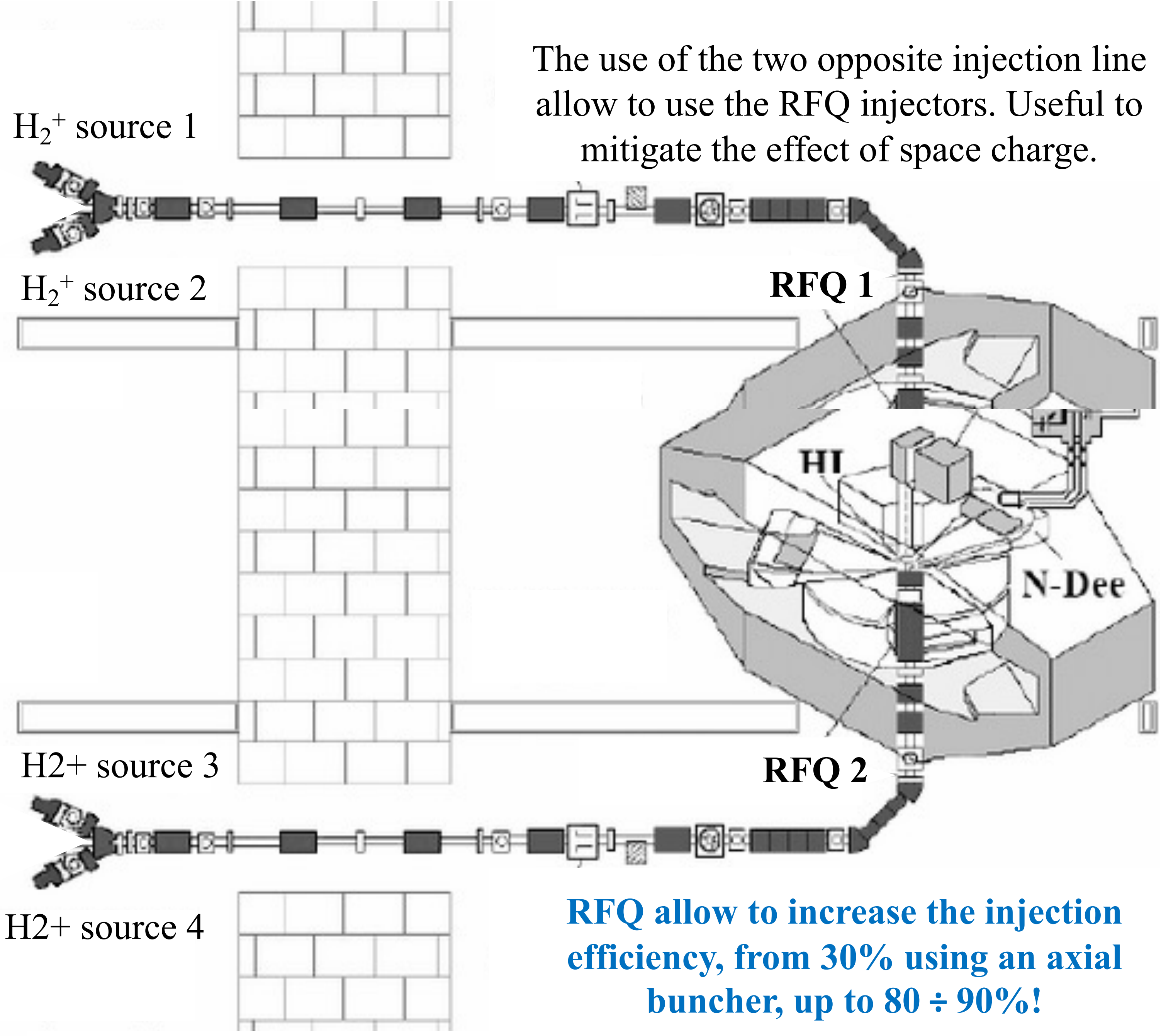
Using the stripping extraction, it is not relevant to have a single acceleration trajectory, nor well separated turns at the extraction.



We could investigate this option to work with only two ion sources in operations and the other two in stand by, to be used when maintenance is requested.

Typical scheduled maintenance for ion source of the type under developing at MIT is 1 week.

Other ion sources, like ECR driven by microwave, need maintenance at least one time per month.



The use of the two opposite injection line allow to use the RFQ injectors. Useful to mitigate the effect of space charge.

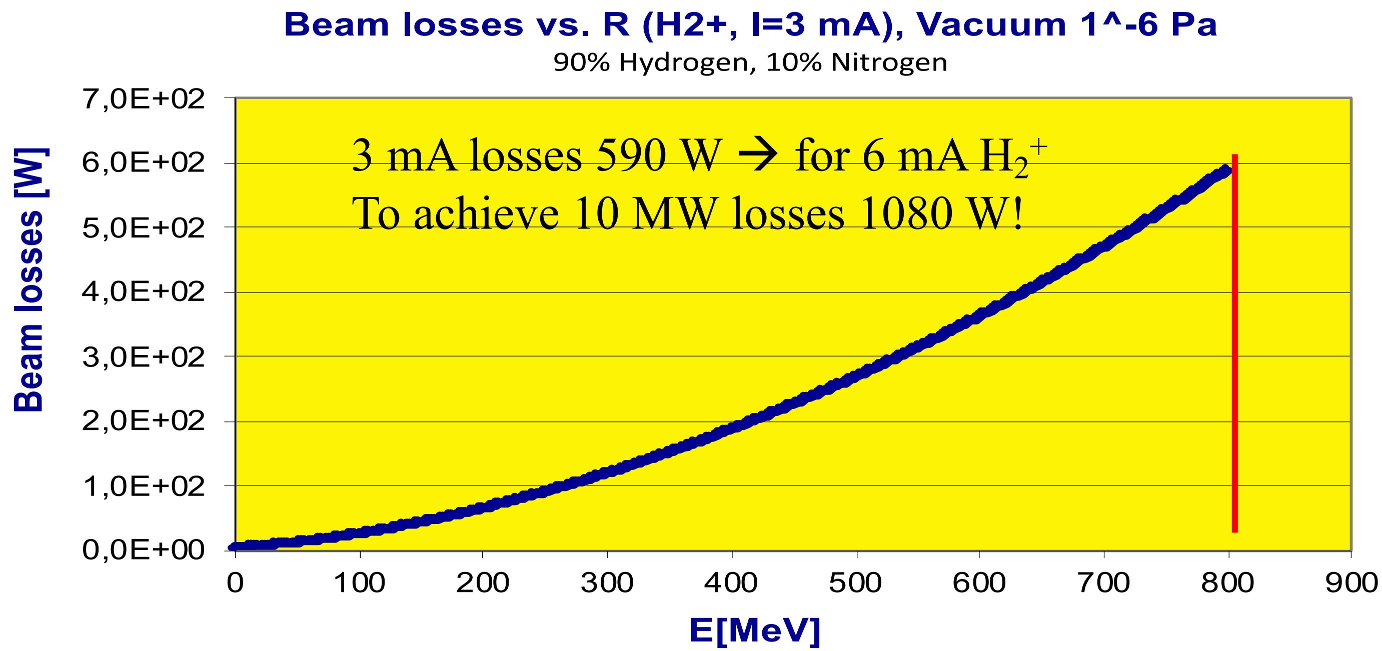
RFQ allow to increase the injection efficiency, from 30% using an axial buncher, up to 80 ÷ 90%!

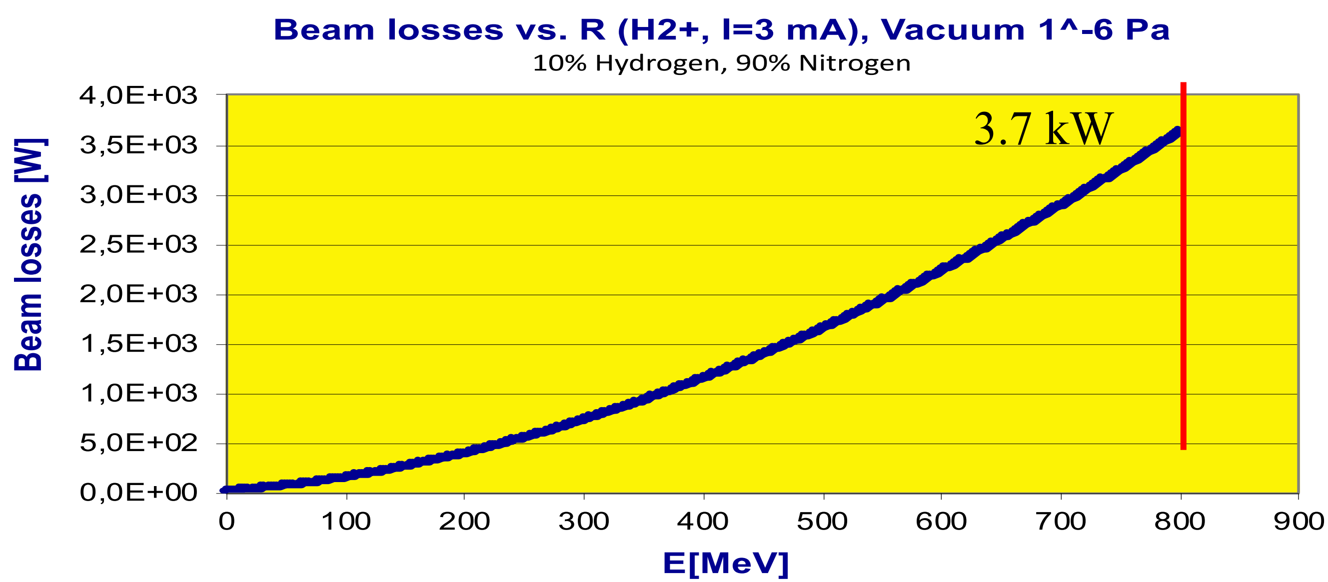
Now we start to discuss the problems of H_2^+!

AIMA solution:
Central field 7.9 kGauss,
Rmax=7.1 [m],
RF 36.3 MHz

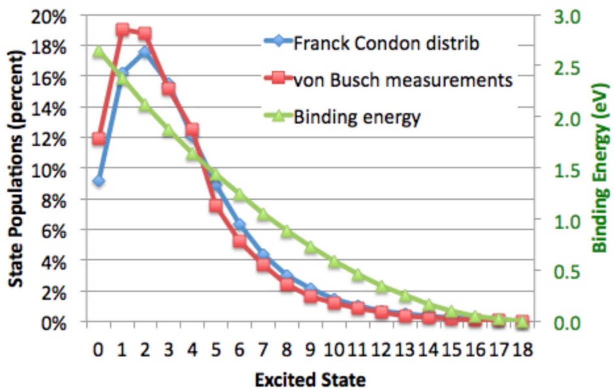
The vacuum level and the composition of the residual vacuum are key items!
Vacuum level better than 10^{-6} Pa are mandatory.
Cryogenic panel + NEG pumps are a viable solution.

In the perspective of a 10 MW cyclotron the circulating beam current double and the beam losses too!





Population of Excited States



DAEδALUS

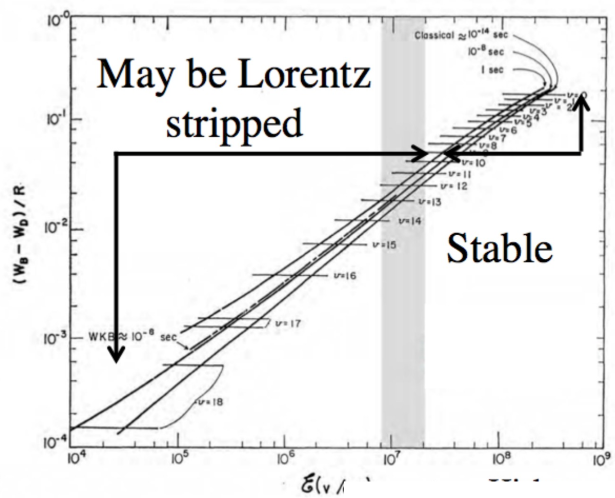
The most serious problems!

Complications

- The lowest electronic state of H_2^+ has 19 bound vibrational states
- Removing an electron from a neutral hydrogen molecule may leave the remaining ion in an excited vibrational state
- In the presence of an external field some states may be unbound

v	Energy below dissociation limit (eV)	Franck–Condon distribution
0	2.6495	0.087
1	2.3780	0.155
2	2.1222	0.171
3	1.8816	0.151
4	1.6559	0.120
5	1.4446	0.089
6	1.2474	0.064
7	1.0642	0.045
8	0.8948	0.031
9	0.7392	0.022
10	0.5974	0.0156
11	0.4696	0.0107
12	0.3561	0.0076
13	0.2571	0.0053
14	0.1732	0.0037
15	0.1051	0.0025
16	0.0534	0.0016
17	0.0192	0.0008
18	0.0030	0.0002
19	0.0001	0.000014

States at Risk for Lorentz Stripping



~5% of beam may be lost!

DAEδAL

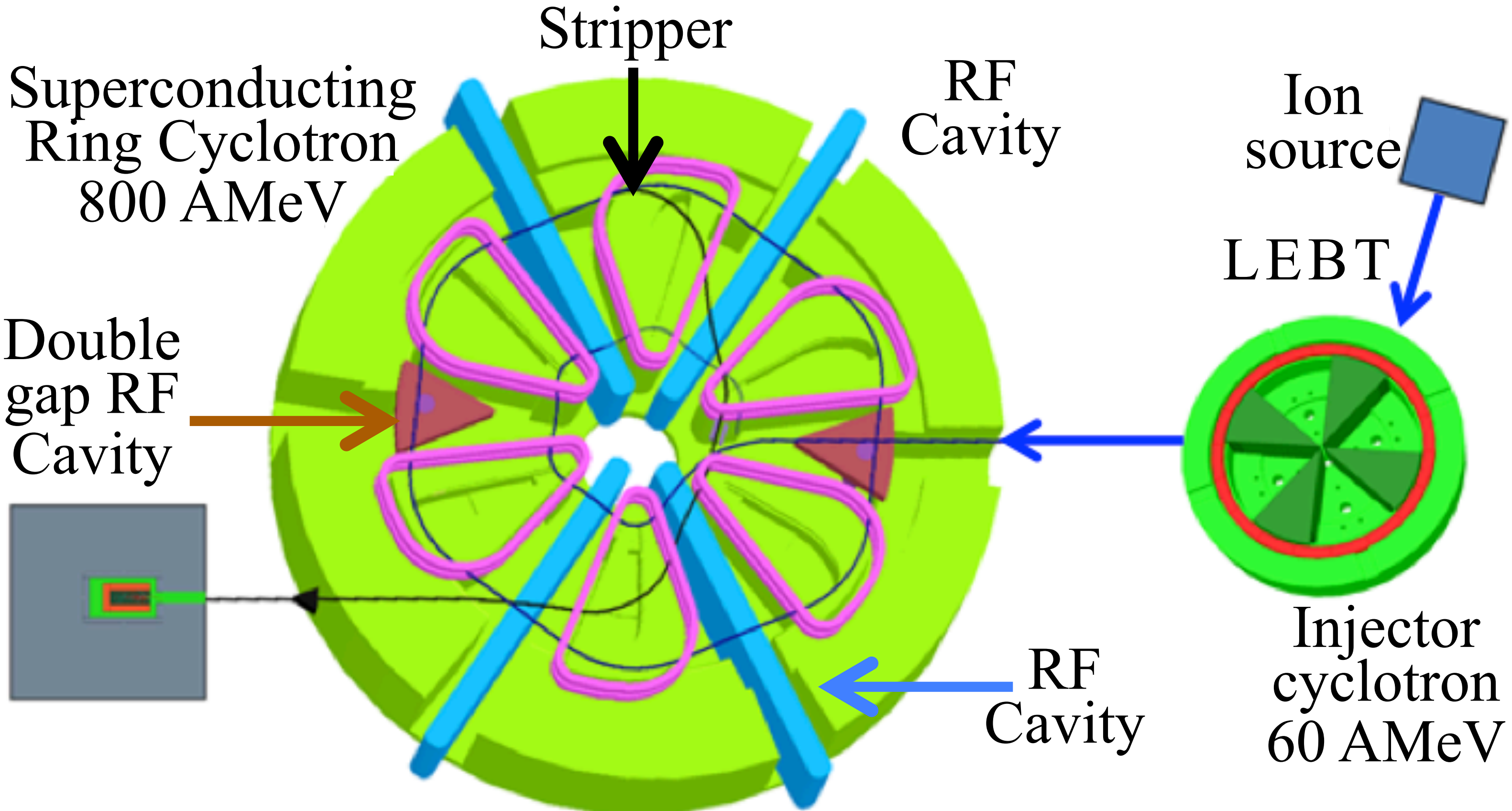
10	0.5974	0.0156
11	0.4696	0.0107
12	0.3561	0.0076
13	0.2571	0.0053
14	0.1732	0.0037
15	0.1051	0.0025
16	0.0534	0.0016
17	0.0192	0.0008
18	0.0030	0.0002
19	0.0001	0.000014

5% *10 MW → ≈ 400 kW

Mitigation Possibilities

- In Ion source:
  - Collisional dissociation of weakly-bound states with noble gases
    - Reaction rate is slow, requires confinement time of ms
    - Verified by experiment at ORNL
- In transport line at 60 MeV/amu
  - Lorentz strip between DIC and DSRC
    - Requires 10 T to dissociate highest vibrational states that could be dissociated inside the Ring cyclotron at energy below 400 MeV (a 20T magnetic field should be sufficient to dissociate all the vibrational states)
- Controlled loss at high energy
  - Selected magnetic bumps
    - Possible to contain lost particles

DAEδALUS Cyclotron Cascade project, when equipped with two injector cyclotrons could deliver a beam power exceeding 10 MW!



Drawbacks:

- Electrostatic deflector in the injector cyclotron;
- construction cost

François Meòt and Malek designed the injection line to the ring cyclotron

Dissociation of vibrational states at 60 MeV/amu in a dedicated channel

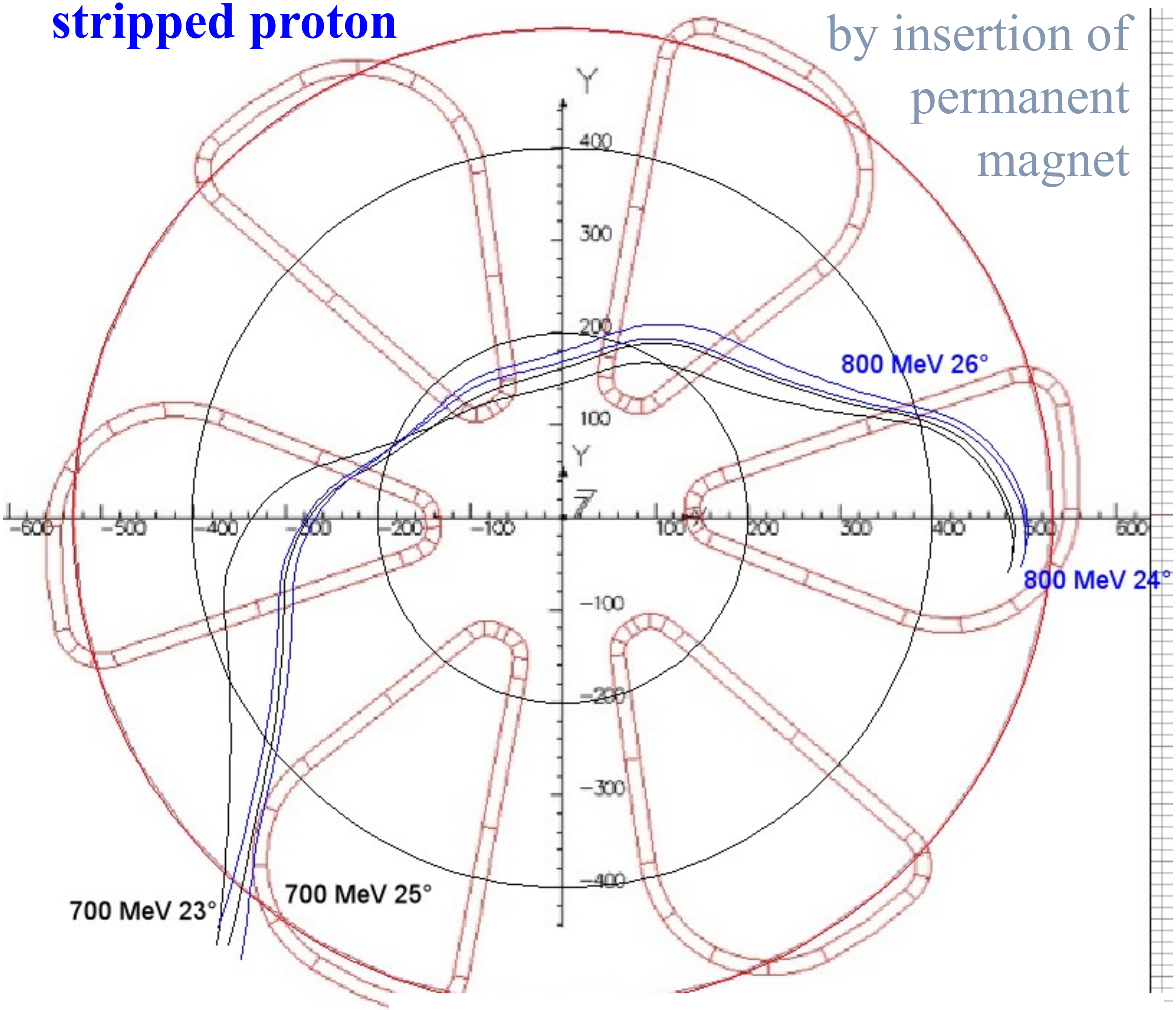
Lorentz stripping: E (MV/cm) = 3 β γ B (T)

Requested Magnetic Field acting on the 60 MeV/amu H_2^+ to dissociate the vibrational states. Total power removed about 30 kW instead of 400 kW inside the booster!

Magnetic field [T]	Energia MeV/amu	Gamma	Beta	βγ	Magnetic field on the dissociation line [T]	<R> [m]	E [MV/cm]
	60	1,064	0,343	0,364	1	2	
	100	1,107	0,430	0,475			
3,3	200	1,215	0,568	0,689	6,240	0,320	6.82
3,45	300	1,322	0,654	0,864	8,181	0,244	8.94
3,6	400	1,429	0,715	1,021	10,083	0,198	11.0
3,9	500	1,537	0,759	1,1669	12,4801	0,160	13.65
4,2	600	1,644	0,794	1,305	15,031	0,133	16.44
4,4	700	1,752	0,821	1,438	17,350	0.115	18.98
4,6	800	1,859	0,842	1,567	19,766	0.101	21.62

Trajectories of the stripped proton

6 High field region by insertion of permanent magnet



Increasing suddenly the local magnetic field of about 2÷4 kGauss at the azimuth θ=-6°÷4° (label 24° 26°), the H_2^+ vibrational states are dissociated at this proper position and protons go out exactly where we like!

800 MeV/amu, See Blue lines

Similarly with H2+ with energy of 700 MeV/amu.

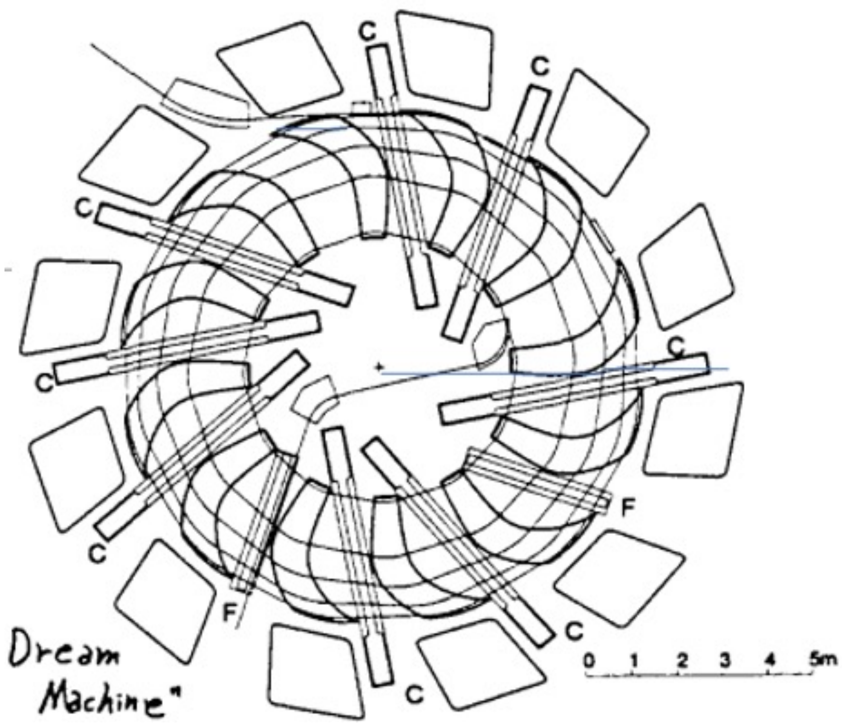
See Black lines.

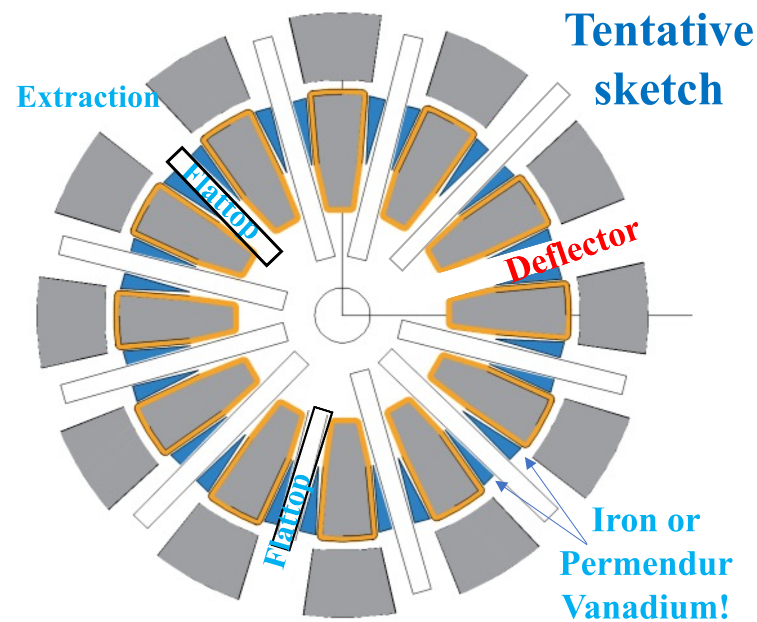
To take advantage of the single stage superconducting cyclotron stripper extraction of H_2^+ (AIMA project or DAEδALUS) it is mandatory a strong program of R&D on the ion source to deliver H_2^+ beam almost free of the highest vibrational states or significantly reduce their percentage of an order of magnitude!

In the meanwhile …

800-1000 MeV cyclotron Accelerator

- Injector Cyclotron like IsoDAR/PSI, 4/6 sectors, 4/6 RF cavities, ion beam H_2^+, but with stripper extraction, and double injection energy at 100-150 keV, and Extraction energy 120/200 MeV/amu to deliver 10-14 mA proton beam;
- Main Ring "Dream Machine like" (T. Stambach et al. PSI 1998): 12/14 separated superconducting sectors, 9 or more RF cavities, proton beam, injection energy 120/200 MeV, Extraction energy by Deflector at 800/1000 MeV. Main check: reliability of extraction also in the bad case of one/two RF cavities OFF!






A warm thanks
for your attention!