A Multi Mega Watt Cyclotron Complex

to Search for CP violation in neutrino sector

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CSFN&SM, Catania

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Expression of Interest for A Novel Search for CP Violation in the Neutrino Sector:

DAEδALUS

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H.T. Baumgartner, A. Bernstein, E. Blucher, L. Bugel, L. Camilleri,
R. Carr, J.M. Conrad, Z. Djurcuc, A. de Gouvêa, P.H. Fisher,
C.M. Ignarra, B.J.P. Jones, C. Jones, G. Karagiorgi, T. Katori,
S.E. Kopp, R.C. Lanza, W.A. Loinaz, P. McIntyre, G.B. Mills,
V. Papavassiliou, M. Sanchez, K. Scholberg, W.G. Seligman,
M.H. Shaevitz, S. Shalgar, T. Smidt, J. Spitz,
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R. Van de Water, M.O. Wascko, R. Wendell, L. Winslow

DAEδALUS

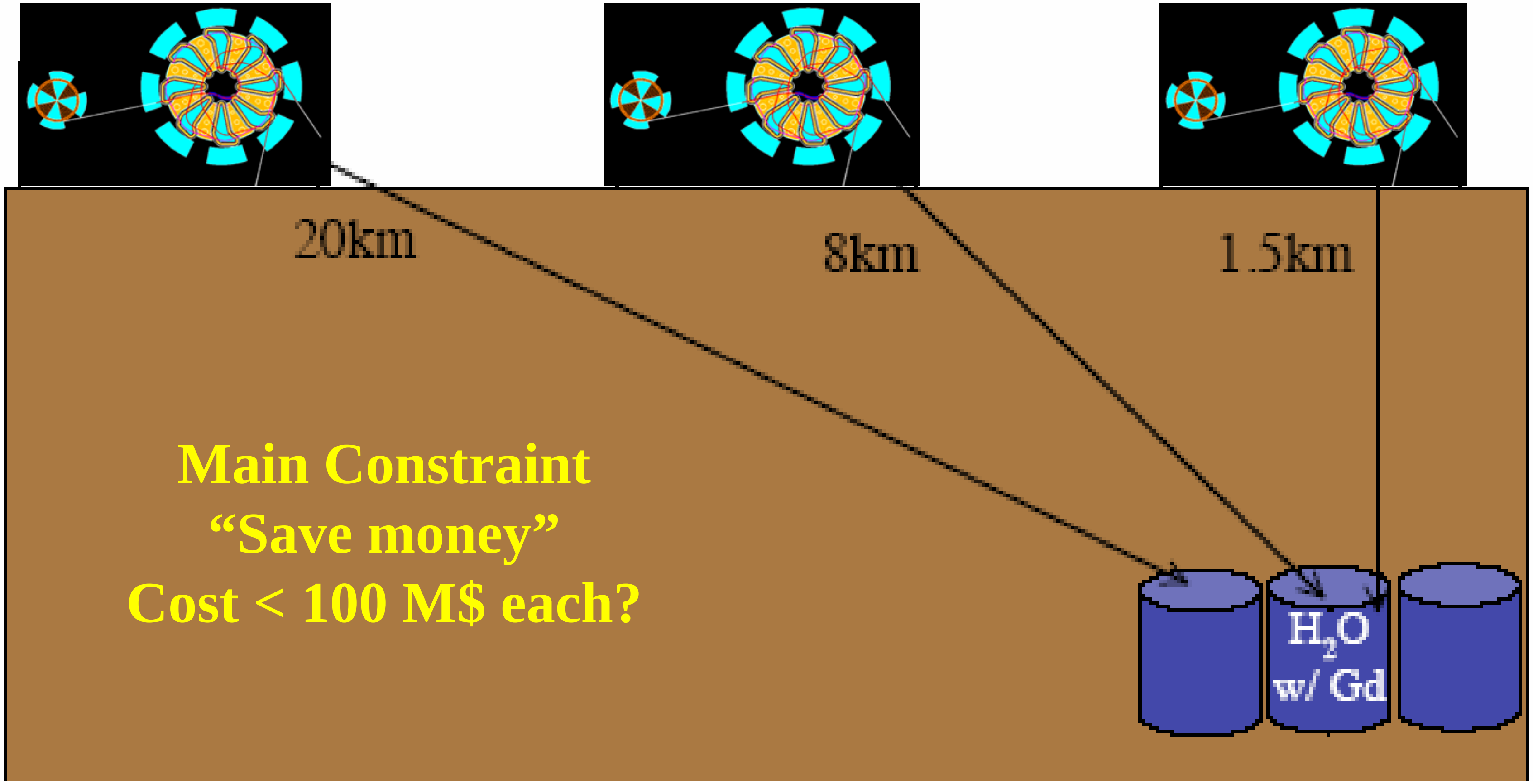
DAEdALUS, a Decay-At-rest Experiment for δ_{CP} studies At the Laboratory for Underground Science, provides a new approach to search for CP violation in the neutrino sector. The design utilizes high-power proton accelerators to provide neutrino beams with energy up to 52 MeV from pion and muon decay-at-rest.

The experiment searches $\nu_\mu \rightarrow \nu_e$ for at short baselines. The ν_e will be detected in the 300 kton volume Gd-doped water Cerenkov neutrino detector proposed for the Deep Underground Science and Engineering Laboratory (DUSEL).

proton beam
800 MeV @ 3 MW

proton beam
800 MeV @ 2 MW

proton beam
800 MeV @ 1 MW



Lay-out of the DAEALUS Experiment. Three neutrino source locations are used in conjunction with the 300 kton water Cerenkov detector complex at the 1.5 km level of DUSEL.

DAEALUS needs 1 ÷ 1.5 MW proton beam @ 800 MeV

The beam time structure being 100 msec beam on, 400 msec beam off duty cycle= 20% → peak power 5÷8 MW → Peak current 6÷10 mA

- **Superconducting linacs provide the most conservative technology option but they are expensive**

- **Space and cost constraints suggest that high-power cyclotrons could be a less expensive option.**

We propose a Multi-Megawatt Cyclotron Ring (MMC), to accelerates H_2^+ for two main reasons:

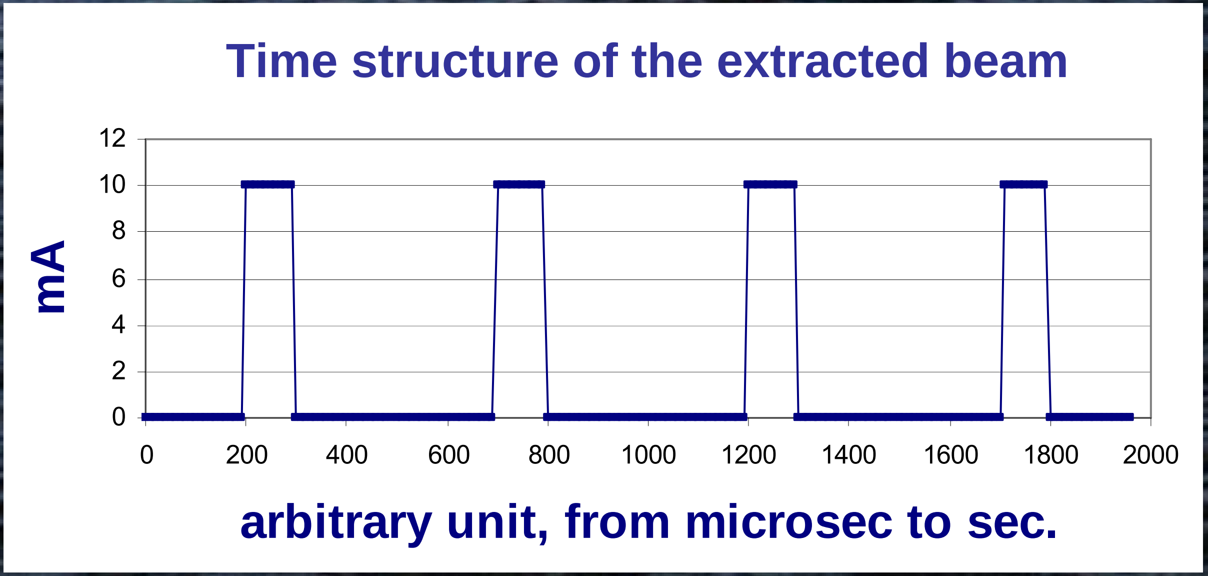
-Vantages of stripper extraction vs. the Electrostatic Deflectors extraction

-Space charge effects reduced by a factor $\sqrt{2}$ vs. proton beam

Why the Stripper Extraction?

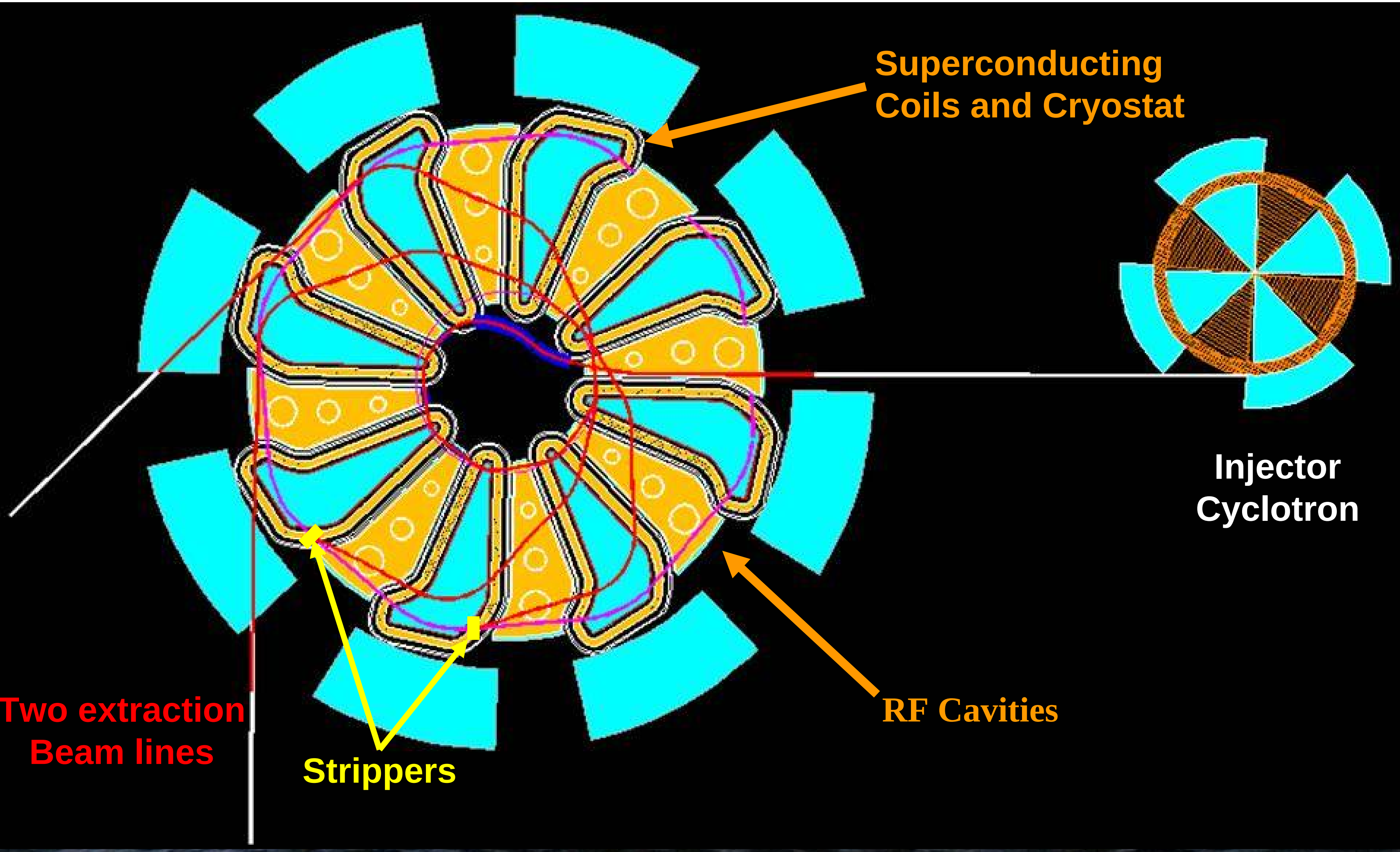
The cyclotron has to operate with high current beam 6÷10 mA, regime of high beam loading. It has to accelerate a short beam bunch to minimize the radial beam size which depend on the energy spread

This could be a problem for extraction by Electrostatic Deflectors, while it is not relevant for extraction by stripper



The Stripper Extraction allow to deliver two or more beams at the same time

Two beam dumps are better than a one dump to dissipate the 1.5 MW power



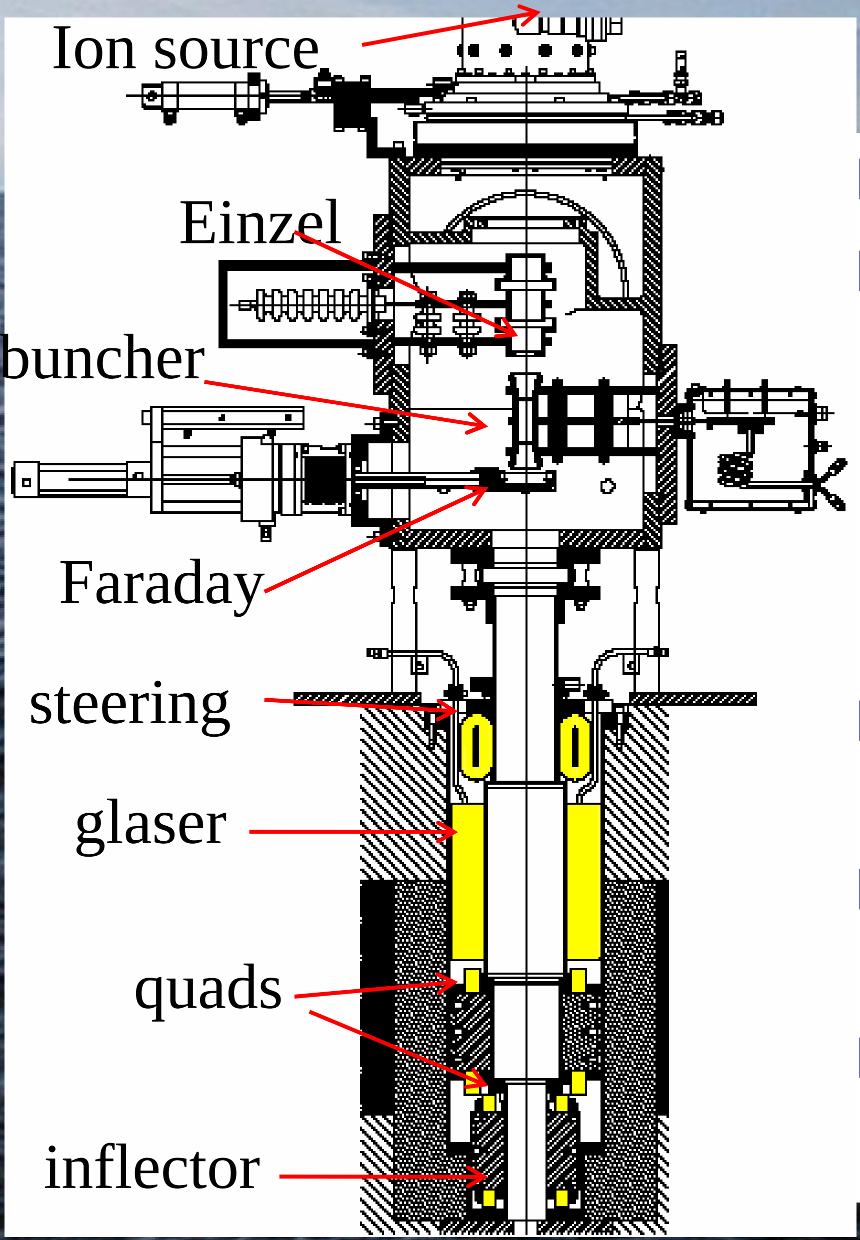
To deliver a proton beam with 10 mA peak current we have to accelerate an H_2^+ beam with a 5 mA peak current

The Generalized Perveance is the parameter which measure the space charge effect, it is defined by this formula [M. Reiser]:

$$K = \frac{qI}{2\pi \cdot \varepsilon_o \cdot m \cdot v^3}$$

	E_p=30 keV, E_{H2}=30 keV β_p= 1.414β_{H2}		E_p=30 keV, E_{H2}=70 keV β_p= 0.926β_{H2}		E_p=30 keV, E_{H2}=70 keV β_p= 0.926β_{H2}
Proton 10 mA	K_p 1.245 10^{-3}	Proton 2 mA	K_p 0.249 10^{-3}	Proton 2 mA	K_p 0.249 10^{-3}
H2+ 5 mA	K_{H2} 0.881 10^{-3}	H2+ 5 mA	K_{H2} 0.247 10^{-3}	H2+ 3.5 mA	K_{H2} 0.148 10^{-3}
	K_{H2}/K_p=0.707		**K_{H2}/K_p=0.992**		**K_{H2}/K_p=0.595**

Cyclone-30 is able to delivers up to 2 mA



- 15 mA high-brightness H^- source
- Reduce H^- stripping losses
  - Differential pumping
  - Compact design
  - Axial bore elements in separate housing at atmospheric pressure (no outgassing)
- Two pairs of steering magnets for beam alignment at inflector
- Cyclotron iron is used as return yoke for the solenoid
- Magnetic shielding of turbo-pumps

IBA Cyclone 30 Imax=2 mA			
Einj	30 keV	Emax	30 MeV
Rinj	30 mm	Rext	0.75 m
<B> at Rinj	1.0 T	<B> at Rext	1.3 T
Sectors N.	4	N. Accel. Cavities	2
RF	66 MHz	Harmonic	4^{th}
ΔE/Turn	170 kV	Ion Source current H^-	15 mA
EBCO TR-30 Imax=1.6 mA			
Einj	25 keV	Emax	30 MeV
Rinj	25 mm	Rext	0.66 m
<B> at Rinj	1.2 T	<B> at Rext	1.24 T
Sectors N.	4	N. Accel. Cavities	2
RF	73 MHz	Harmonic	4^{th}
ΔE/Turn	200 kV	Emittance (normalized)	0.43 π mm.mrad

Main parameters are extrapolated from commercial compact cyclotron: C30, TR-30

Commercial cyclotron are able to deliver 1.5 ÷ 2 mA proton beam using injection energy and acceleration voltage moderate and multicusp ion source

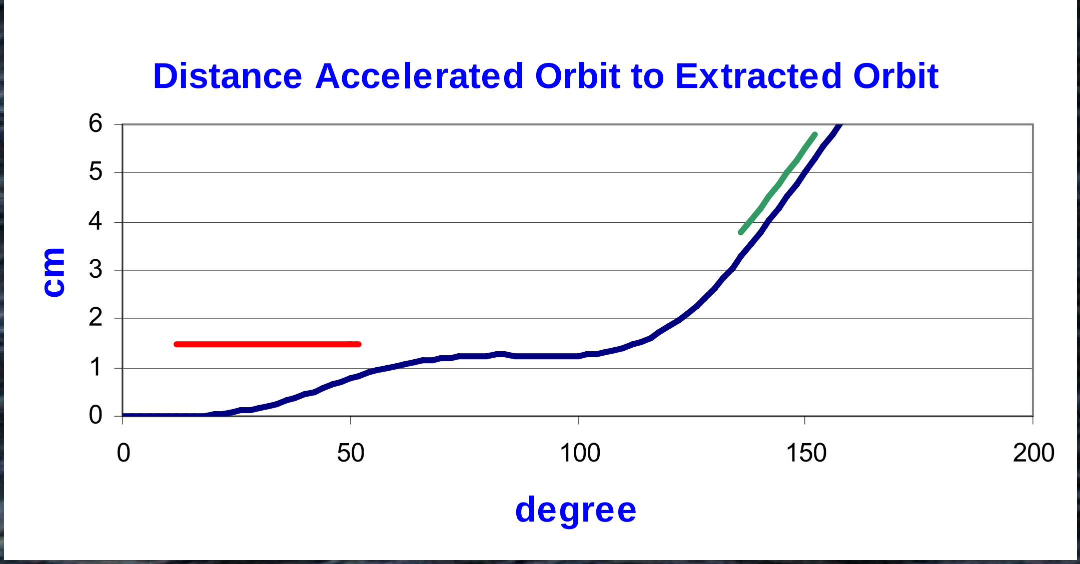
H2+ Injector
Einj=70 keV vs. 25-30 keV

Central field 1.3 vs. 1.0-1.2T
→ smaller beam size

DE/turn>420 keV vs. 170-200 keV
DE/turn>1500 keV vs. 170-200 keV
→phase compression

New Generation ECR ion source with emittance 0.1 ÷ 0.2 vs. 0.4

MMC-I Injector Cyclotron Parameters			
Einj	35 keV/n	Emax	50 MeV/n
Rinj	41.6 mm	Rext	1.44 m
<B> at Rinj	1.29 T	<B> at Rext	1.39 T
Sectors N.	4	Cavities N.	4
RF	30 MHz	Harmonic	3rd
V-inj	> 70 kV	V-ext	250 kV
ΔE/turn	1.8 MeV	ΔR at Rext	11.6 mm
Δx at Rext	< 3.5 mm	Turns N.	< 83
1 Electrostatic Deflector (ED) + 2 Magnetic Channels			
E. D. Gap	12 mm	E.D. field	40 kV/cm



Main parameters are extrapolated from existing commercial compact cyclotron: C30 and TR-30

Injection energy and acceleration voltage are higher vs. C30/TR-30

30 MeV/n after 60 turn vs. 150, or 6 μsec vs. 8.1 μsec

Increasing acceleration voltage →shrink the bunch

Beam Power at target
1 ÷ 1.5 MW
Duty cycle 20%
Beam on 100 msec
Beam off 400 msec

<I>=1.4 ÷ 2 mA →
I_{pulse}=6.8 ÷ 10 mA

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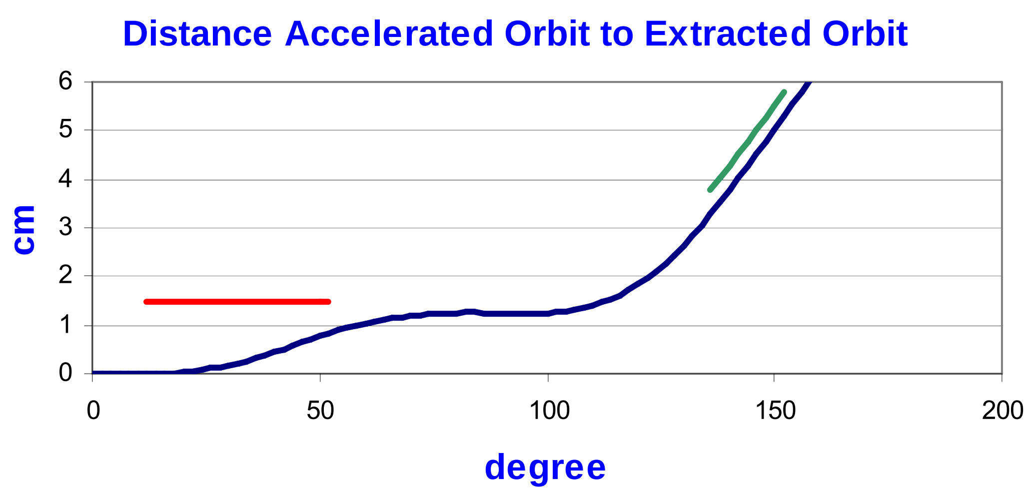

Beam losses @ injection

1° post 3 kW @ 100 keV

2° post 3 kW @ 200 keV

3° post 2.6 kW @ 350 keV

Extraction efficiency > 99.8%

Beam power max. = 200 kW

Power lost <400 W

H_2^+ peak current 3.5 ÷ 5 mA

Current requested to the H_2^+ ion source: 24 ÷ 34 mA acceptance efficiency 15%, or ± 27° without buncher

Serious problem at the injection due to the space charge effect!

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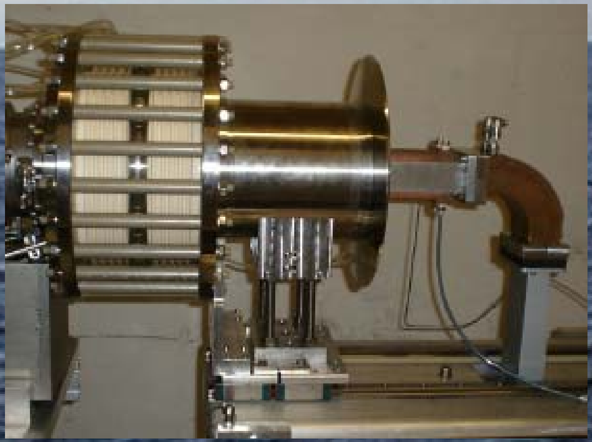
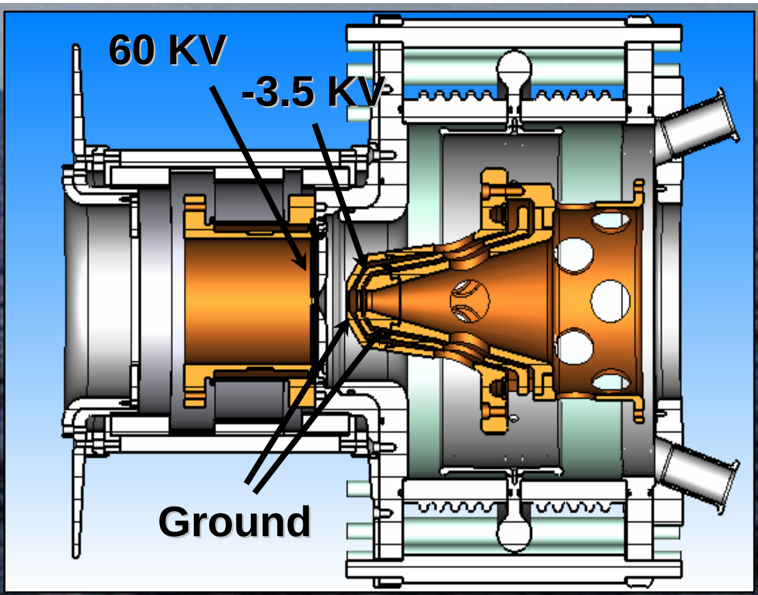
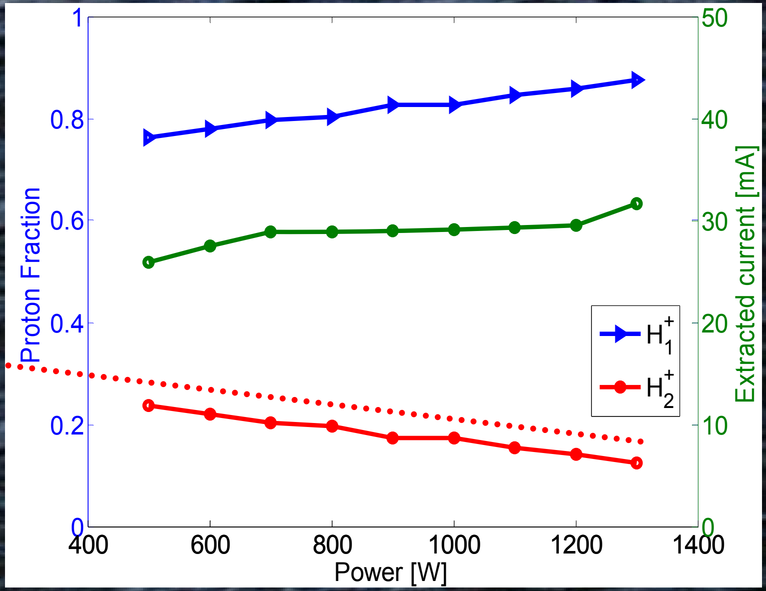
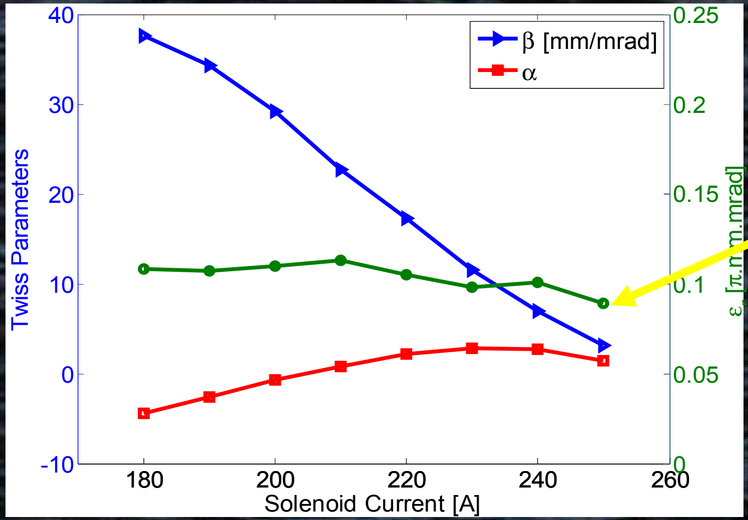
Versatile Ion Source (VIS) Developed at LNS-Catania by Gammino, Ciavola, Celona et Al.



VIS could deliver more than 20 mA of H2+ adjusting some parameters like: RF Power, Vacuum Pressure, Position of the permanent magnets







Good emittance

Catania Versatile Ion Source is a "cheaper" solution

VIS could deliver the required 35 mA of H_2^+ at 70 keV and with a good normalized emittance $\varepsilon < 0.2\ \pi$ mm.mrad, after minor adjustment

The IFMIF project is developing an injector prototype, SILHI like

A scaled down version of this source could be an alternative solution, but it is more complex and expensive

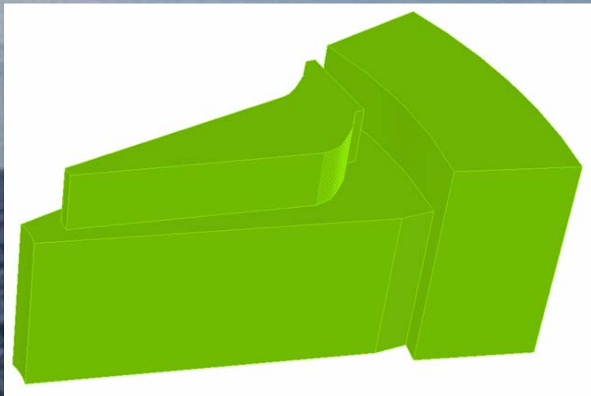
The IFMIF ion source will be tested by delivering an H_2^+ beam!

IFMIF preinjector main parameters:

- **Maximum Energy 100 keV;**
- **Maximum current for D+ 100-140 mA;**
- **Normalized rms. emittance <0.30 π mm.mrad**
- **Beam current noise < 2% at frequencies below 1 MHz**
- **Beam turn-off time < 20 msec from 100% to 10% beam intensity**

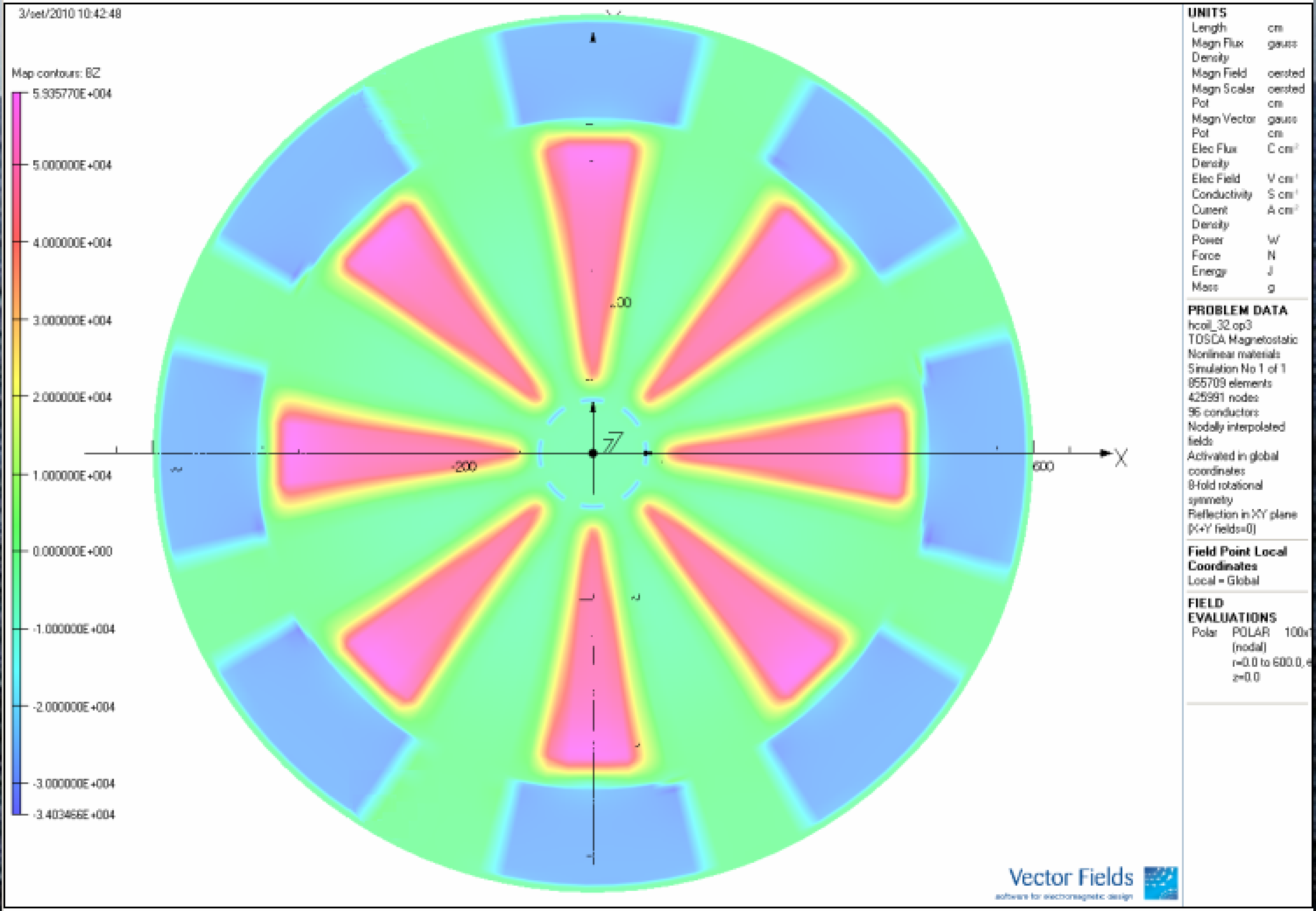
MMC-R Superconducting Ring Cyclotron Parameters			
Einj	50 MeV/n	Emax	800 MeV/n
<Rinj>	1.44 m	Rext	4.05 m
<B> at Rinj	1.39 T	<B> at Rext	2.28 T
Pole Gap	≥ 50 mm	Bmax	< 6 T
Hill width	20°	Sector height	< 5 m
Outer radius	≤ 6 m	Sector weight	< 300 Tons
Flutter	1.7 ÷ 1.27	Spiral angle	< 40°
Sectors N.	8	Cavities N.	8
Cavities type	λ/2	Cavities type	Double gap
RF	59 MHz	Harmonic	6th
V-peak	300 kV	ΔE/turn	2.5÷3.2 MeV
ΔR at Rinj	> 15 mm	ΔR at Rext	1.5 mm
Δx at Rinj	3 mm	Δx at Rext	1.5 mm

ε_x=0.4 π mm.mrad, emittance normalized



$$\frac{dR}{dN} = R\frac{E_g}{E}\frac{\gamma}{\gamma+1}\frac{1}{\nu_r^2}$$

$$\Delta x = \sqrt{\frac{4R}{\beta\gamma\nu_r}\cdot\frac{\varepsilon_x}{\pi} + \left(\frac{dR}{dN}\frac{\Delta E}{E_g}\right)^2}$$


3/set/2010 10:42:48
Map contours: BZ
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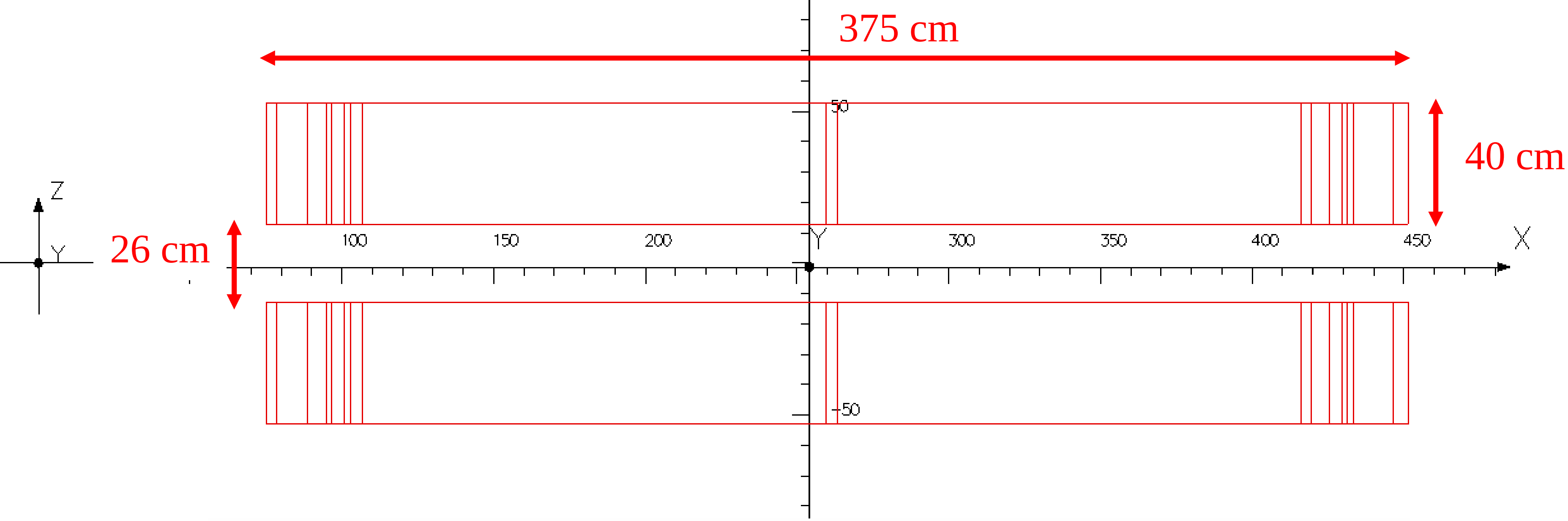
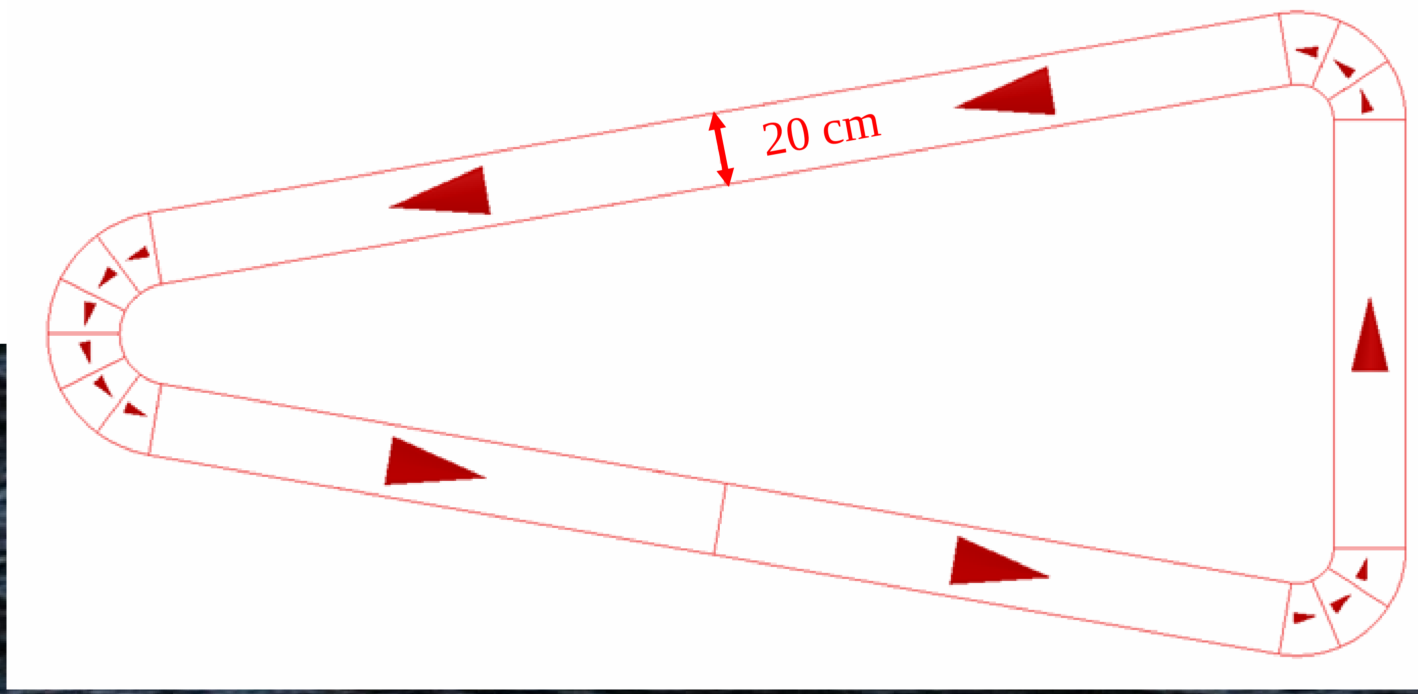
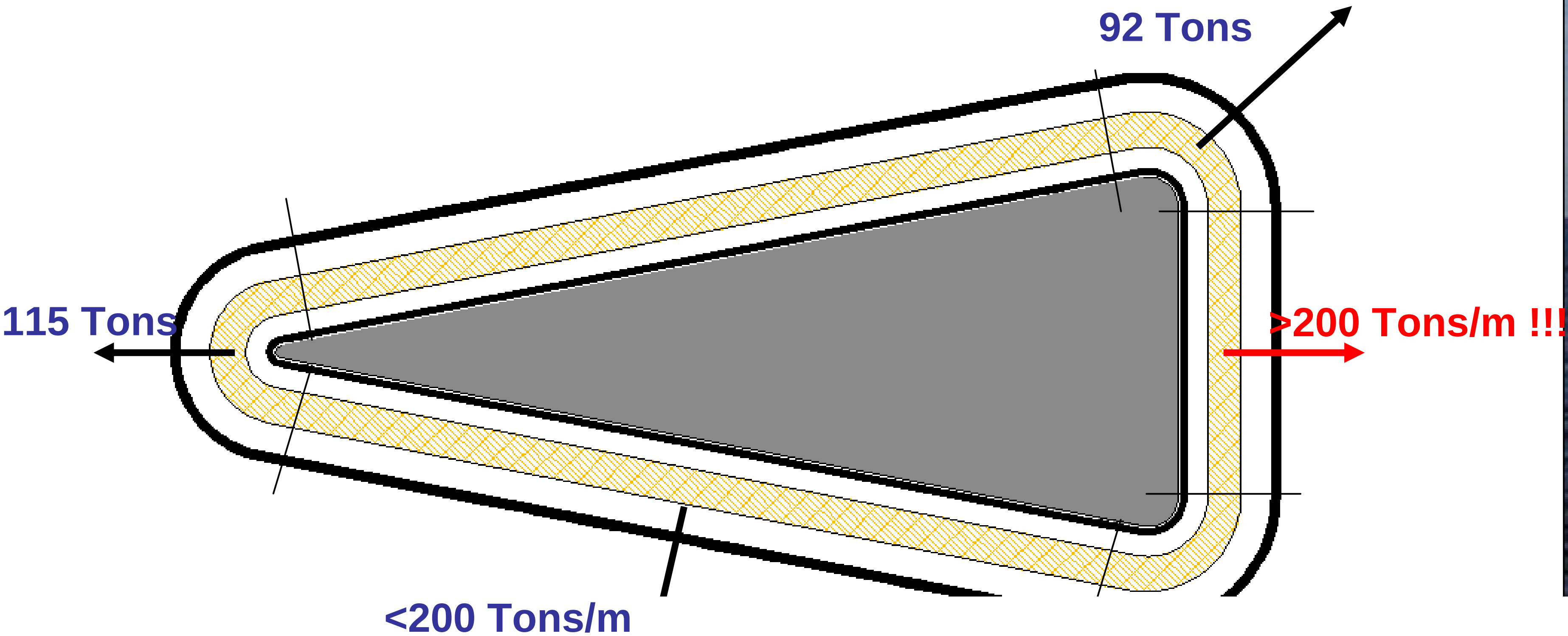
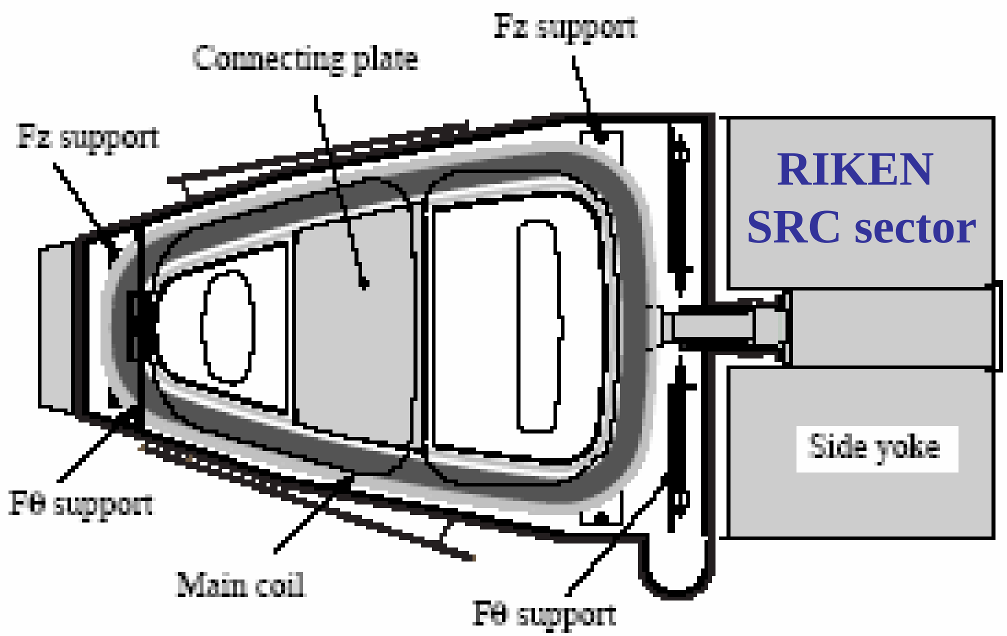
5.000000E+004
4.000000E+004
3.000000E+004
2.000000E+004
1.000000E+004
0.000000E+000
-1.000000E+004
-2.000000E+004
-3.000000E+004
-3.403466E+004
-200
600
X
Z
UNITS
Length cm
Magn Flux Density gauss
Magn Field oersted
Magn Scalar Pot oersted cm
Magn Vector Pot gauss cm
Elec Flux Density C cm⁻²
Elec Field V cm⁻¹
Conductivity S cm⁻¹
Current Density A cm⁻²
Power W
Force N
Energy J
Mass g
PROBLEM DATA
hcoil_32.op3
TOSCA Magnetostatic
Nonlinear materials
Simulation No 1 of 1
855709 elements
425991 nodes
96 conductors
Nodally interpolated fields
Activated in global coordinates
8-fold rotational symmetry
Reflection in XY plane (X+Y fields=0)
Field Point Local Coordinates
Local = Global
FIELD EVALUATIONS
Polar POLAR (nodal)
r=0.0 to 600.0,
z=0.0
Vector Fields
software for electromagnetic design


375 cm
40 cm
26 cm
Z
Y
X
50
-50
100
150
200
300
350
400
450


20 cm



Superconducting Coil parameters	
Width	20 cm
Height	40 cm
Current	43 A/mm^2
Conductor	NbTi
Maximum field on conductor	< 6 Tesla



The Main problem to solve is to achieve a good vertical focusing

We verified that a ν_z values in the range 0.5 ÷ 1 allow to achieve a vertical beam size smaller than 3 mm

According to the well know formula of the ν_z and due to the high γ value (1.86) we need to use high flutter values to minimize the spiral angle

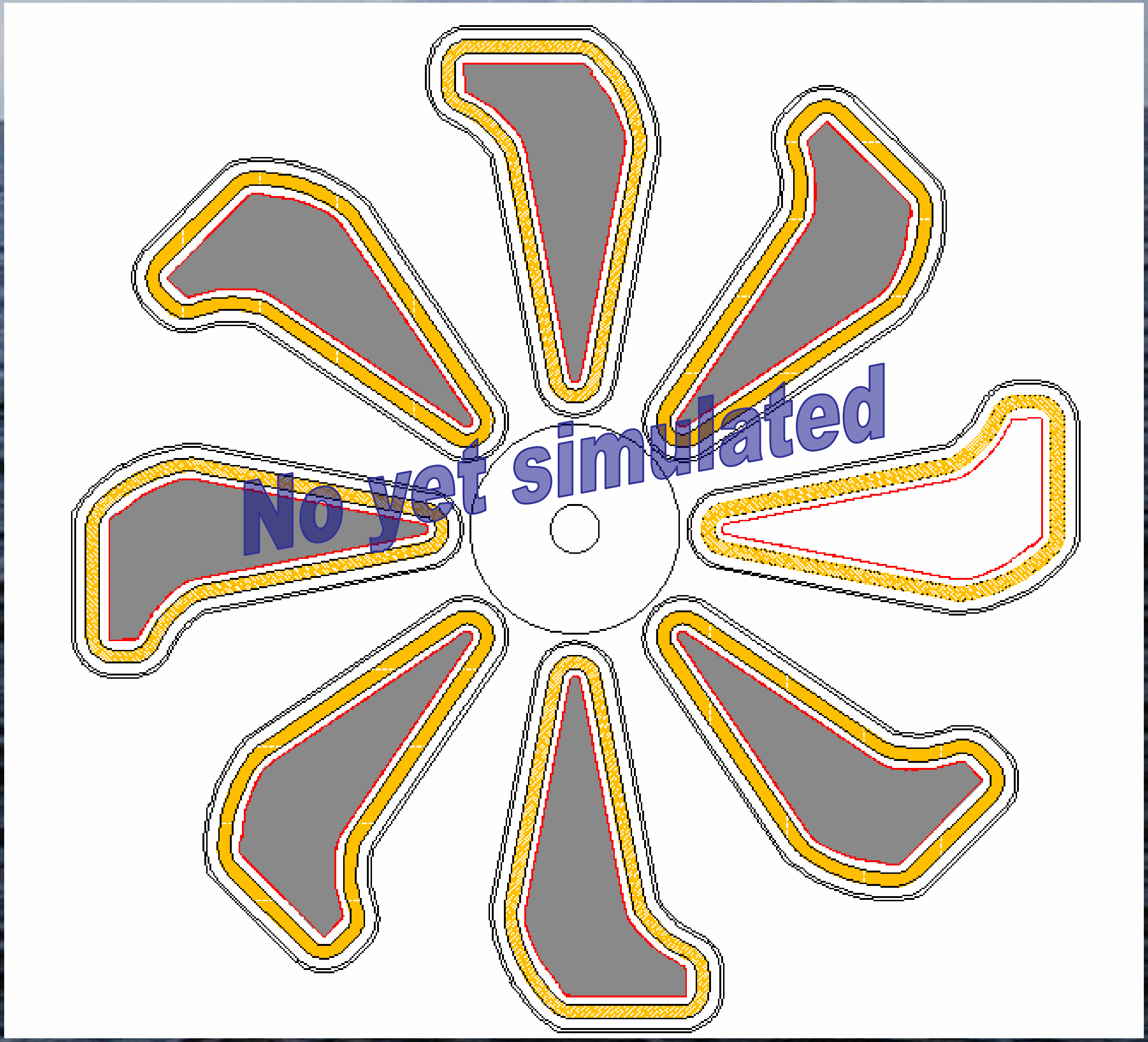
Small value of spiral angle leaves more space for the cavities in the valleys

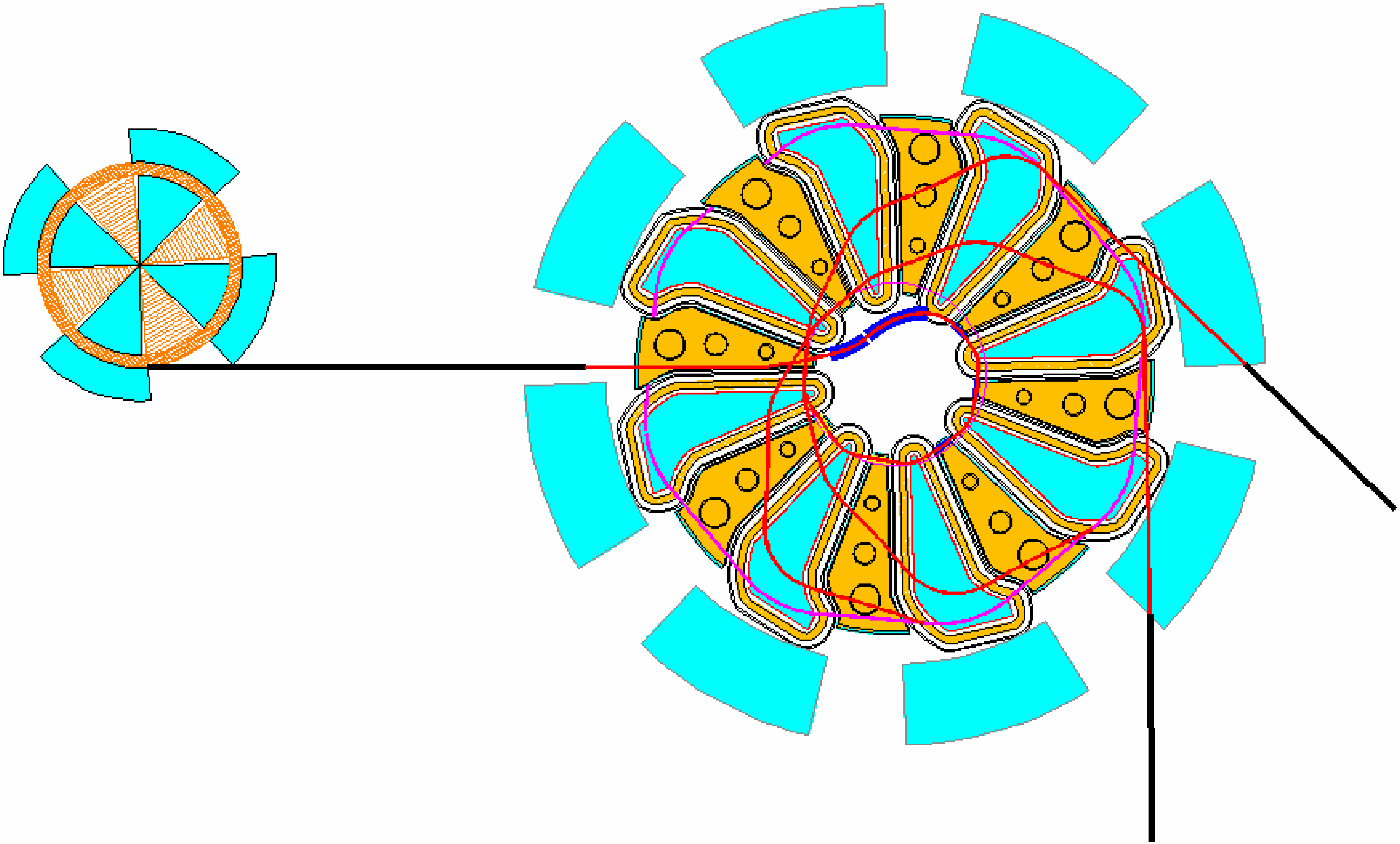
$$\gamma=1.86 \rightarrow 1-\gamma^2\beta^2=-1.45$$

$$1.95 < \frac{N^2}{N^2-1} F_l \left(1+2\tan^2\xi\right) < 2.45$$

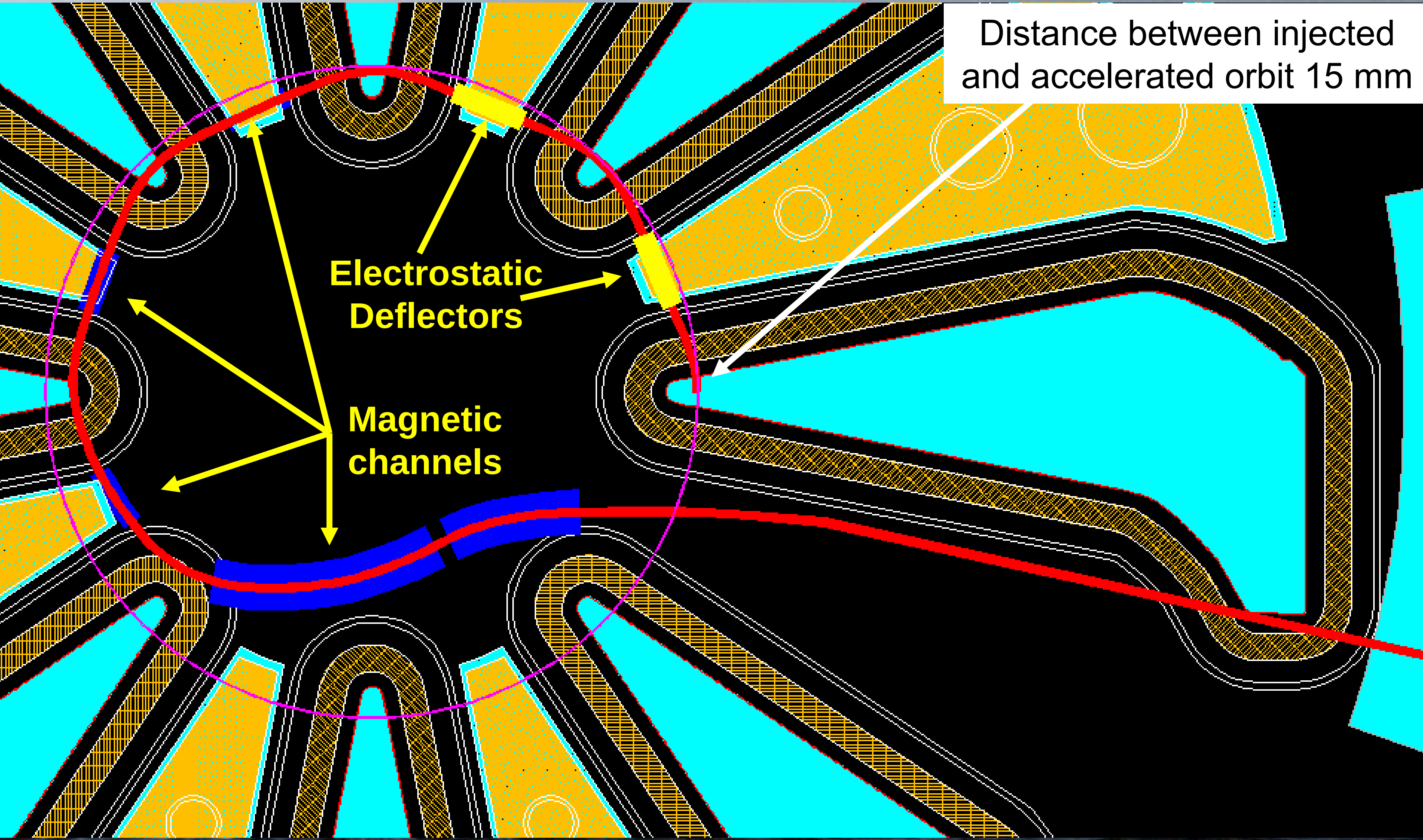
$$F_l=1.27 \rightarrow \xi=27$$

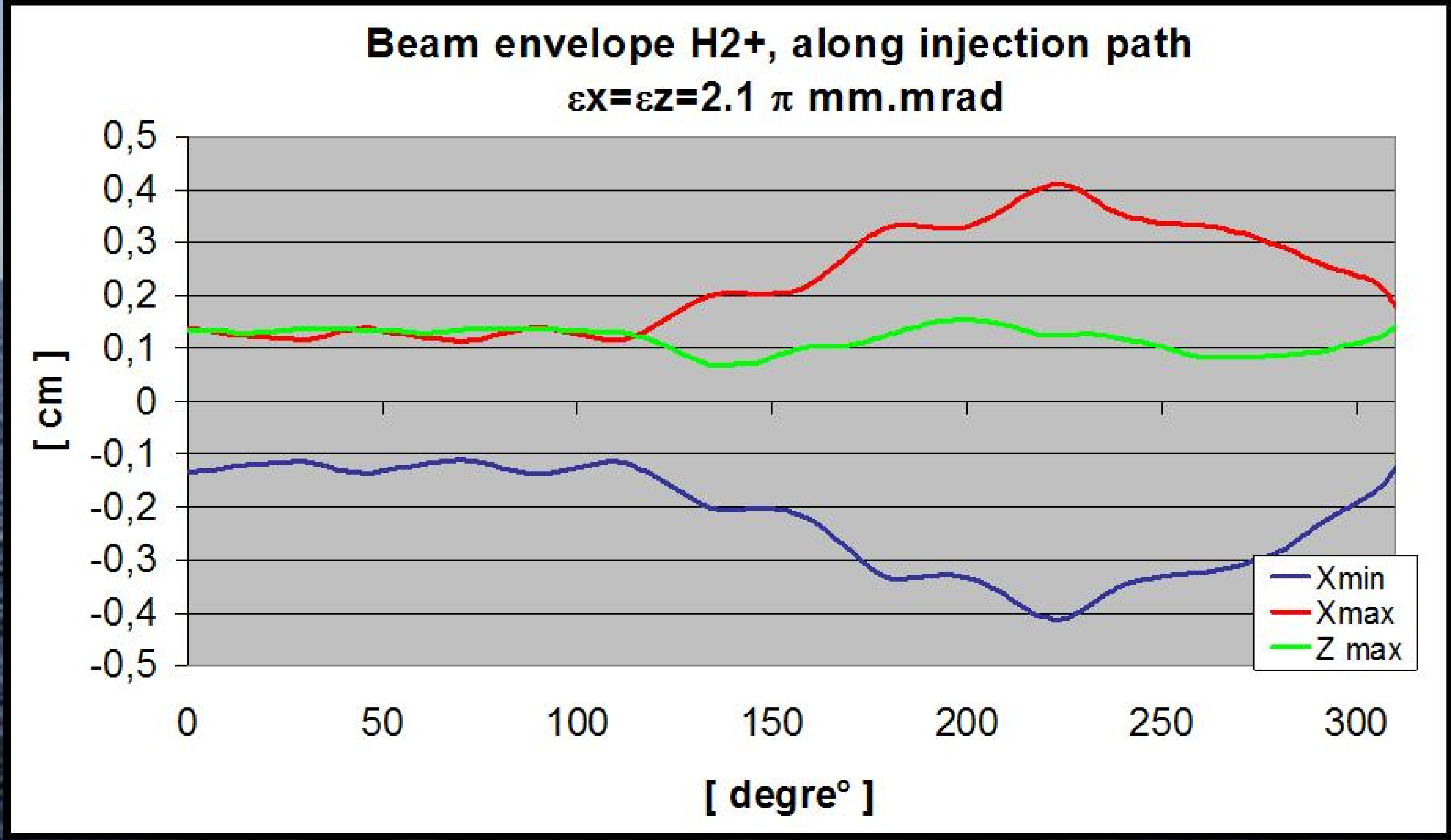
$$F_l>2.1 \rightarrow \xi=0,\ \ \text{Bhill}>6.6\ \text{T}$$

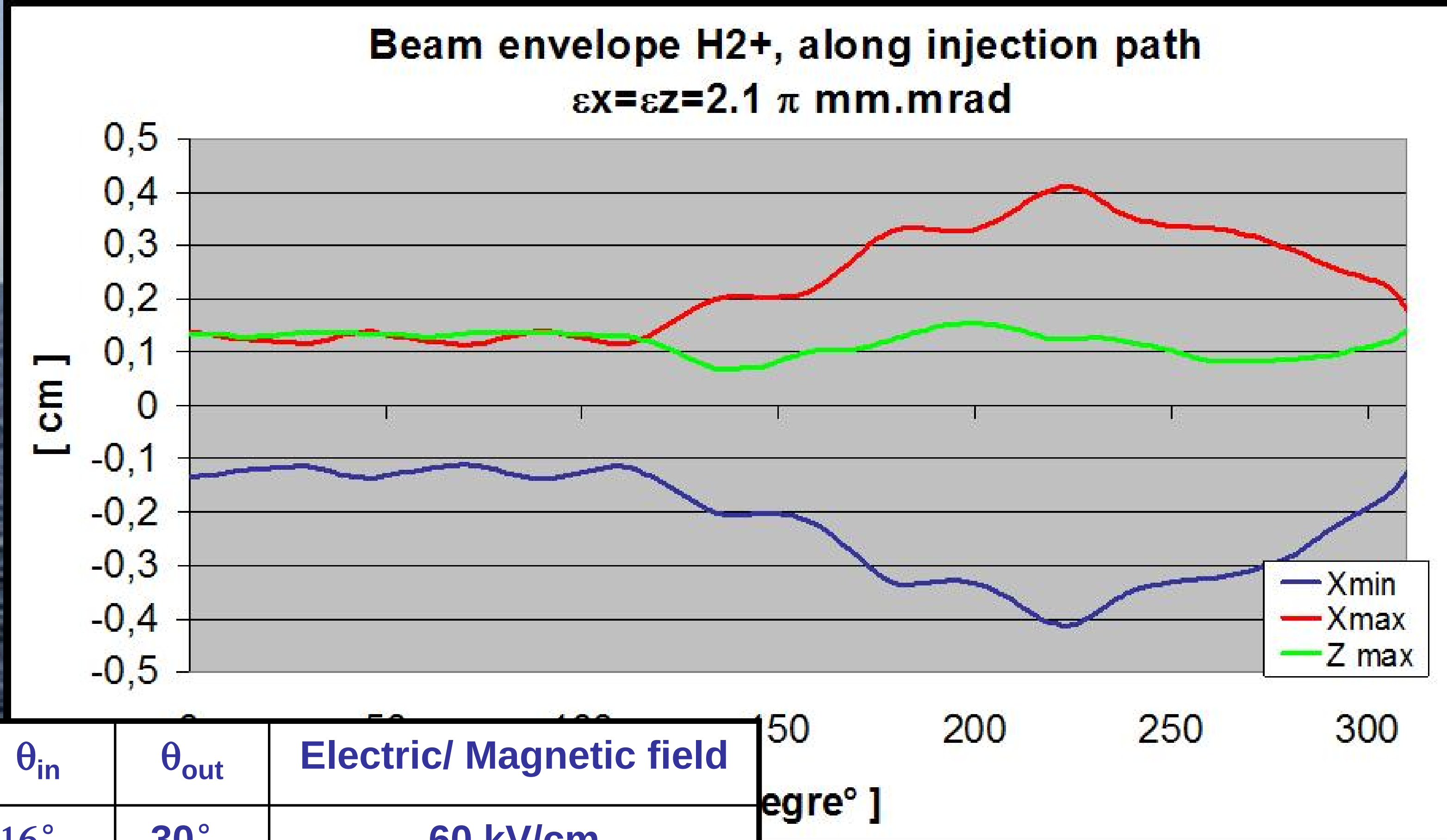

No yet simulated



Injection Trajectory



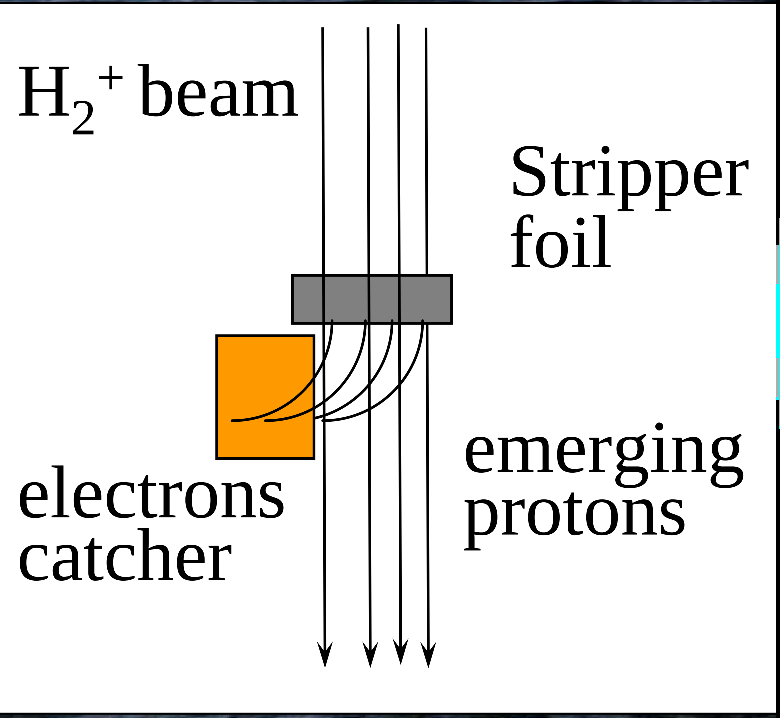

Beam envelope H2+, along injection path
εx=εz=2.1 π mm.mrad
0,5
0,4
0,3
0,2
0,1
0
-0,1
-0,2
-0,3
-0,4
-0,5
[cm]
0
50
100
150
200
250
300
[degre°]
Xmin
Xmax
Z max

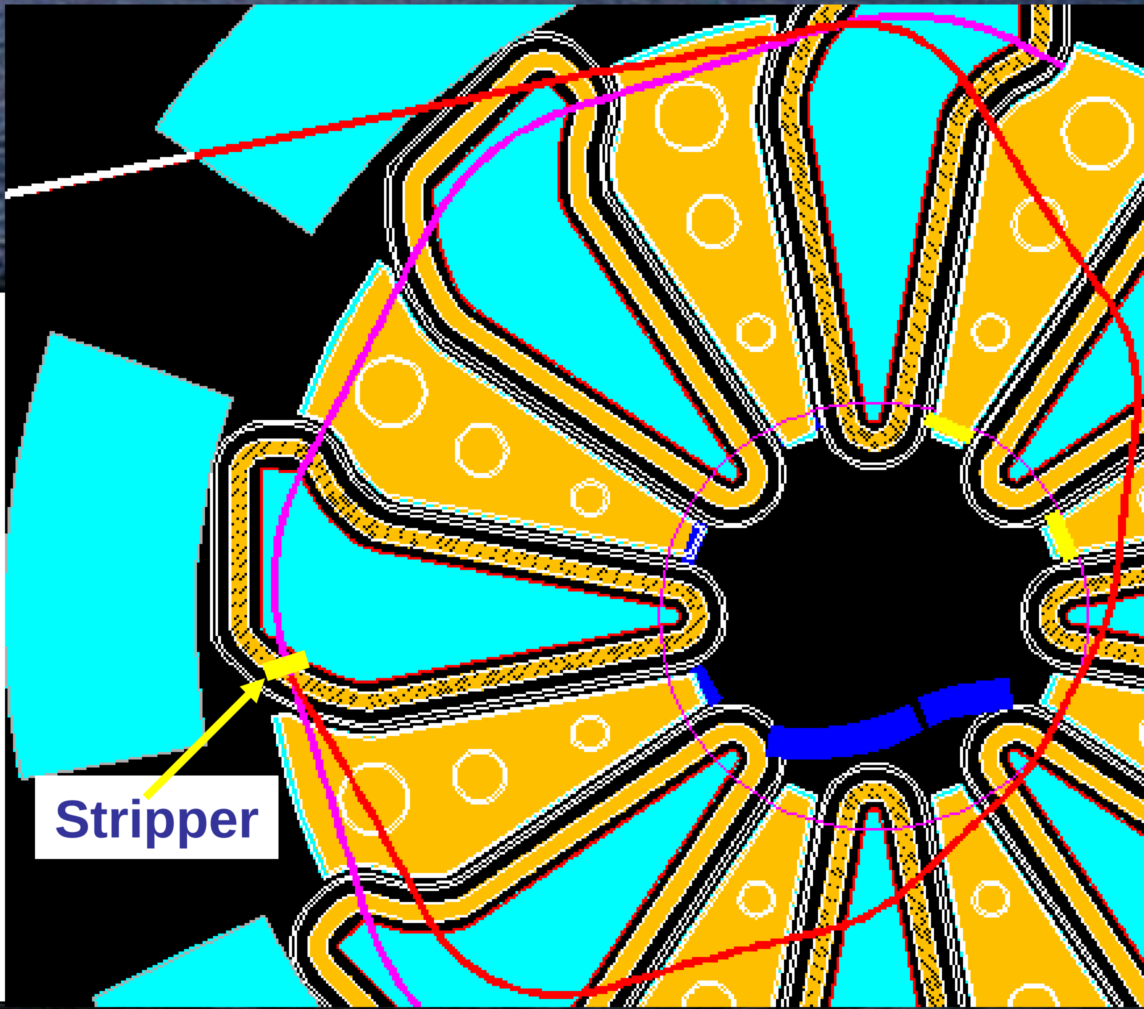


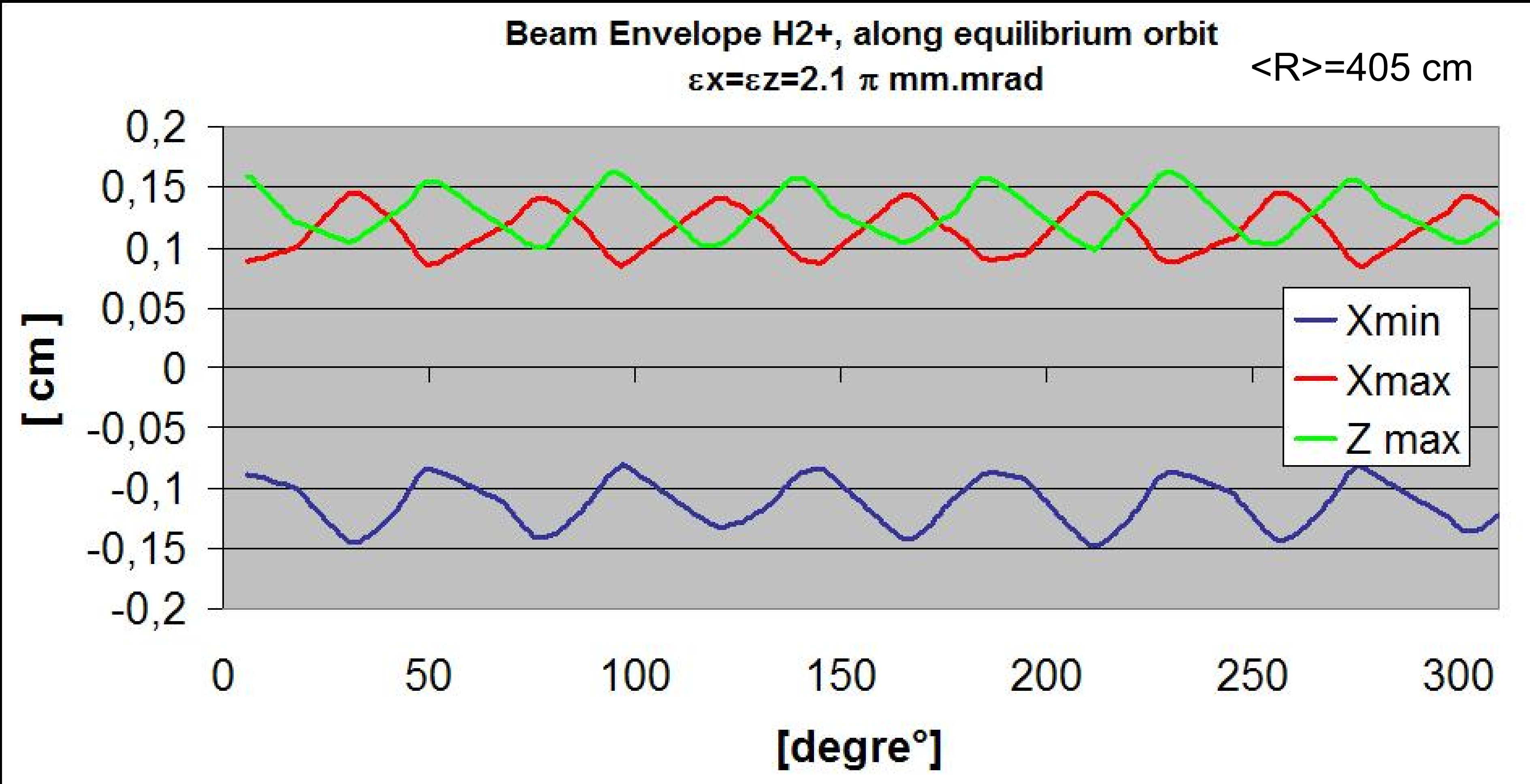
gap 8 mm	θ_{in}	θ_{out}	Electric/ Magnetic field
E.D.1	16°	30°	60 kV/cm
E.D.2	60°	76°	60 kV/cm
M. Ch. 1	106°	118°	-4 kGauss
M. Ch. 2	152°	164°	-6 kGauss
M. Ch. 3	192°	220°	-14 kGauss
M. Ch. 4	230°	292°	-14 kGauss
M. Ch. 5	298°	328°	-17.5 kGauss

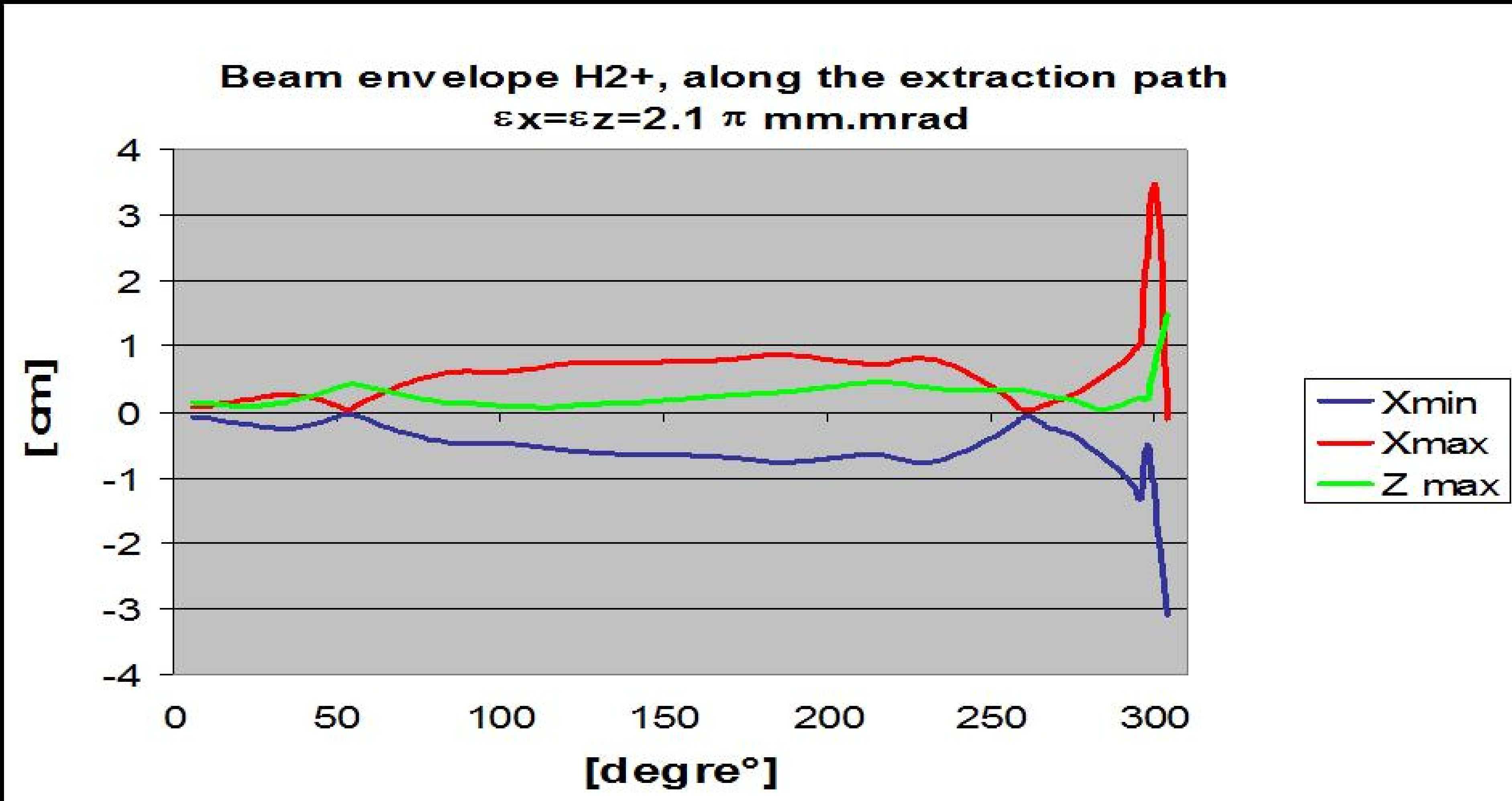
Stripper position is chosen to achieve:

- **Beam extraction**
- **Good beam envelope**
- **no interference with injection devices**
- **Magnetic Field positive**






Beam Envelope H2+, along equilibrium orbit
εx=εz=2.1 π mm.mrad
<R>=405 cm
[cm]
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
0
50
100
150
200
250
300
[degre°]
Xmin
Xmax
Z max


Beam envelope H2+, along the extraction path
εx=εz=2.1 π mm.mrad
[cm]
4
3
2
1
0
-1
-2
-3
-4
0
50
100
150
200
250
300
[degre°]
Xmin
Xmax
Z max

1.5 MW beam @ 800 MeV → power lost < 6.6 W on each stripper foil, thickness 2 mg/cm^2, 2 strippers solution

The electrons removed by the strippers have a full power of 1.5 $MW*M_e/M_{H2}$=1.5/(2*1822)=411 W (205 W per stripper)

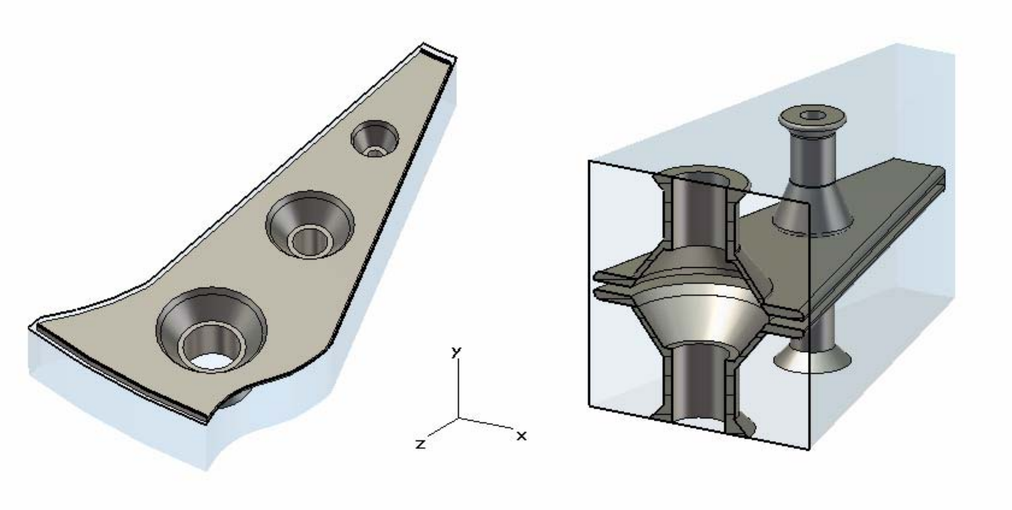
The electrons can be stopped before strike the stripper foil

Experimental stripper mean life for H- and extrapolated value for H2+

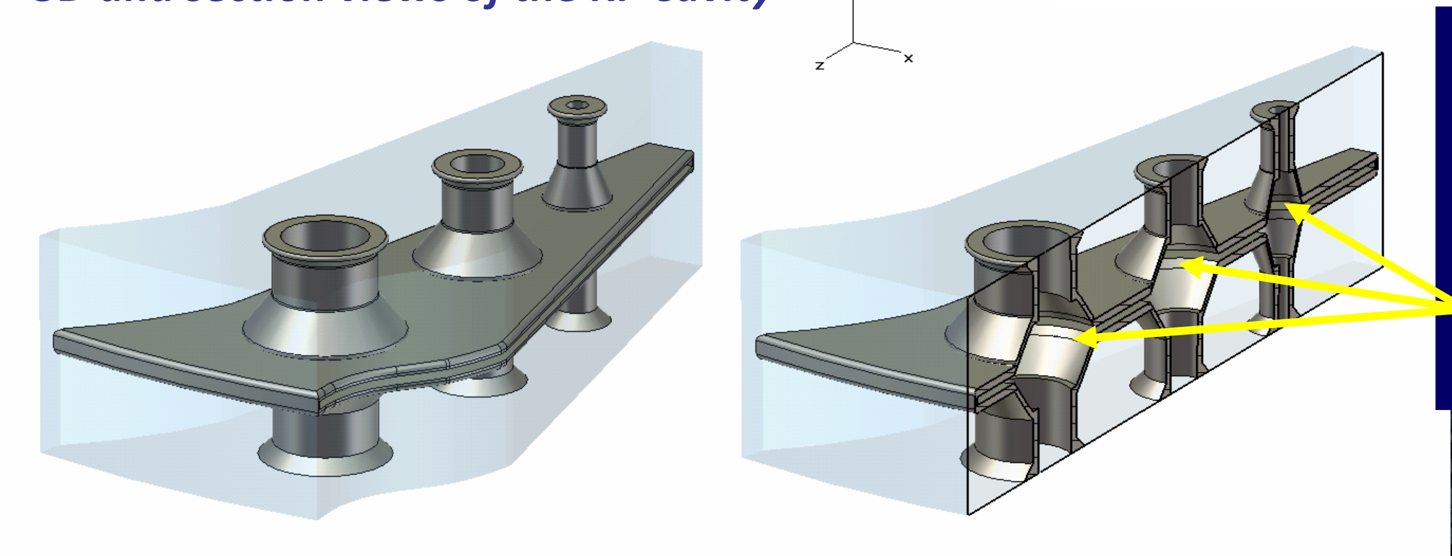
Ion	Beam energy	Foil thickness	I beam	Electrons energy	Electrons power	Mean life	Mean life
H^-	30 MeV	20 $\mu g/cm^2$	1 mA	16 keV	32 W	40 mAh	40 h
H^-	30 MeV	40$\mu g/cm^2$	1 mA	16 keV	32 W	20mA h	20 h
H^-	520 MeV	2 mg/cm^2	0.5 mA	290 keV	87 W	20 mA h	40 h
H_2^+	1600 MeV	2 mg/cm^2	<1> mA	440 keV	205 W	20 mAh	20 h

Stripper Thickness can be also thinner because no risk of neutral beam

RF Cavity preliminary simulation



3D and section views of the RF Cavity



RF Cavity Characteristics

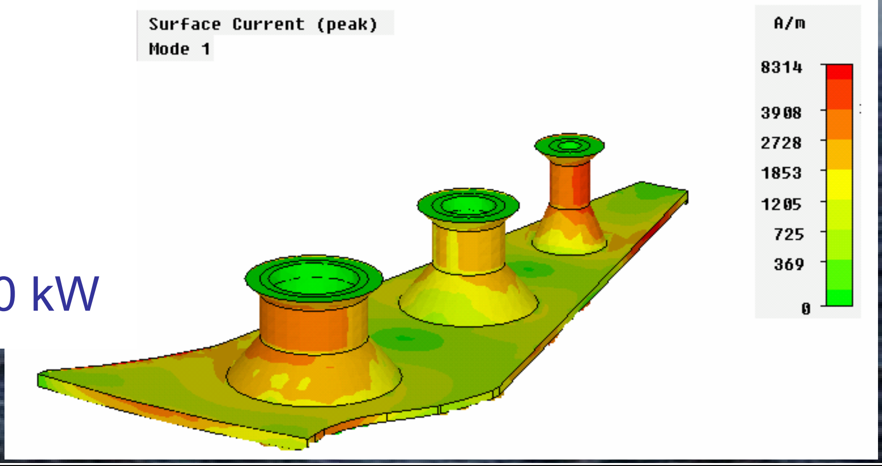
- λ /2, double gap
- 3 hollow stems to allow vacuum pumping
- Total height: 800 mm
- Cavity angular extension ≈ 13° -16°
- Radial extension ≈ from 1300 mm to 4200 mm

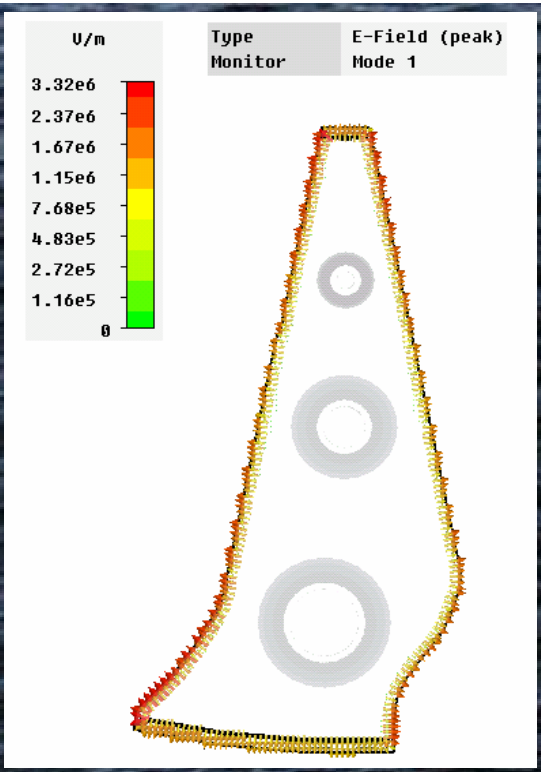
Inside the stems we have enough room to install cryogenic pumps or cryogenic panel

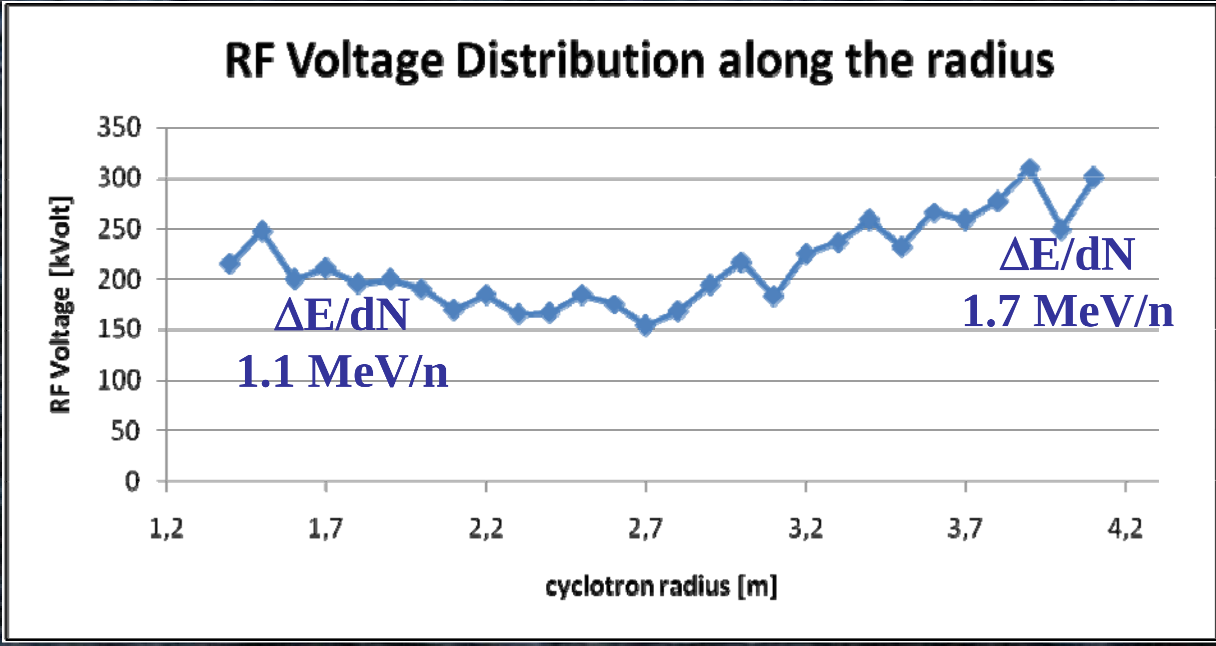
RF Cavity preliminary simulation

RF Cavity Performances

- Resonant Frequency ≈ 62 MHz
- Quality Factor ≈ 12.000
- Power dissipation @300kV (peak) ≈ 250 kW







Electrical dissociation

The probability to remove the electron from the H- or from the H2+ ion is ruled by these formulas:

$$D = \frac{1}{2}\int_0^1 \exp(-\frac{\alpha}{\mu})d\mu \qquad \alpha = \frac{4}{3}\sqrt{2\frac{m}{h^2}}W^{\frac{3}{2}} / eE \qquad E=0.3\beta\gamma B \text{ [MV/cm]}$$

Where:

μ is the cosine of the angle between the electric field and the direction of the Electron motion

m and e are the mass and charge of the electron

W is the binding energy of the electron

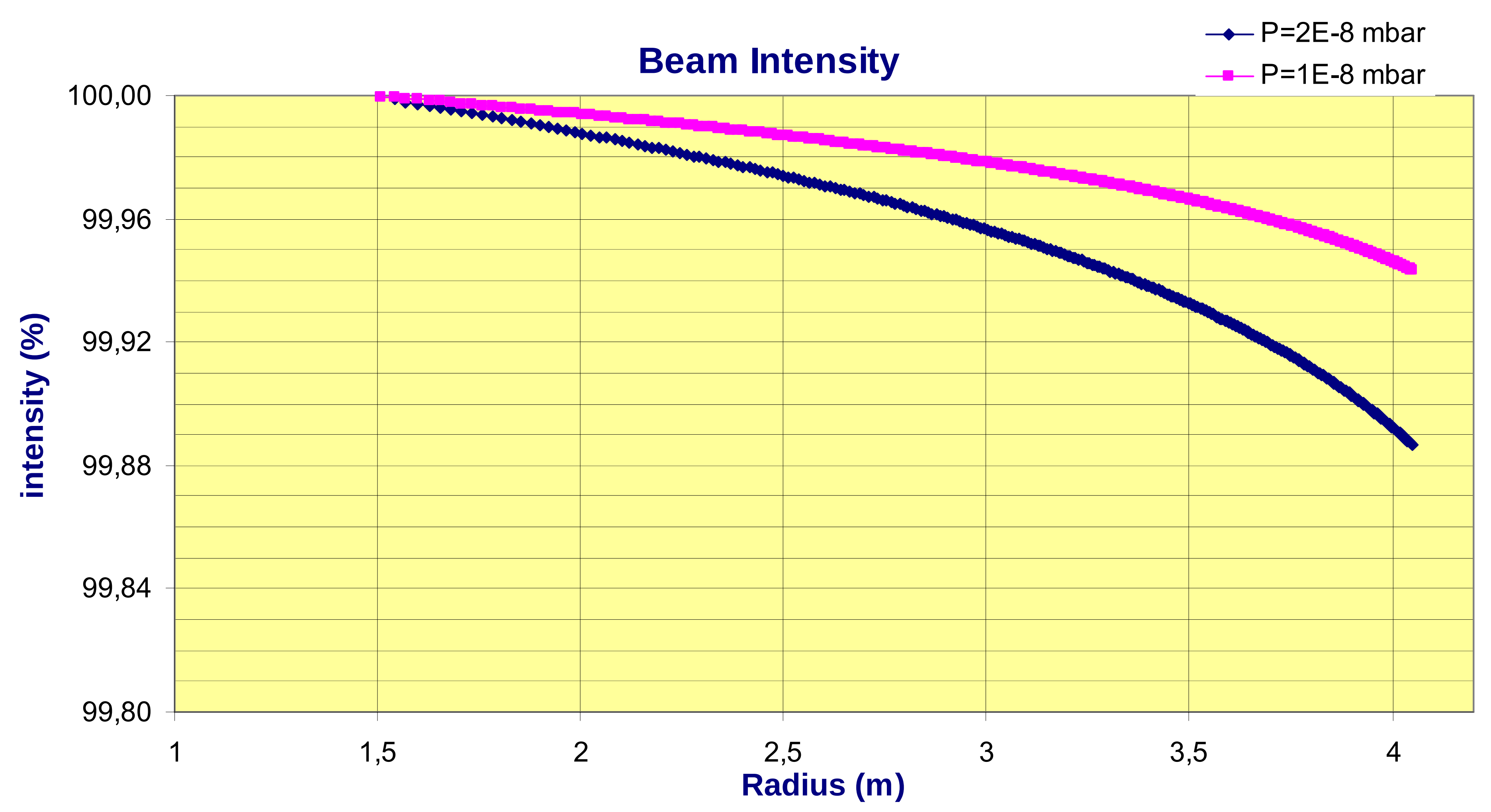
E is the electric field acting on the electron due to the Magnetic field

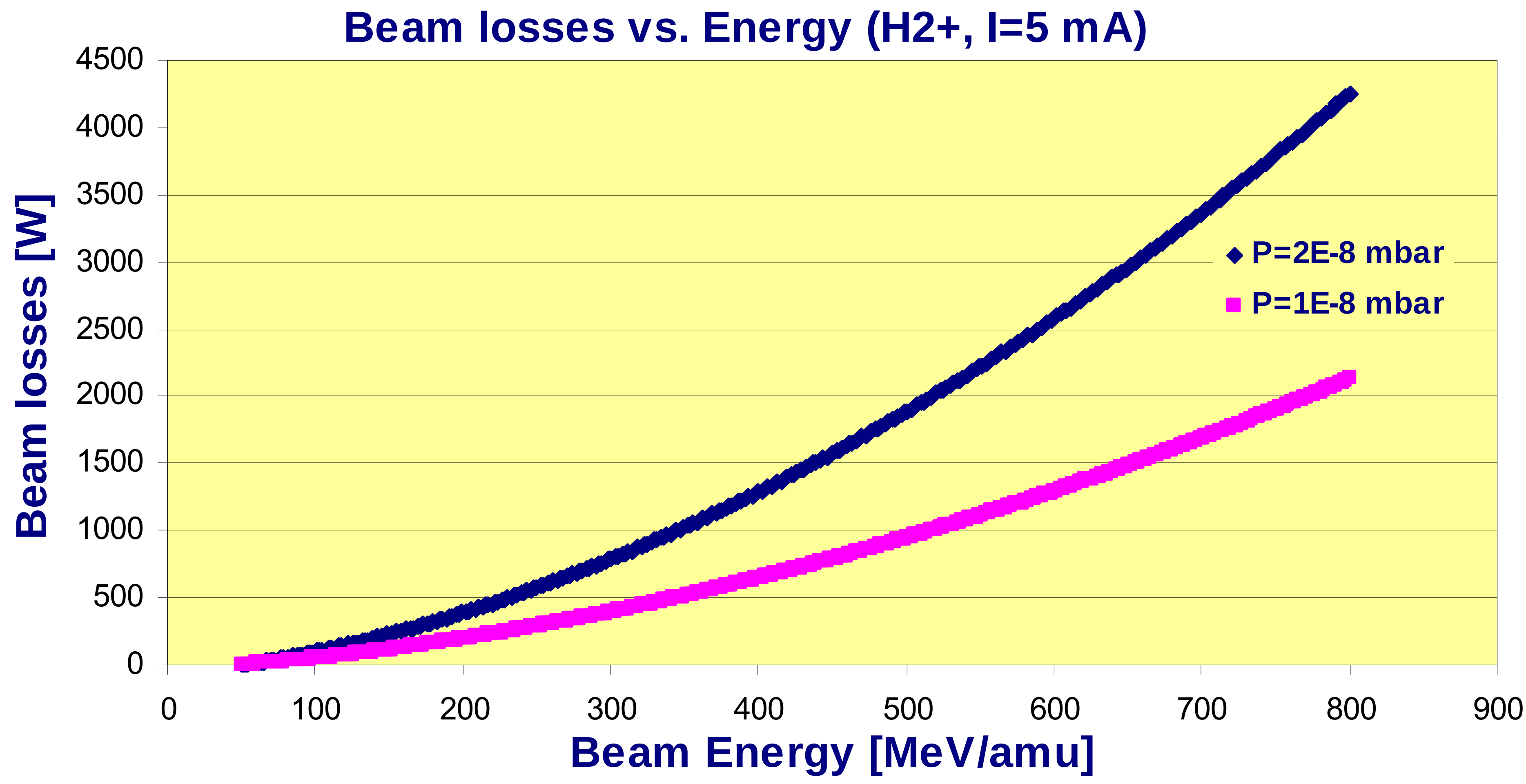
	H-	H2+
Binding energy	**0.755 eV**	**15.1 eV**
Magnetic field	**<1.3> T**	**10 (6) T**
Energy (MeV/n)	**30 MeV**	**800**
Electric field (MV/cm)	**0.998**	**47 (28.2)**
α (arbitrary unit)	**0.657**	**1.248 (2.08)**

Main Source of beam losses is interaction with residual gases

$$T = N/N_0 = \exp(-3.35\ 10^{16} \int \sigma_i(E)\ P\ dl)$$

$$\sigma_i(E) \approx 4\pi a_0^2\ (v_0/v)^2 (Z_t^2 + Z_t)/Z_i$$



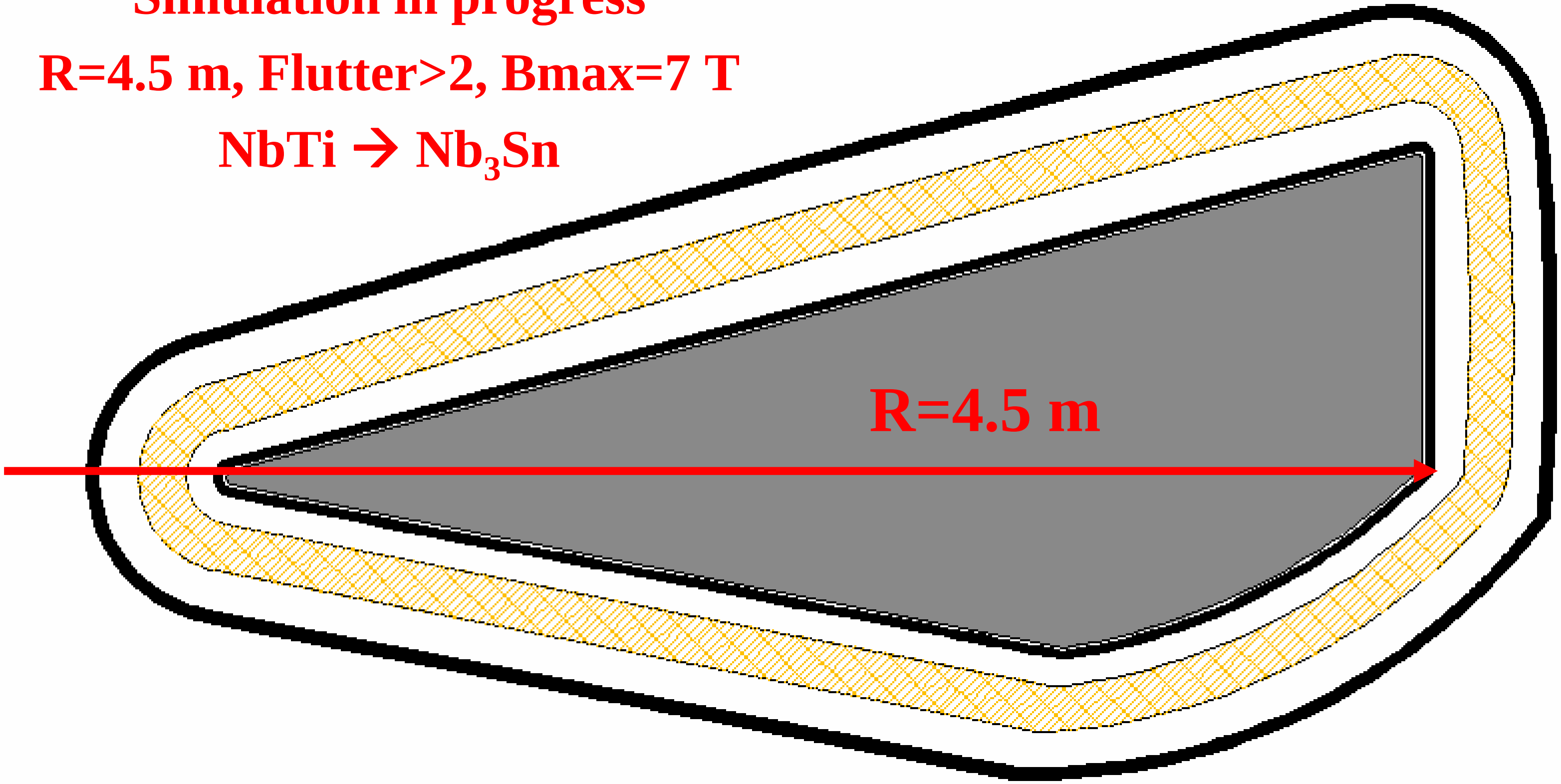


Beam losses vs. Energy (H2+, I=5 mA)
Beam losses [W]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800
900
Beam Energy [MeV/amu]
P=2E-8 mbar
P=1E-8 mbar

Simulation in progress

R=4.5 m, Flutter>2, Bmax=7 T

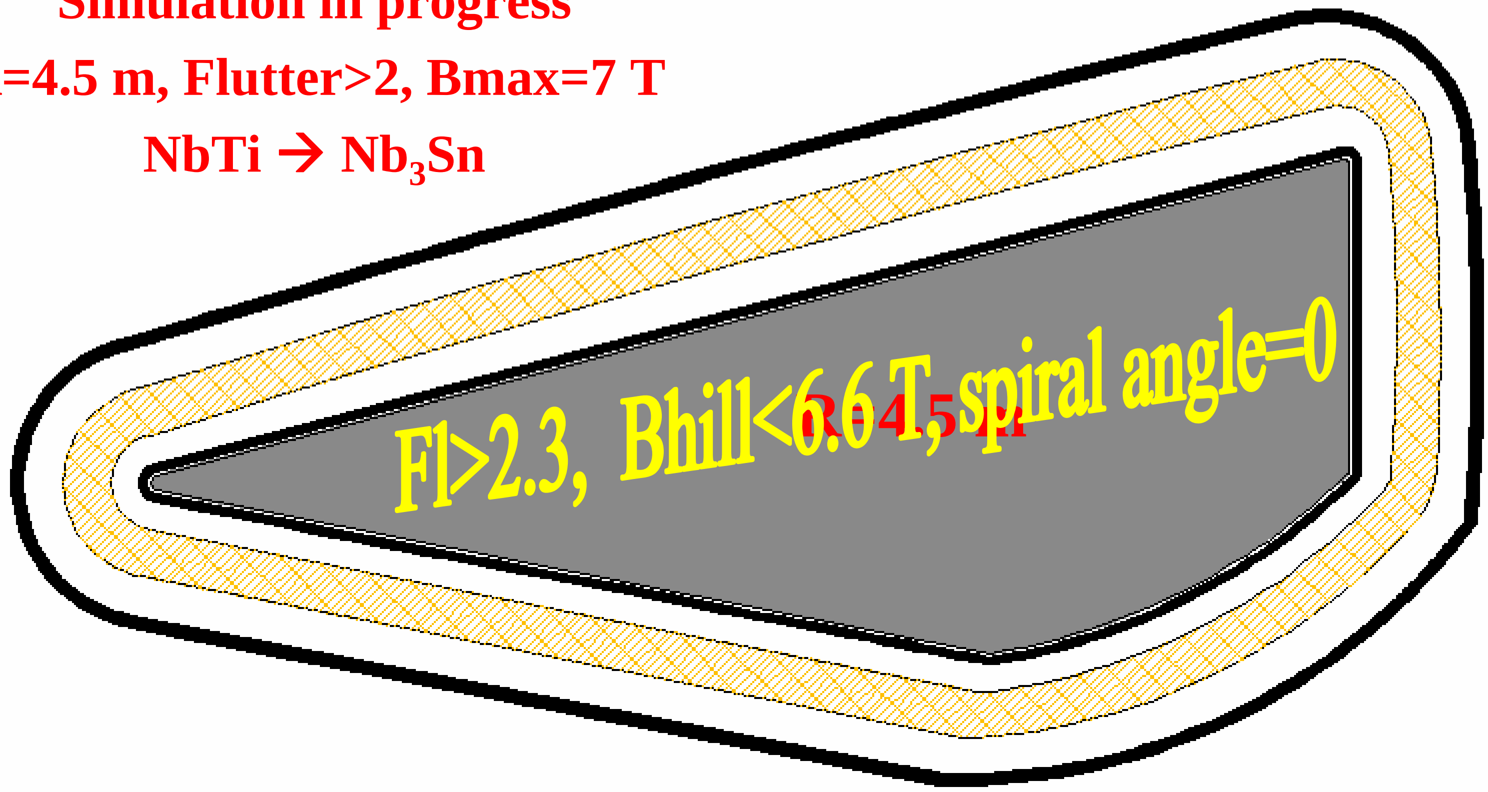
NbTi → Nb_3Sn



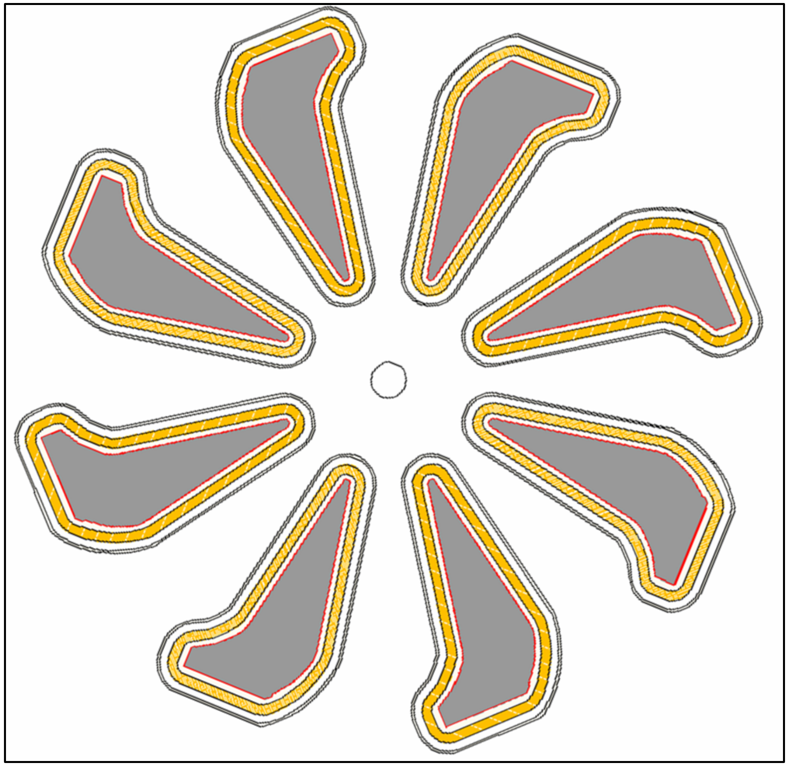
Simulation in progress

R=4.5 m, Flutter>2, Bmax=7 T

NbTi → Nb_3Sn



Daedalus Cyclotron ≈ Daedalus Labirinth



Daedalus designed the labirinth (maze) to keep the Minotaur inside. But then himself has been kept there by Minos. So he flew away, escaping from the Labirinth.

We are Designing the Daedalus Cyclotron, and we do not want to be trapped in!
But we cannot fly!

Daedalus Cyclotron Collaboration

We invite the interested people, to be part of an international collaboration to design a reliable High Energy Cyclotron, putting together our best knowledge.

Thanks for your attention