



# THE COMPACT INJECTOR CYCLOTRON

## FOR DAEDALUS EXPERIMENT



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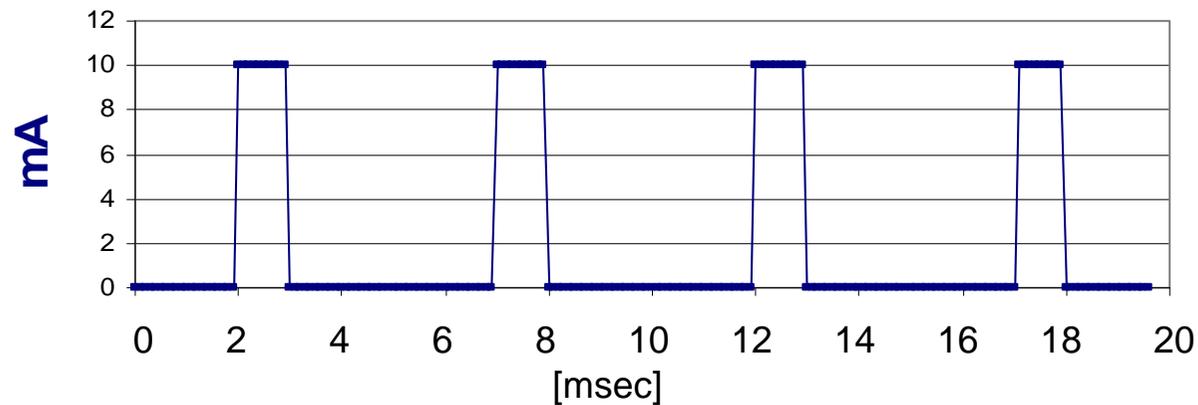
*A. Adelman, J. Yang, PSI, Villigen, CH*

*XXXVIII ECPM, 9-12 May, PSI - Zurich*

**DAEδALUS needs 1 ÷ 2 MW proton beam @ 800 MeV**

**The beam time structure being 1 msec beam on, 4 msec beam off  
duty cycle= 20% → peak power 5÷10 MW → Peak current 6÷12 mA**

**time structure of the extracted beam**



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

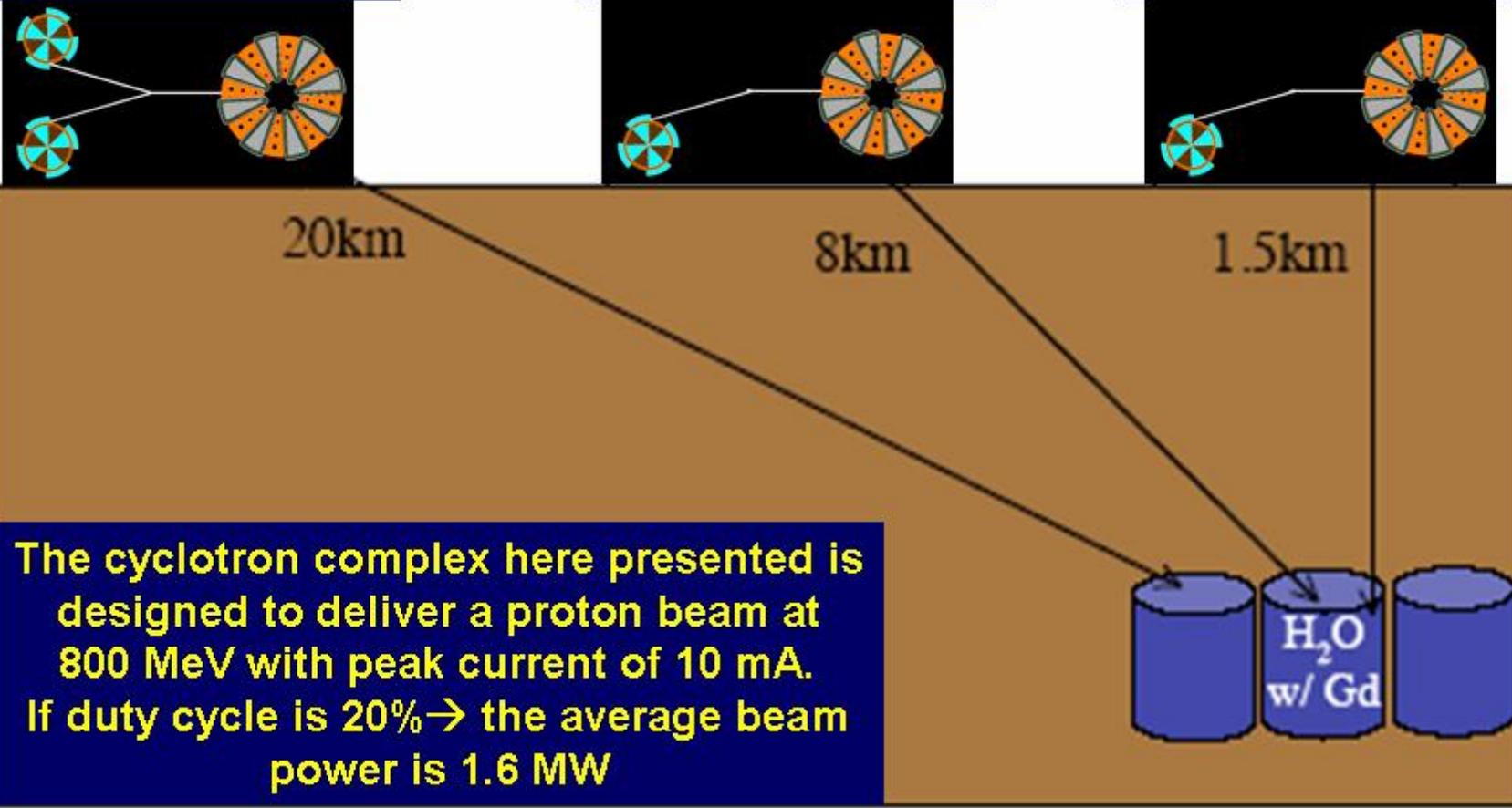
- **Vantages of stripper extraction vs. the Electrostatic Deflectors extraction**
- **Space charge effects reduced by a factor  $\sqrt{2}$  vs. proton beam**

# DAEδALUS Experiment requirements

Proton beam  
800 MeV @ 3.2 MW  
1/5 msec

Proton beam  
800 MeV @ 2 MW  
1.33/5 msec

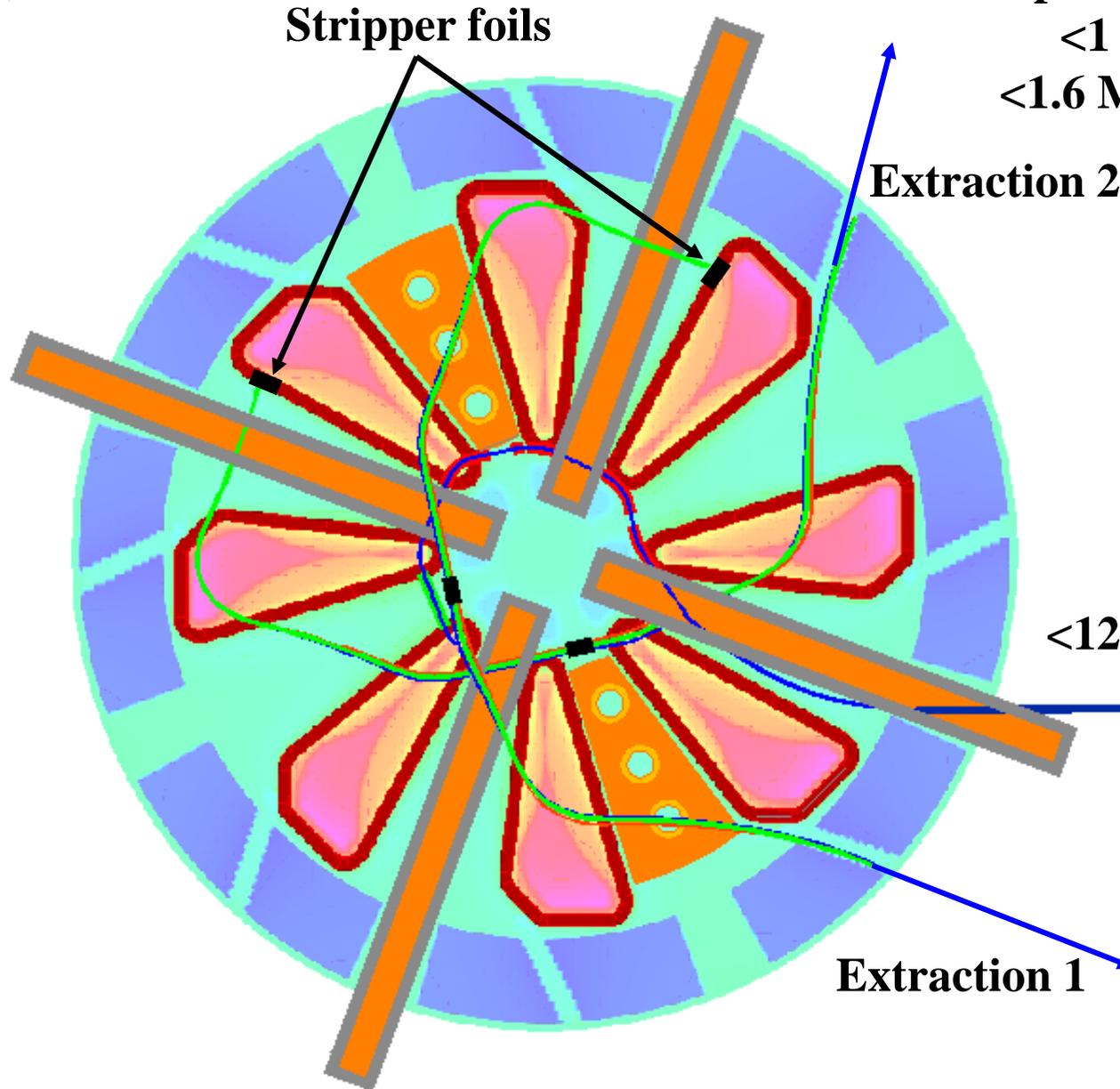
Proton beam  
800 MeV @ 1 MW  
0.67/5 msec



The cyclotron complex here presented is designed to deliver a proton beam at 800 MeV with peak current of 10 mA. If duty cycle is 20% → the average beam power is 1.6 MW

## Superconducting Ring Cyclotron

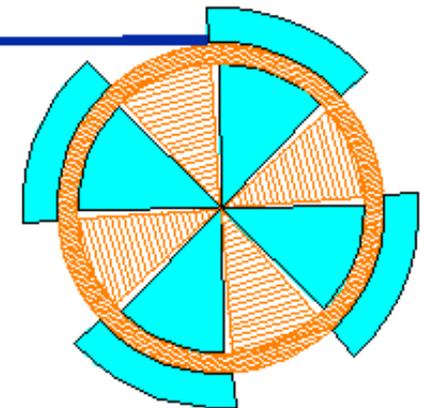
<1 mA> H<sub>2</sub><sup>+</sup> 800 MeV/n,  
<1.6 MW>, Peak power 8 MW



Extraction 2

## Injector Cyclotron

< 1 mA> H<sub>2</sub><sup>+</sup> 60 MeV/n  
<120 kW>, peak power 600 kW



Extraction 1

To deliver a proton beam with 10 mA peak current we have to accelerate an H<sub>2</sub><sup>+</sup> 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]:

$$K = \frac{qI}{2 \cdot \pi \cdot \epsilon_0 \cdot m \cdot \gamma^3 \beta^3}$$

	E <sub>p</sub> =30 keV, E <sub>H2</sub> =30 keV β <sub>p</sub> = 1.414β <sub>H2</sub>		E <sub>p</sub> =30 keV, E <sub>H2</sub> =70 keV β <sub>p</sub> = 0.926β <sub>H2</sub>
Proton 10 mA	<b>K<sub>p</sub></b> 1.245 10 <sup>-3</sup>	Proton 2 mA	K <sub>p</sub> 0.249 10 <sup>-3</sup>
H2+ 5 mA	K <sub>H2</sub> 0.881 10 <sup>-3</sup>	H2+ 5 mA	<b>K<sub>H2</sub></b> 0.247 10 <sup>-3</sup>
	<b>K<sub>H2</sub>/K<sub>p</sub>=0.707</b>		<b>K<sub>H2</sub>/K<sub>p</sub>=0.992</b>

IBA Cyclone 30 $I_{max}=2$ mA			
$E_{inj}$	30 keV	$E_{max}$	30 MeV
$R_{inj}$	30 mm	$R_{ext}$	0.75 m
$\langle B \rangle$ at $R_{inj}$	1.0 T	$\langle B \rangle$ at $R_{ext}$	1.3 T
Sectors N.	4	N. Accel. Cavities	2
RF	66 MHz	Harmonic	4 <sup>th</sup>
$\Delta E/turn$	170 kV	Ion Source current $H^-$	15 mA
EBCO TR-30 $I_{max}=1.6$ mA			
$E_{inj}$	25 keV	$E_{max}$	30 MeV
$R_{inj}$	25 mm	$R_{ext}$	0.66 m
$\langle B \rangle$ at $R_{inj}$	1.2 T	$\langle B \rangle$ at $R_{ext}$	1.24 T
Sectors N.	4	N. Accel. Cavities	2
RF	73 MHz	Harmonic	4 <sup>th</sup>
$\Delta E/turn$	200 kV	Emittance (normalized)	0.43 $\pi$ mm.mrad

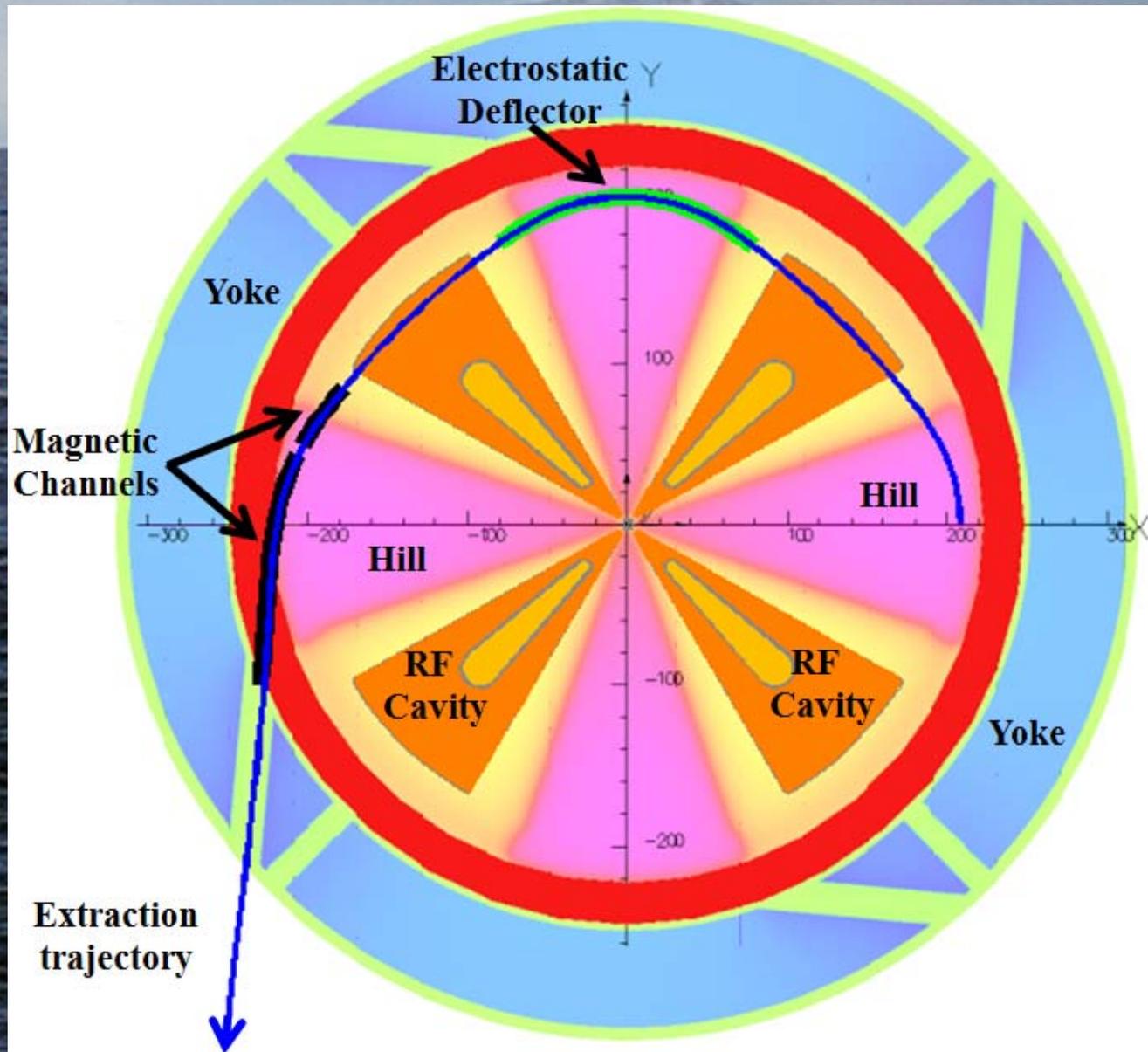
**Main parameters are extrapolated from commercial compact cyclotron: C30, TR-30**

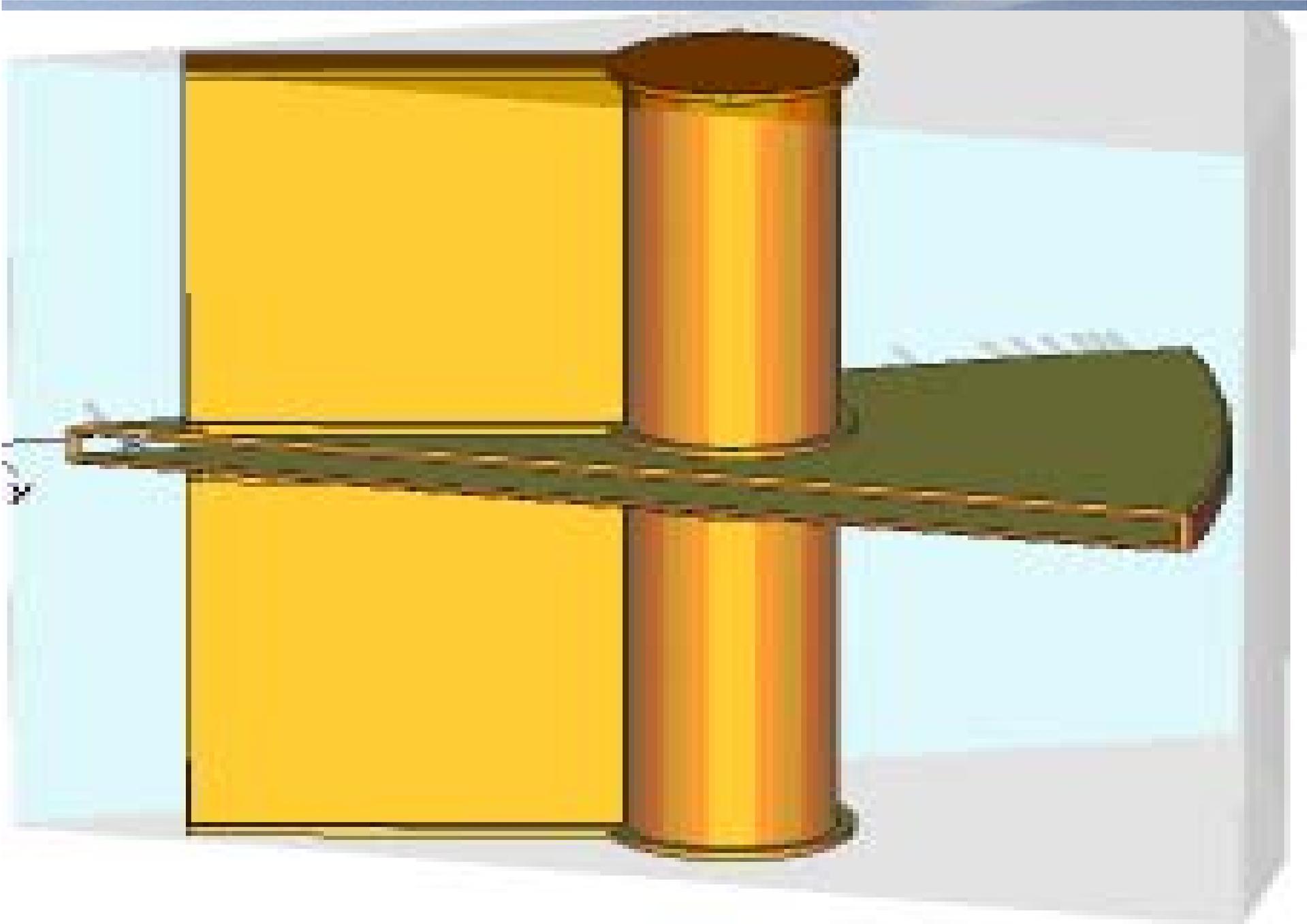
**Commercial cyclotron are able to deliver 1.5 ÷ 2 mA proton beam using injection energy and acceleration voltage moderate and multicusp ion source**

**H<sup>2+</sup> Injector  
 $E_{inj}=70$  keV vs. 25-30 keV**

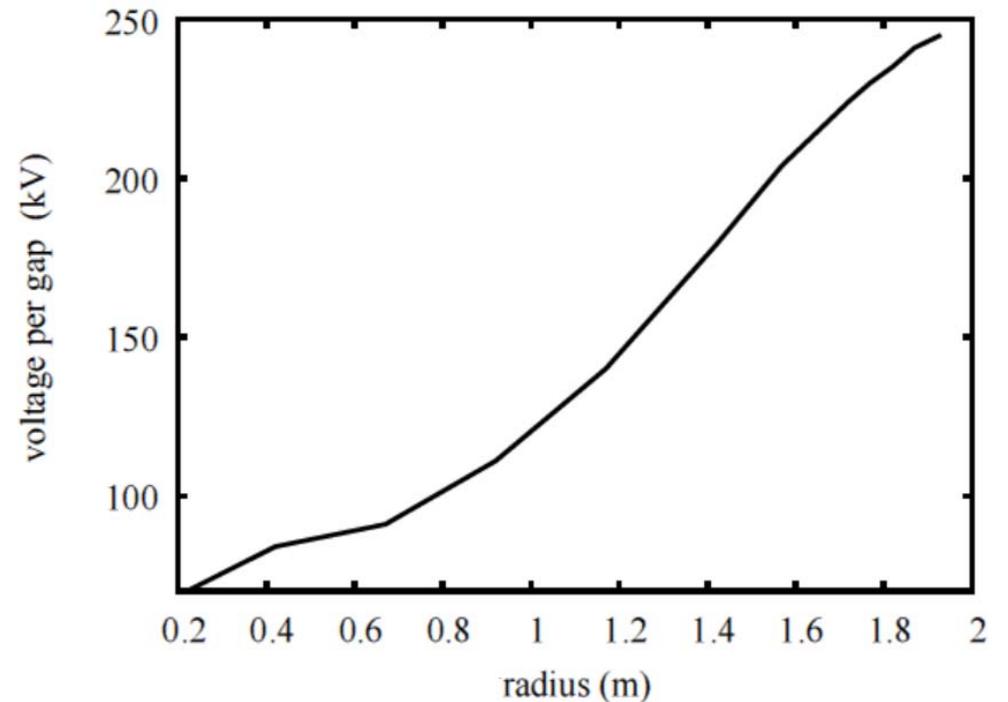
**$\Delta E/turn > 420$  keV vs. 170-200 keV  
 $\Delta E/turn > 1500$  keV vs. 170-200 keV  
 → phase compression?**

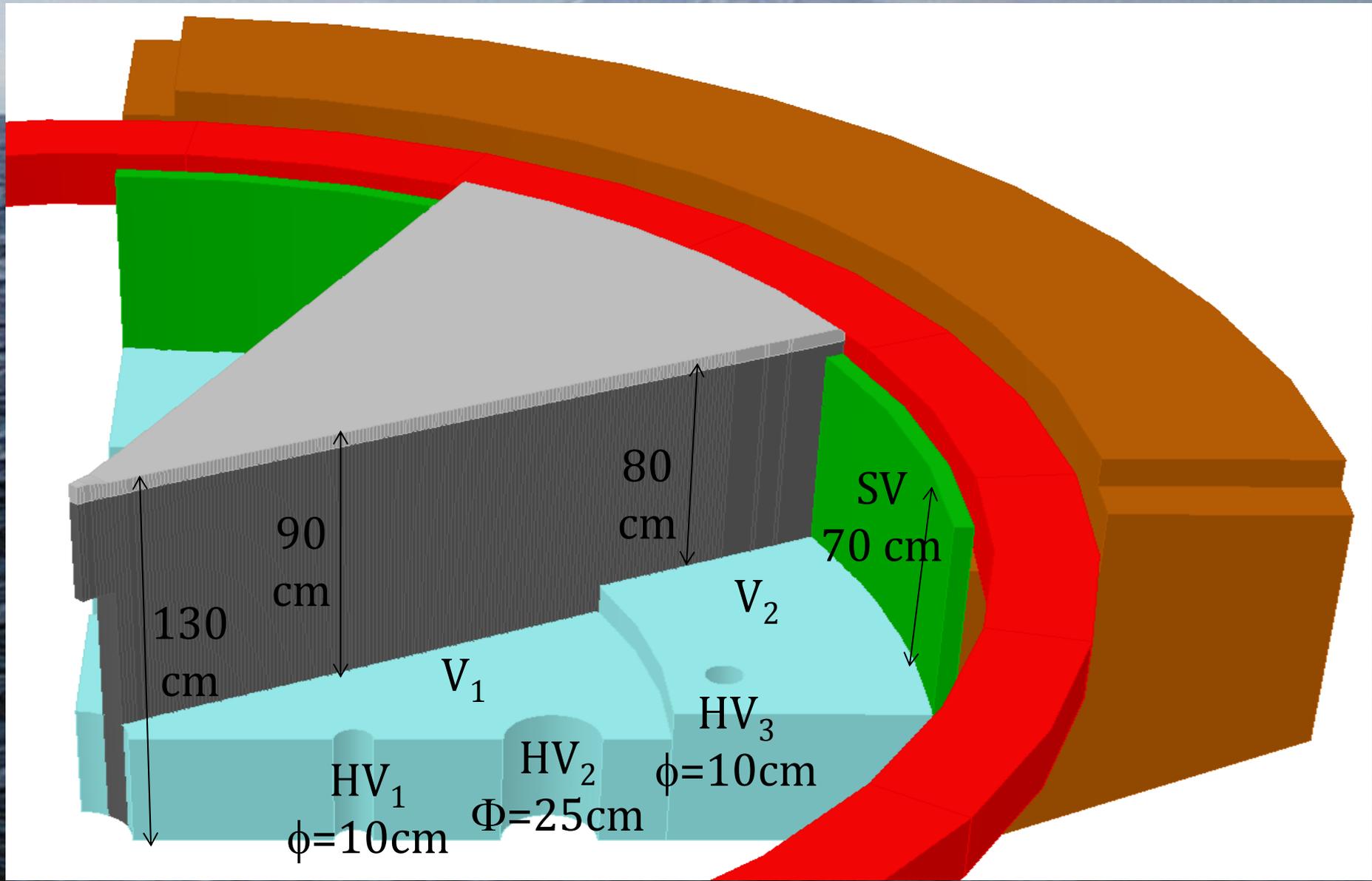
**New Generation ECR ion source with emittance  
 0.1 ÷ 0.2 vs. 0.4**

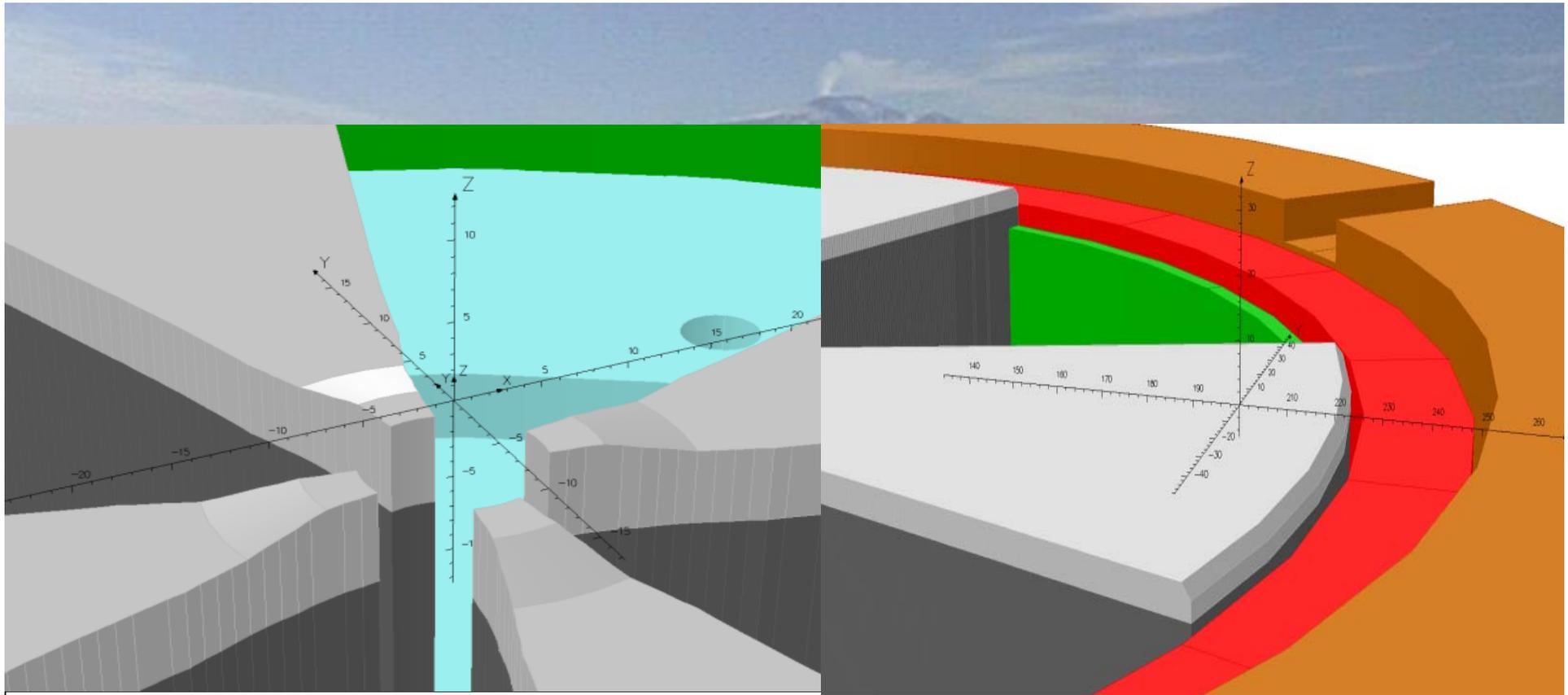




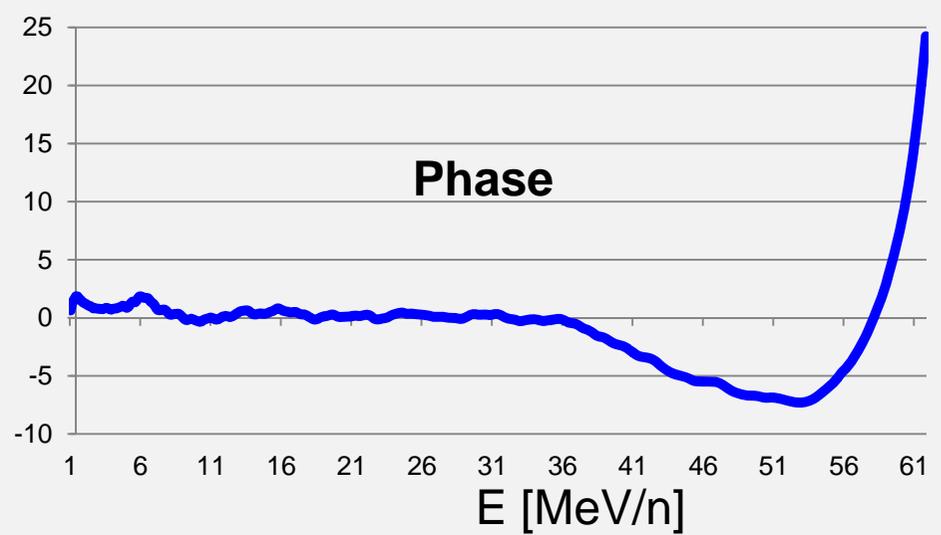
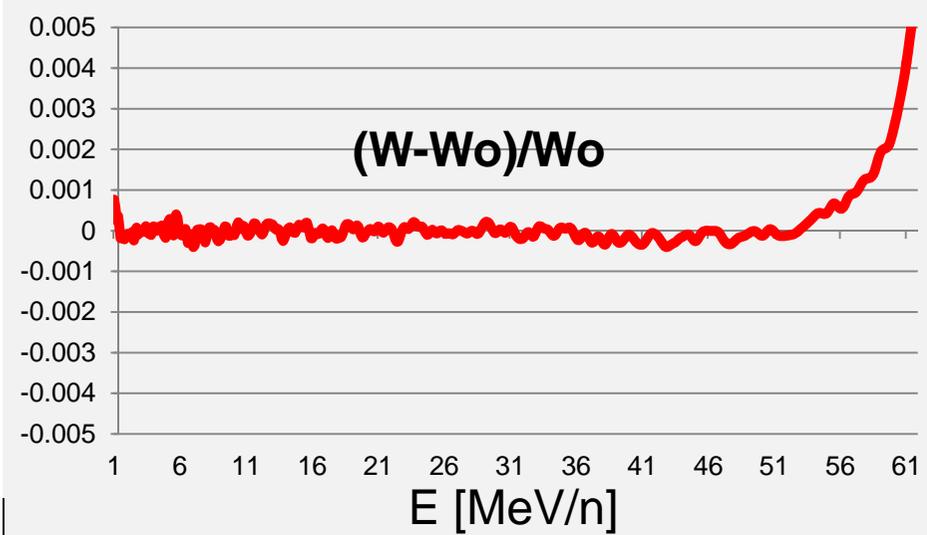
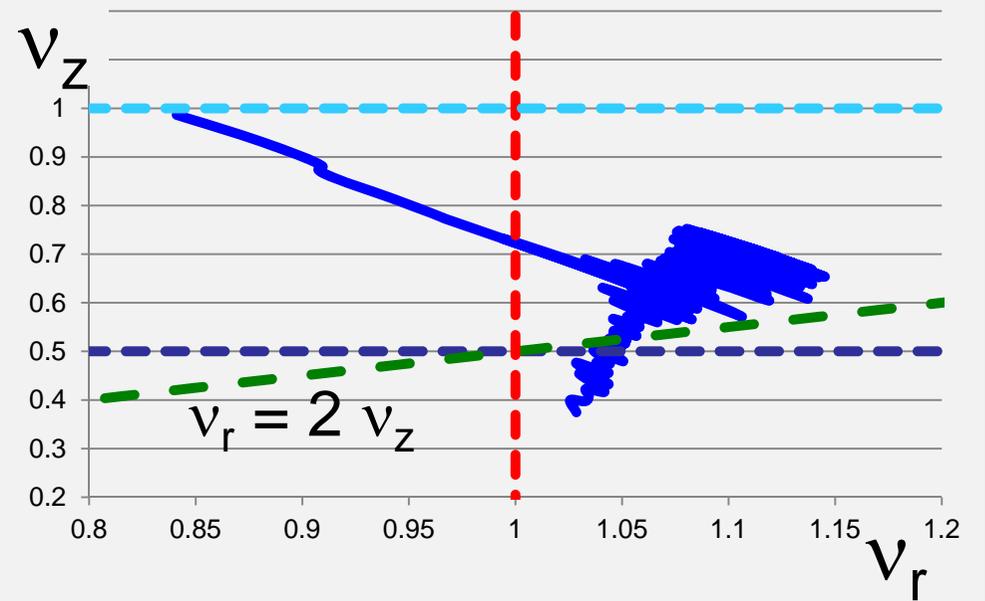
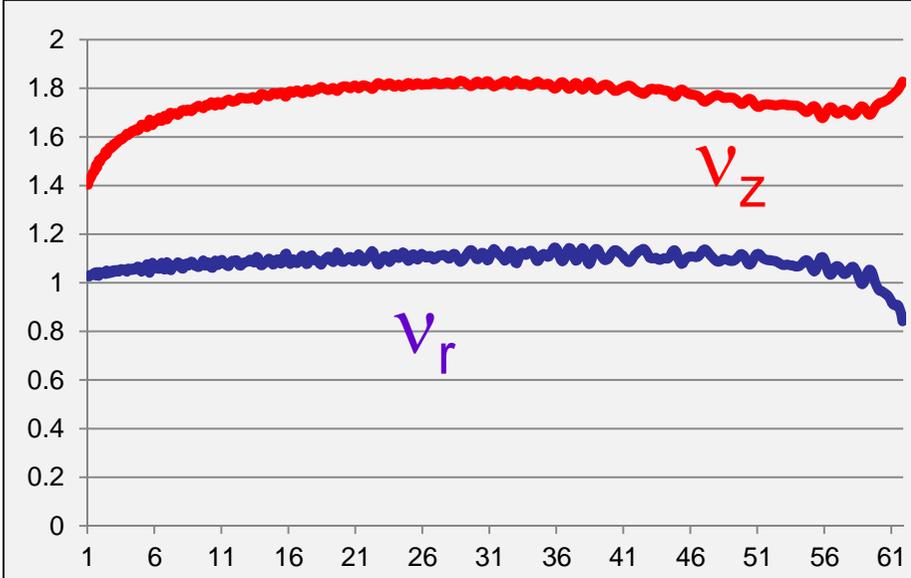
Cavity Height	1700 mm
Cavity Angular Extension (Width)	32°
Cavity Radial Extension (Length)	2100 mm
Dee Angular Extension (Width)	30°
DEE Gap	50 mm
Dee Thickness	20 mm
Stems Radial Extension	320 – 1330 mm
Stems Angular Extension	70 mm
Resonance mode	TM010
Resonance frequency	49.2 MHz
Quality factor	9100
RF power dissipation, cw mode	160 kW
Maximum Voltage	70-250 kV
Max. surface current	160 A/cm
Maximum electric field	6.1 MV/m





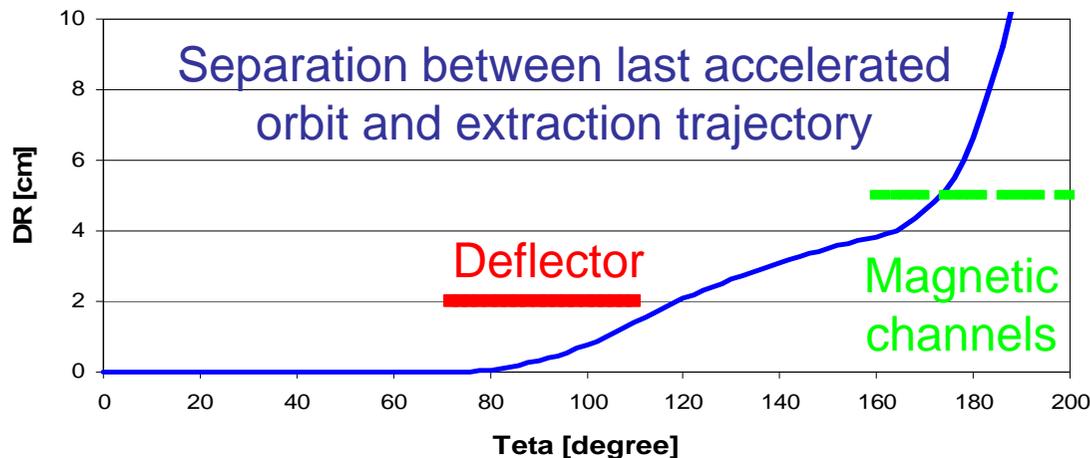


<b>Pole radius</b>	<b>220 cm</b>	<b>Hill gap height</b>	<b>8 cm</b>	<b>from R=5 cm to R=8 cm</b>
<b>Hill width</b>	<b>25.5° - 36.5°</b>		<b>10 cm</b>	<b>from R&gt;13 cm to R=220</b>
<b>Outer diameter</b>	<b>624 cm</b>	<b>Plug diameter</b>	<b>14 cm</b>	<b>up to 45 cm from the median plane</b>
<b>Full height</b>	<b>270 cm</b>		<b>28 cm</b>	<b>from 45 cm to the end</b>



## Injector Cyclotron Parameters

<b>Einj</b>	<b>35 keV/n</b>	<b>E<sub>max</sub></b>	<b>60 MeV/n</b>
<b>Rinj</b>	<b>55 mm</b>	<b>R<sub>ext</sub></b>	<b>1.99 m</b>
<b>&lt;B&gt; at Rinj</b>	<b>0.97 T</b>	<b>&lt;B&gt; at R<sub>ext</sub></b>	<b>1.16 T</b>
<b>Sectors N.</b>	<b>4</b>	<b>Cavities N.</b>	<b>4</b>
<b>RF</b>	<b>49.2 MHz</b>	<b>Harmonic</b>	<b>6<sup>th</sup></b>
<b>V-inj</b>	<b>&gt; 70 kV</b>	<b>V-ext</b>	<b>240 kV</b>
<b>&lt;ΔE/turn&gt;</b>	<b>1.3 MeV</b>	<b>ΔR at R<sub>ext</sub></b>	<b>14 mm</b>
<b>ΔR at Rinj</b>	<b>&gt;56 mm</b>	<b>Turns N.</b>	<b>&lt; 95</b>
<b>1 Electrostatic Deflector (ED) + Magnetic Channels</b>			
<b>E. D. Gap</b>	<b>14 mm</b>	<b>E.D. field</b>	<b>35 kV/cm</b>

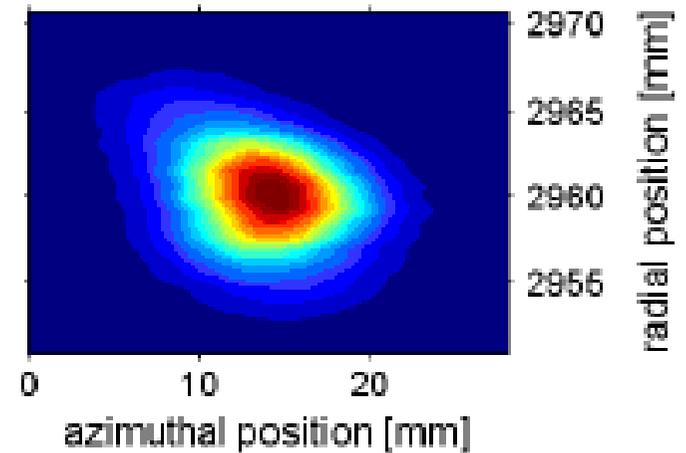


**Main parameters are extrapolated from existing commercial compact cyclotron: C30 and TR-30**

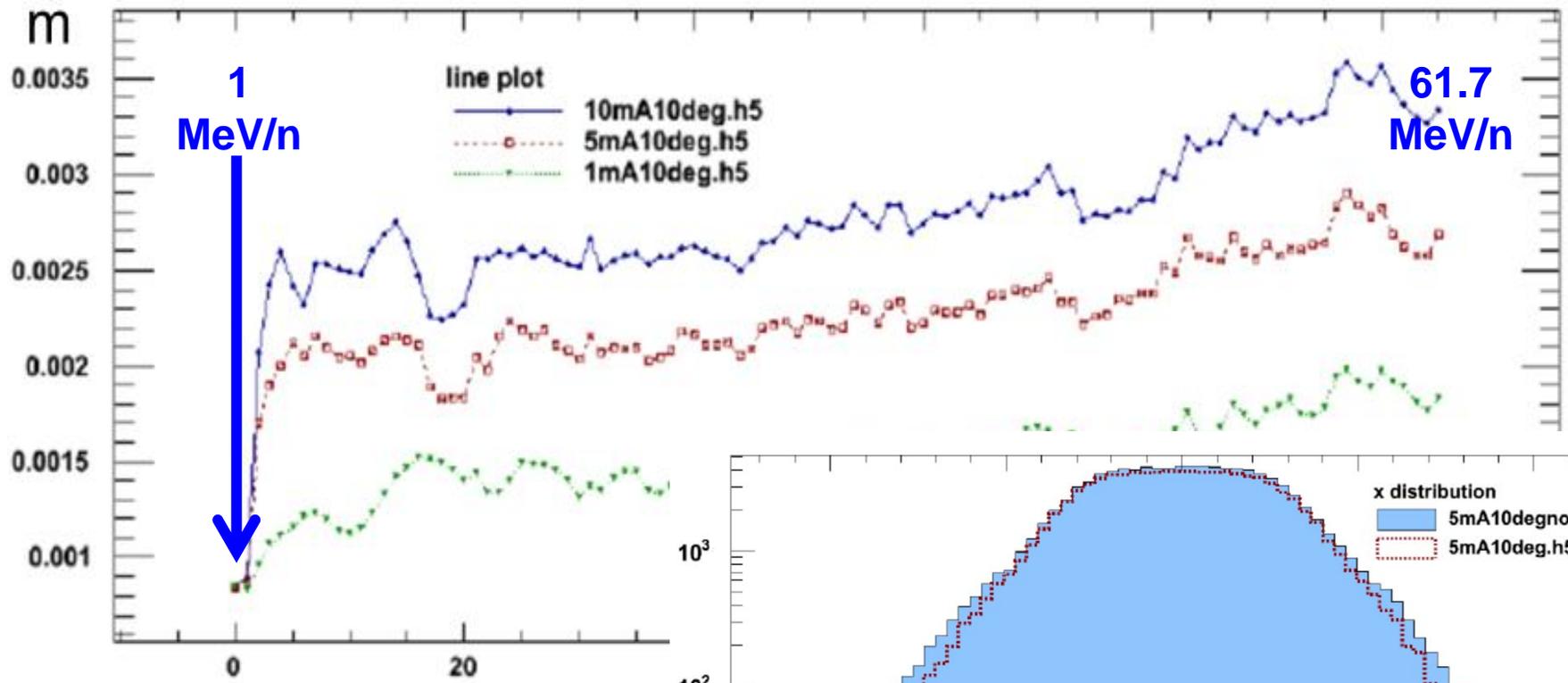
Injection energy and acceleration voltage are higher vs. C30/TR-30

60 MeV/n after 100 turn vs. 150, or 10 μsec vs. 8.1 μsec

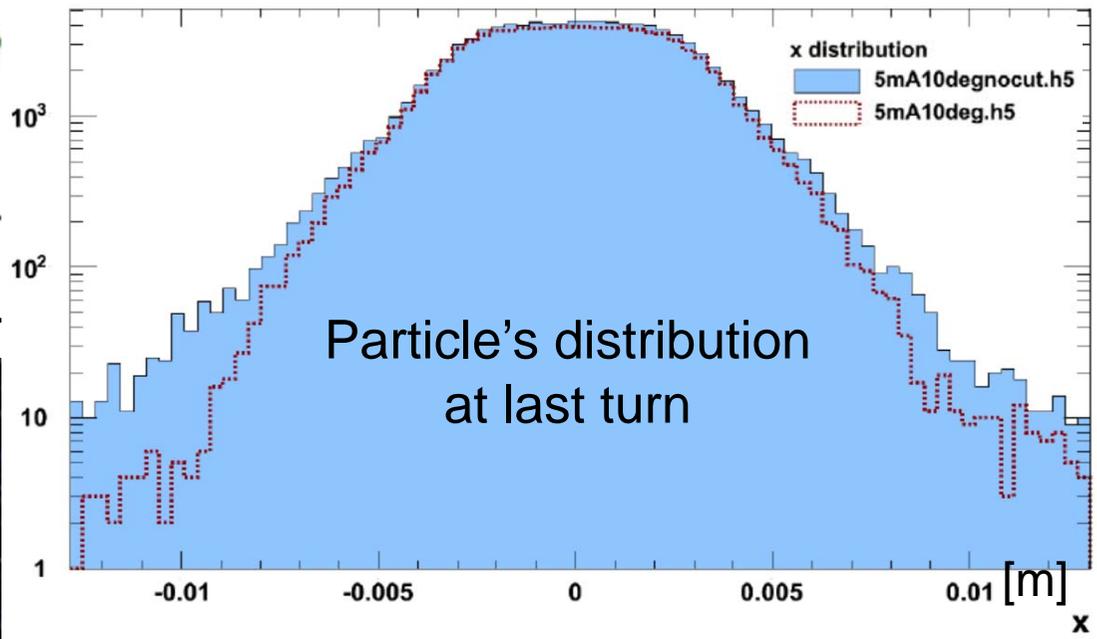
last turn in Injector-2 cyclotron

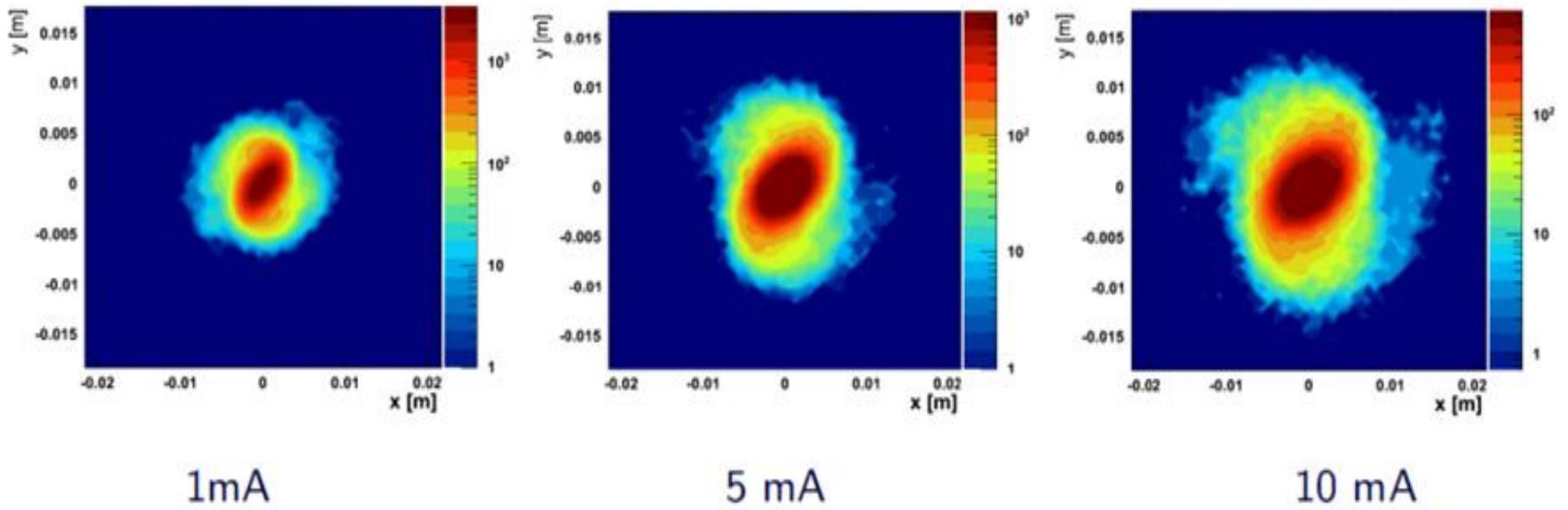


Courtesy of R. Doelling



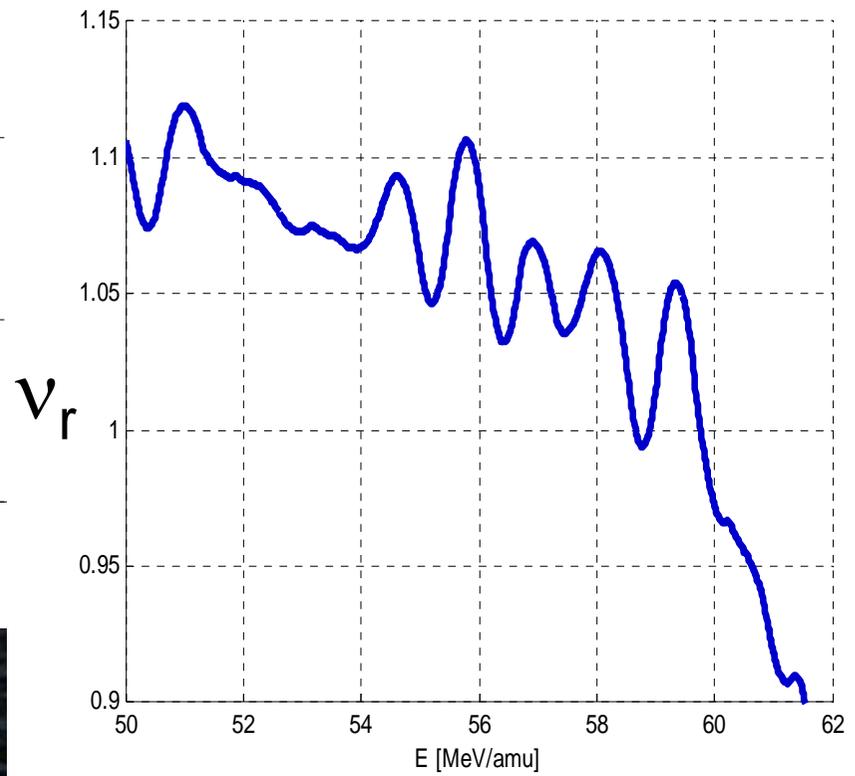
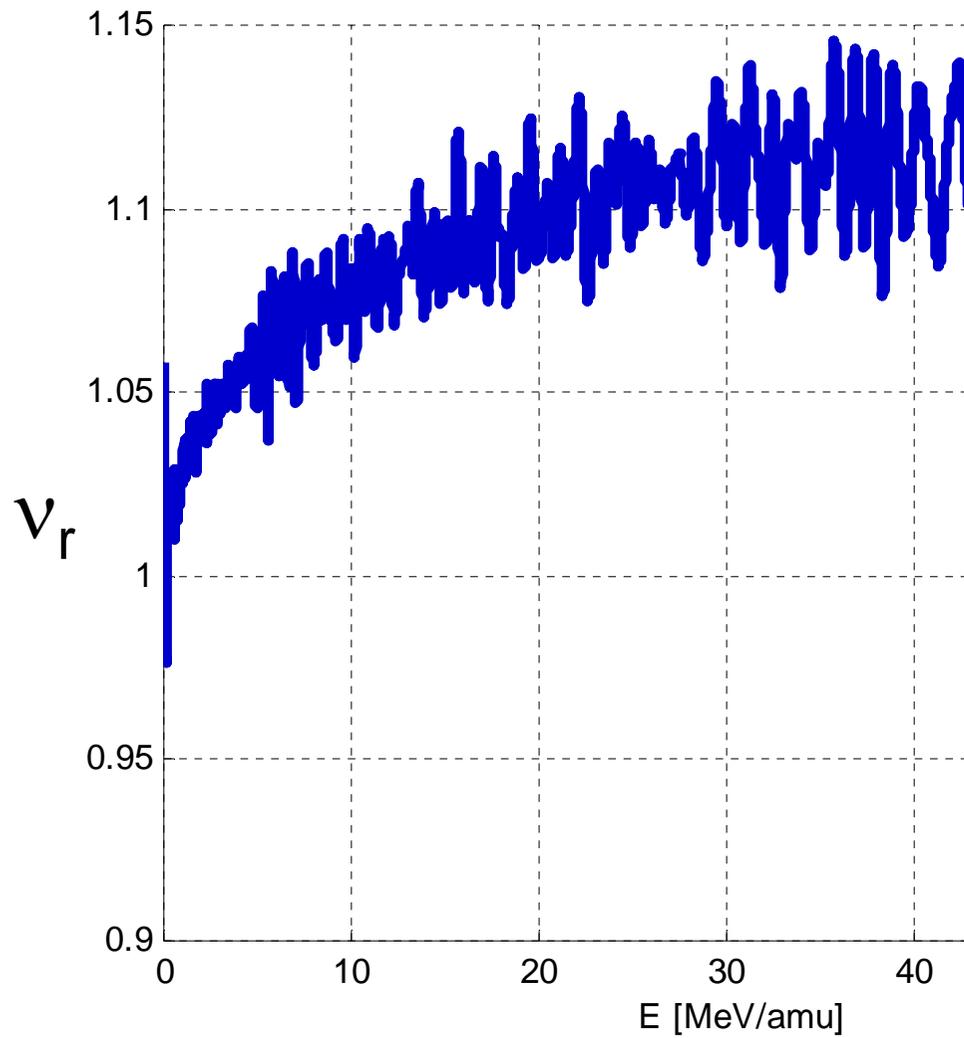
Beam size vs. turns n



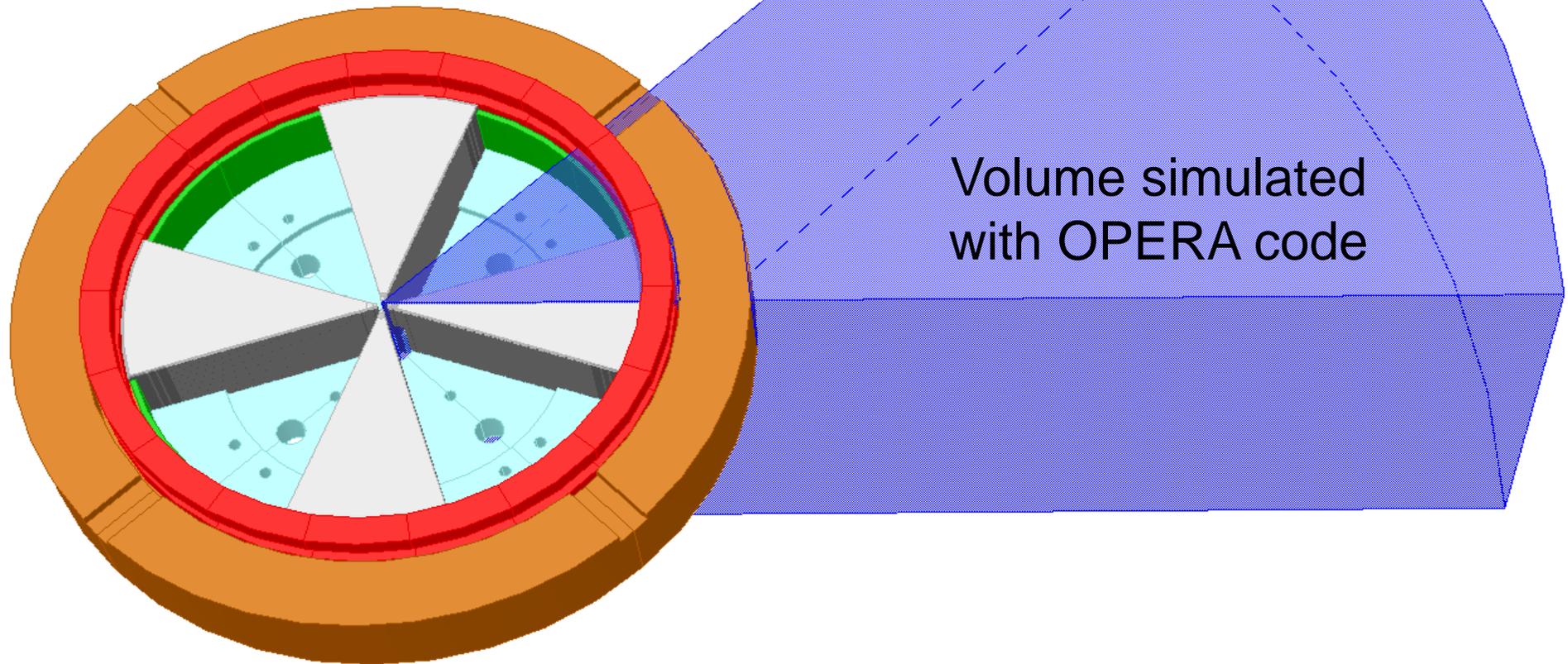


**Beam size at last turn for different beam current**

See, Jianjun Yang presentation

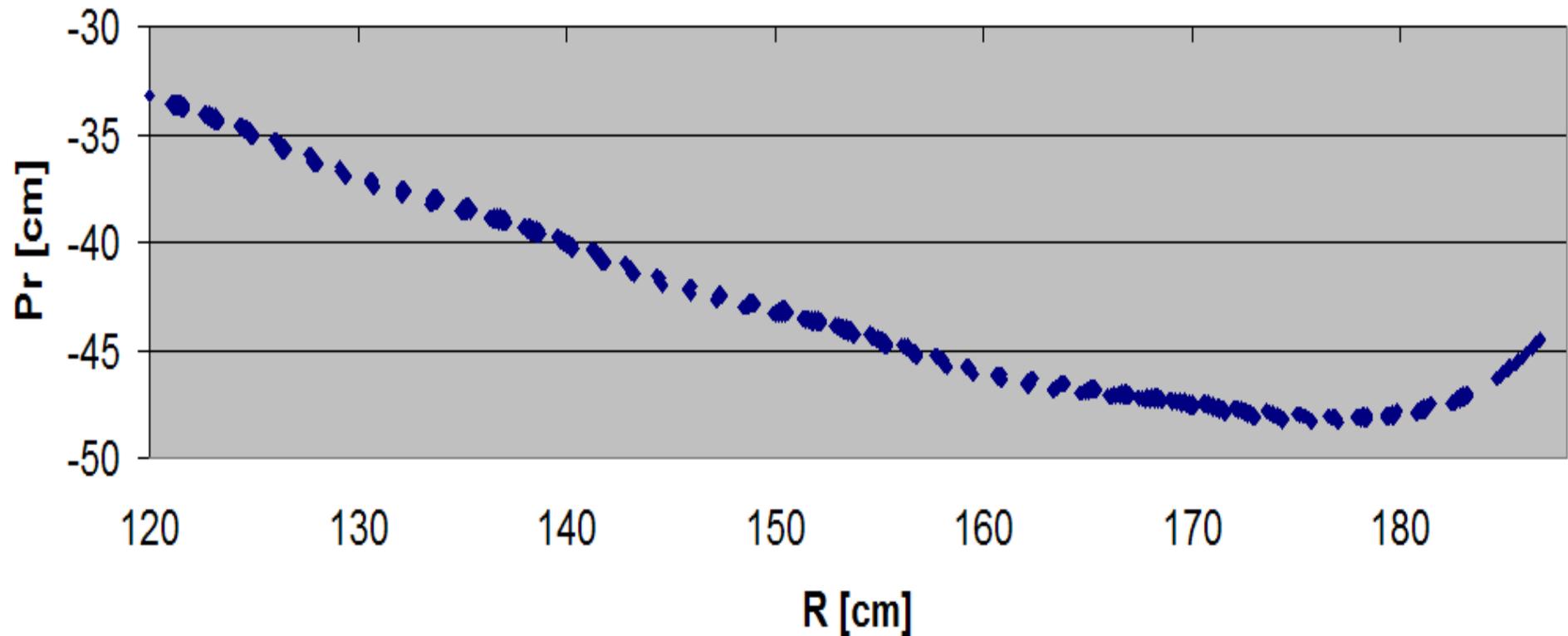


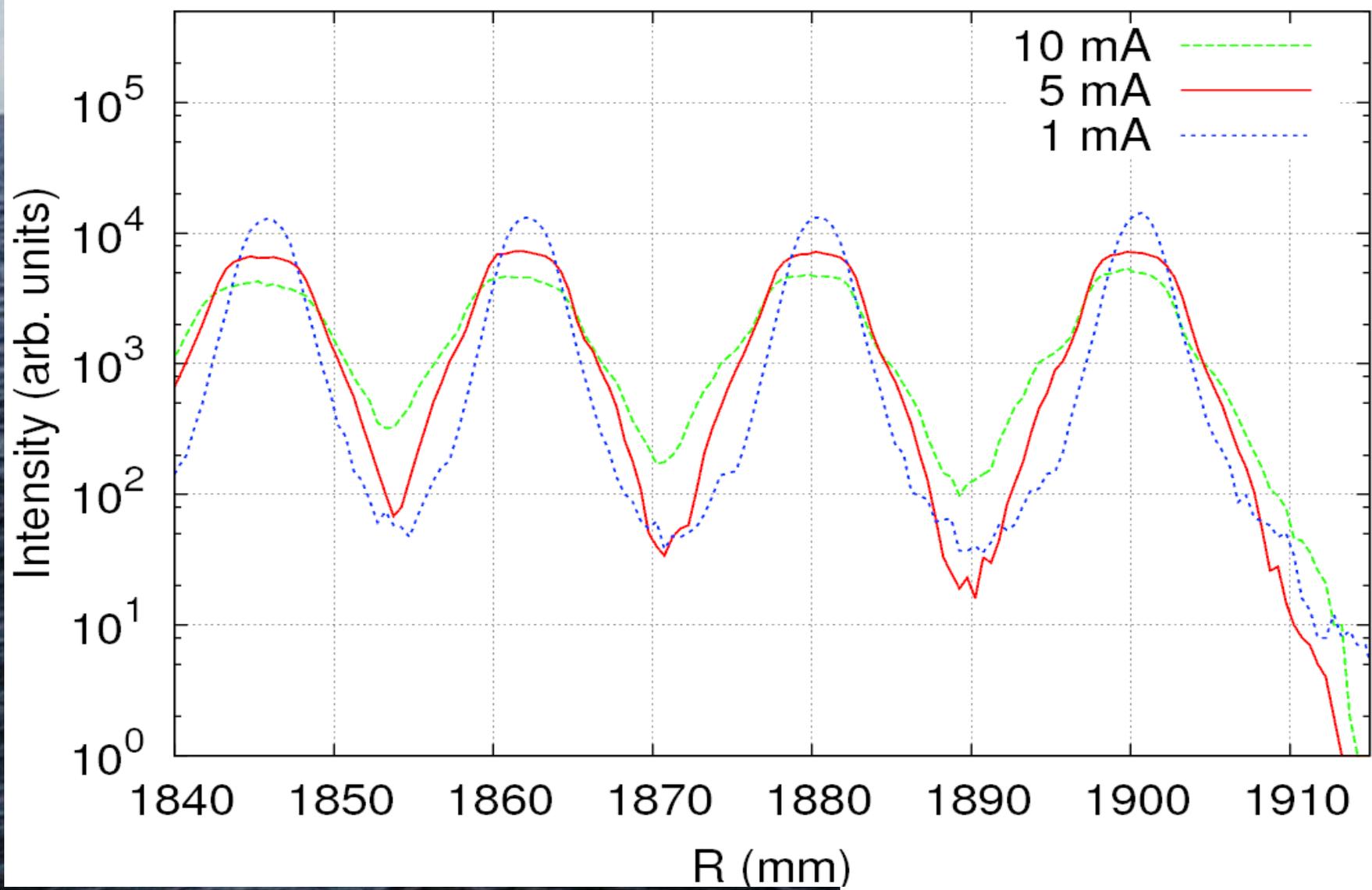
To reduce the mesh size and to achieve a higher field precision, we simulate just 1/16 of the cyclotron volume.



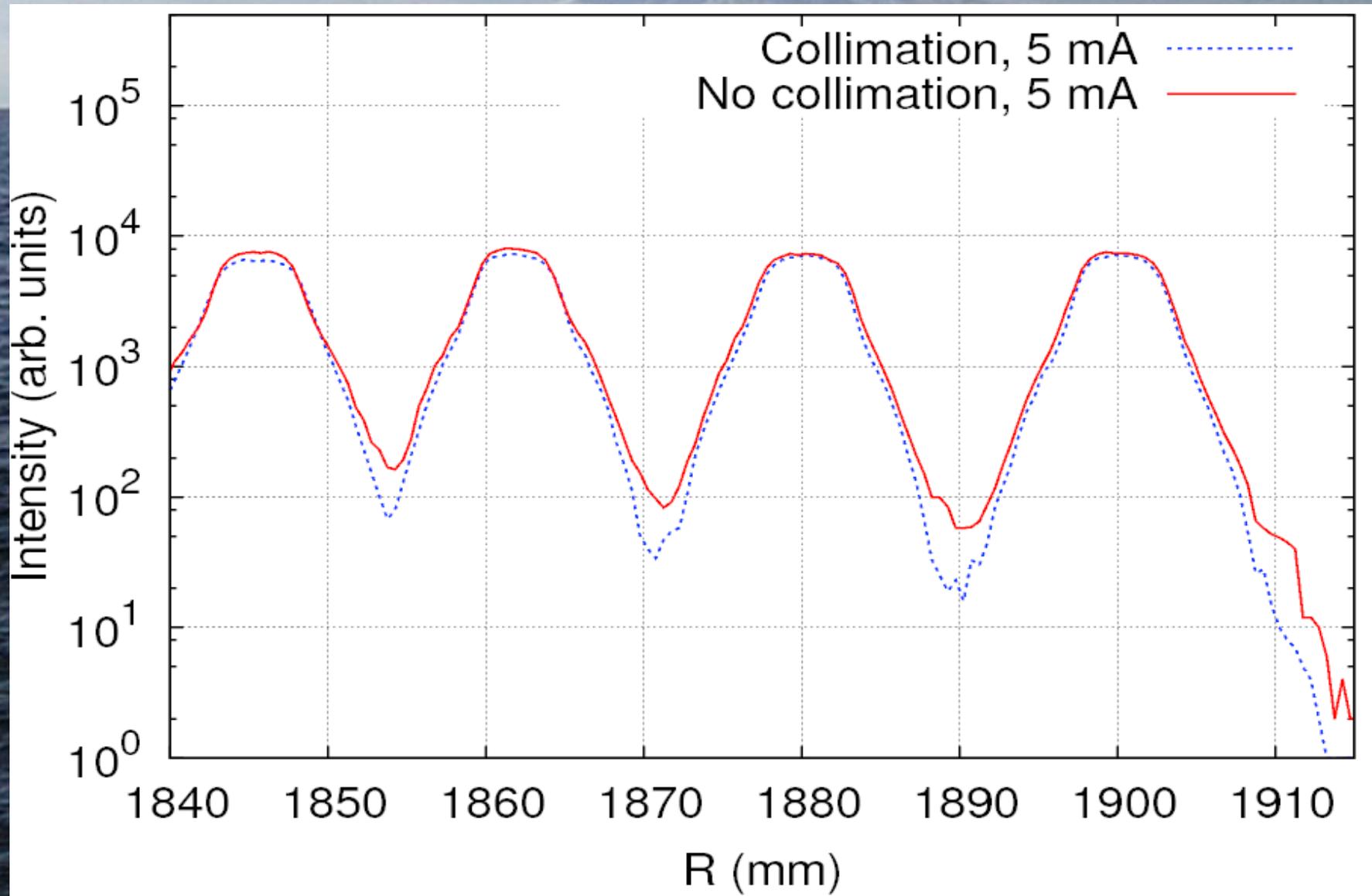


**Beam emittance  $6.4 \pi$  mm.mrad, off center + 3mm at orbit of 1 MeV/n**



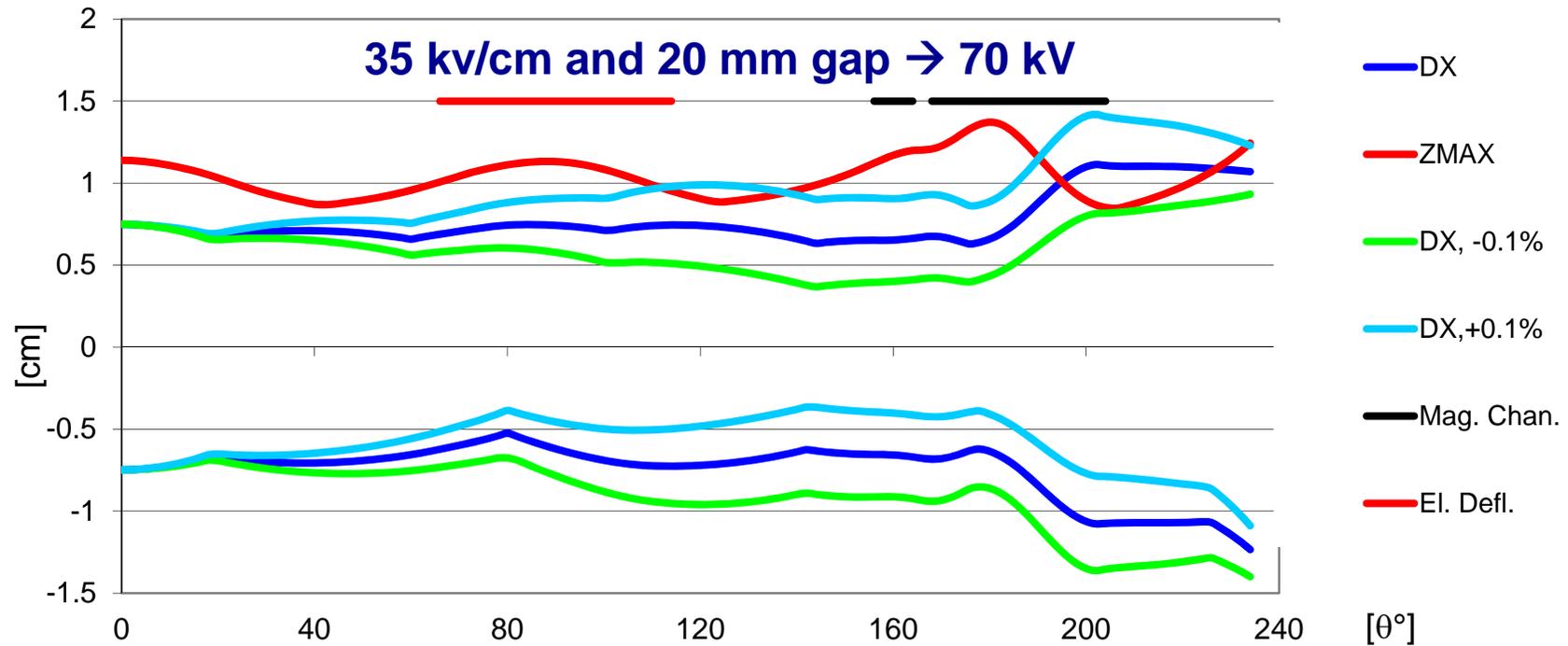


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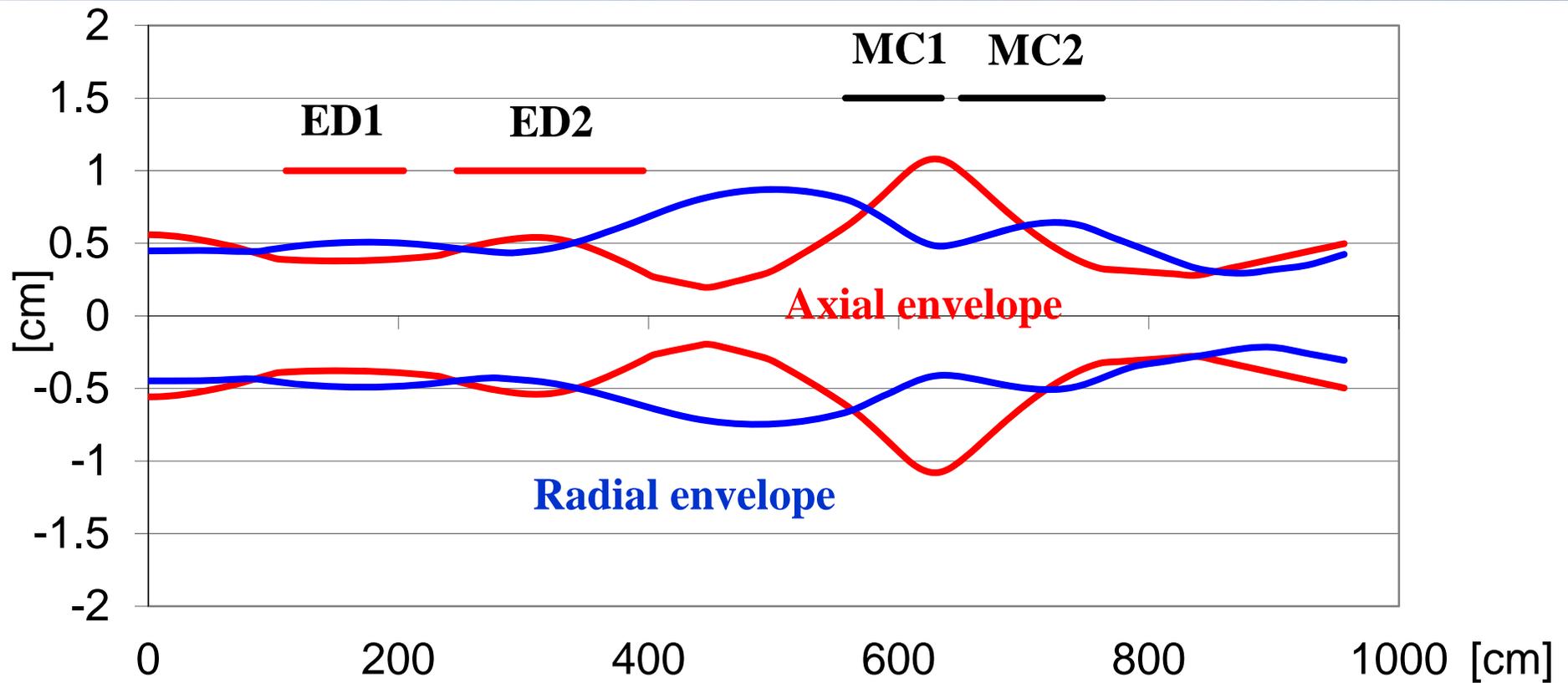




## Beam envelope along the extraction trajectory



Normalized emittance  $\varepsilon=3.3 \pi$  mm.mrad



Electrostatic Deflector	Rin [cm]	Rout [cm]	$\theta_{in}$ [deg]	$\theta_{out}$ [deg]	E [kV/cm]	Gap [mm]
ED1	194.5	194.0	30°	58°	30	20
ED2	203.0	206.1	70°	110°	25	24

