3D Radio Frequency Simulation of the INFN-LNS Superconducting Cyclotron

Presenter: Lorenzo Neri

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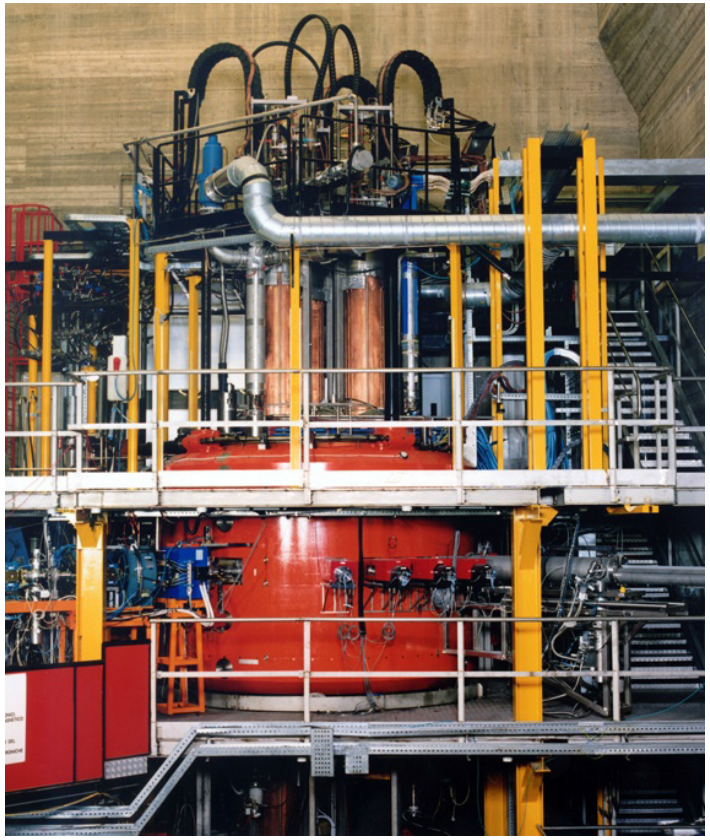


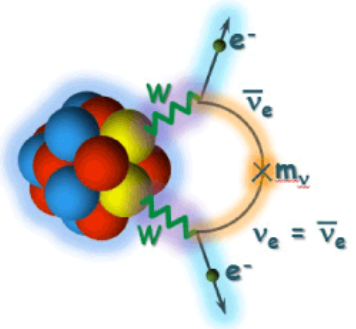
INFN-LNS
Superconducting Cyclotron

Number of cavities	3
Operating Harmonics	1,**2**,3,4
RF frequency	15-48 MHz
Magnetic field	2.2-4.8 T
Bending limit	K=800
Focusing limit	K_{foc}=200
Pole radius	90 cm
Yoke radius	190.3 cm
Yoke height	286 cm
Current	0.04 nA – 0.7 μA

Versatile machine:
Masses from ^{2}H up to ^{238}U
Energy from 10 to 80 MeV/A

Electrostatic extraction limited in power losses:
Maximum extracted beam power ≈ 100 W

Neutrinoless double beta decay



$$1/T_{1/2}^{0\nu}(0^+ \rightarrow 0^+) = G_{01}\left|M^{\beta\beta\,0\nu}\right|^2\left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

Experimental lifetime
Known physic
Numen
New physics beyond standard model

High intensity beam required up to 10 kW

upgrade

Upgrade of INFN-LNS Superconducting Cyclotron

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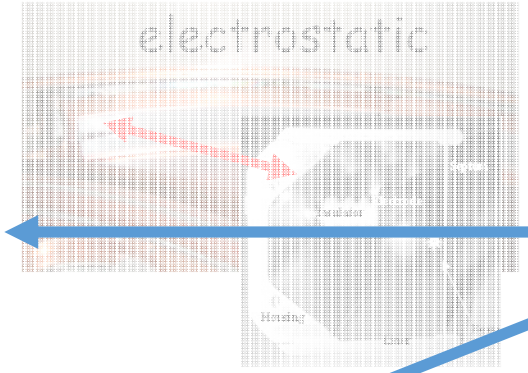
Beam extraction

Existing: electrostatic deflector
Upgrade: stripping foil inside a hill
stripping foil inside a valley



Extraction by stripping

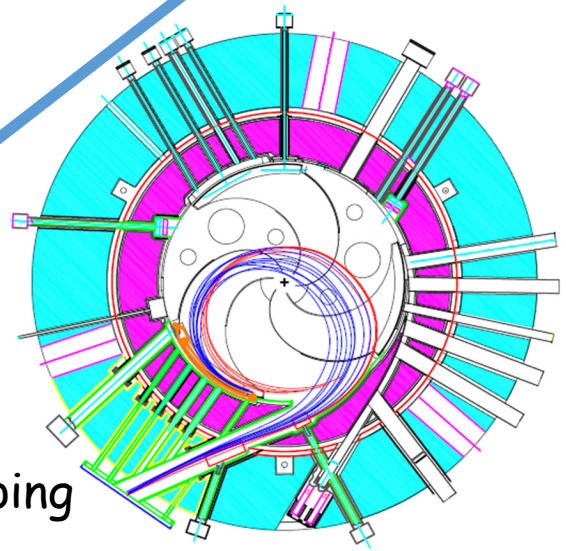
Additional extraction channel
2 new magnetic channels

Gap inside acceleration chamber

Existing: 24 mm
Upgrade: 30 mm

Extraction trajectories

Existing: studied, verified and optimized
Upgrade: under study with custom beam dynamics code



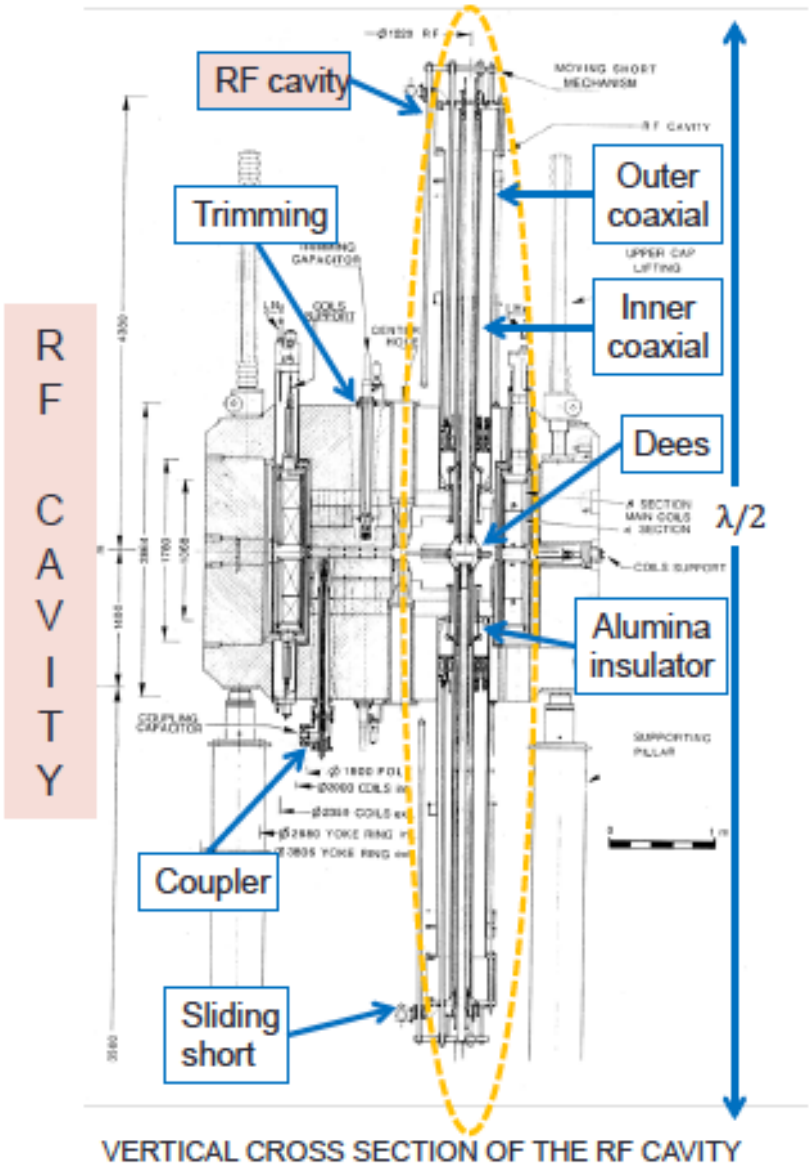
stripping

Radio Frequency cavities simulation

To verify:

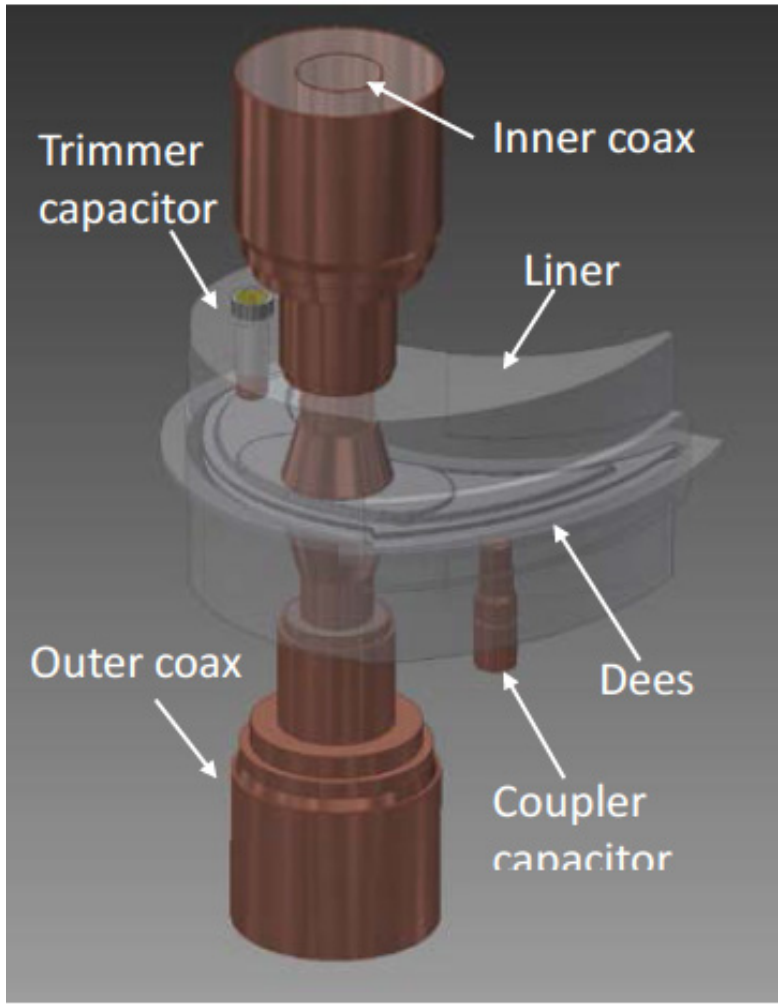
- Housing stripping system inside Dee
- Larger gap
- Accelerated trajectory
- Extracted energy spread
- Contribution to stripped trajectories

Radio Frequency simulation design details

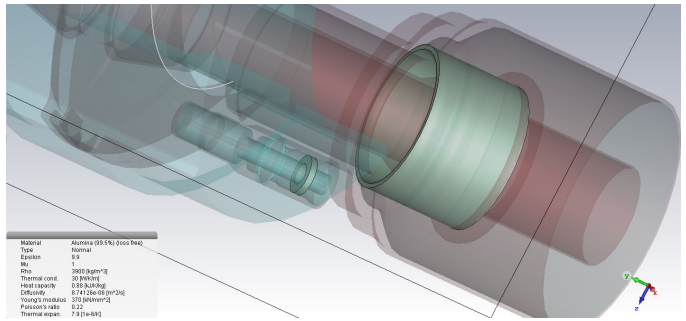


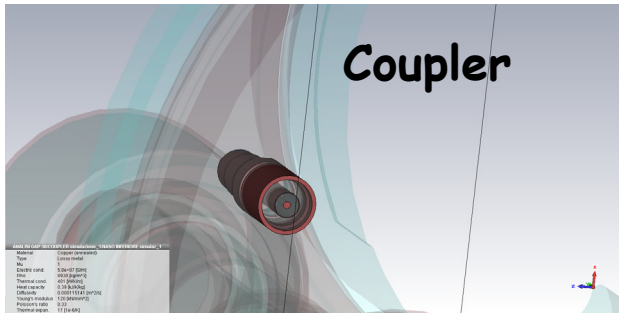
VERTICAL CROSS SECTION OF THE RF CAVITY

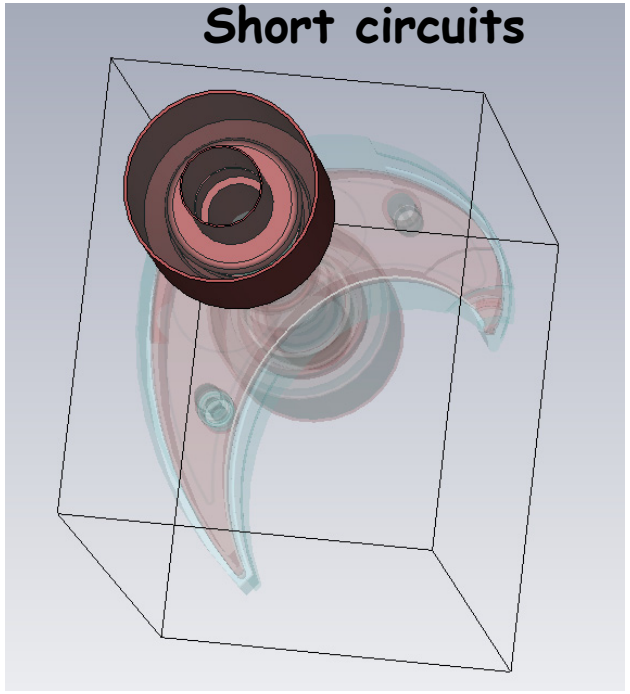
Radio Frequency simulation design details



Alumina parts are included







Movable parts:
Short circuits to change resonant frequency
Coupler and trimmer to RF coupling

Radio Frequency simulation software features

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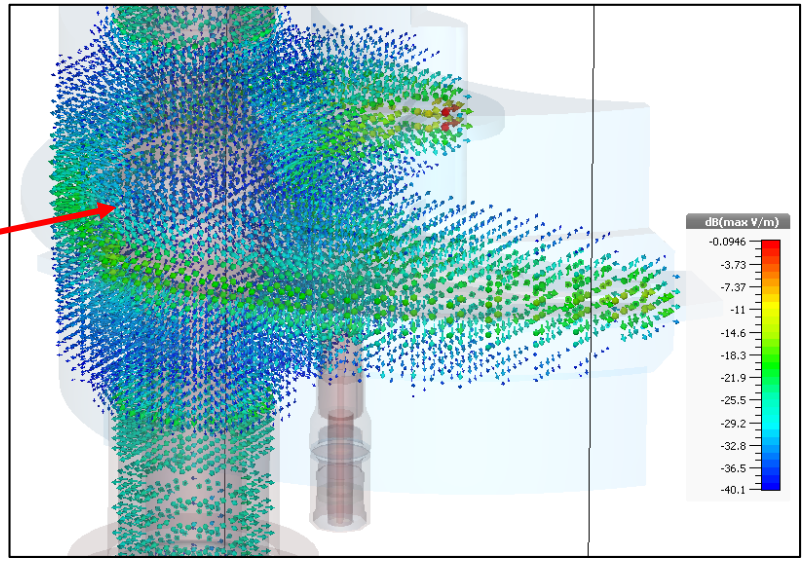
Eigen mode solver:

Analysis in terms of field and frequencies for RESONANT MODES compatible with the designed structure
(software: CST)

1) Different resonant frequency were achieved by changing the short circuit position

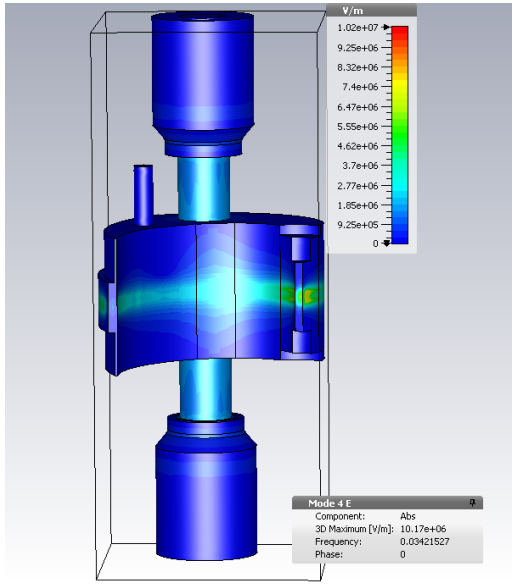
Eigenmode solver results:

Mode	Frequency	Accuracy
1	0 GHz	7.661661e-007
2	0 GHz	8.816619e-005
3	0.03866975 GHz	4.685222e-005
4	0.0474365 GHz	0.0001048406
5	0.09166877 GHz	4.502759e-007
6	0.09866529 GHz	4.789941e-006
7	0.101093 GHz	3.12249e-006
8	0.1396818 GHz	1.495329e-006



Driven solver:

Driven modal analysis (excitation via wave-port)
energy is supplied to the structure from an coaxial coupler
➔ yields fields
➔ port S-parameters S11 = reflected power over given input power
(software: CST and Comsol)



Experimental validation of RF simulation

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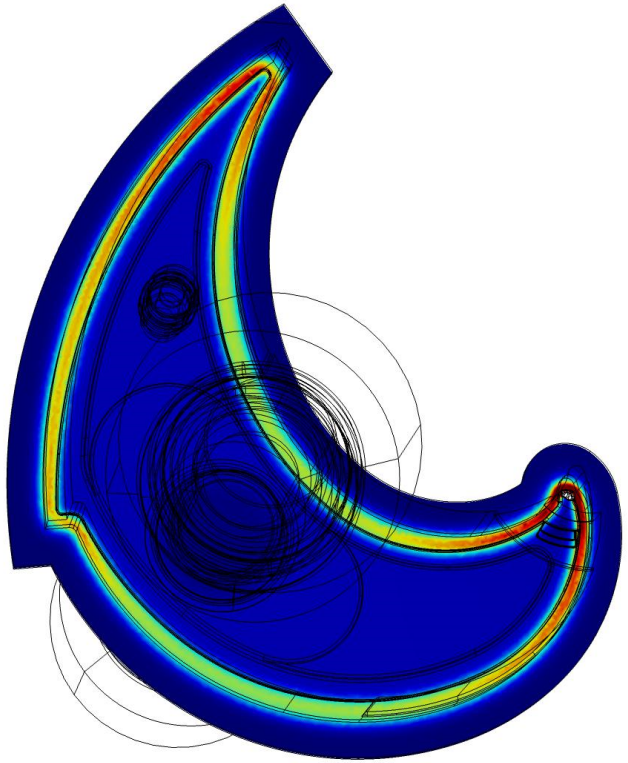
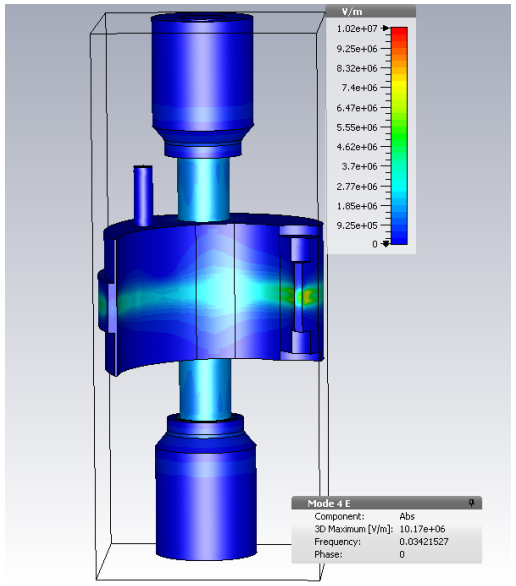
2) The electric field distribution is compatible with what expected

Electric field distribution in middle plane region



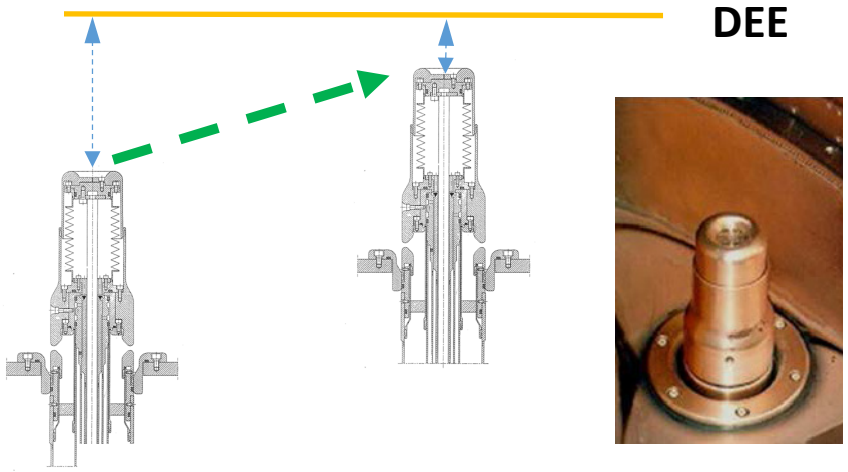
Electric field distribution inside the RF cavity

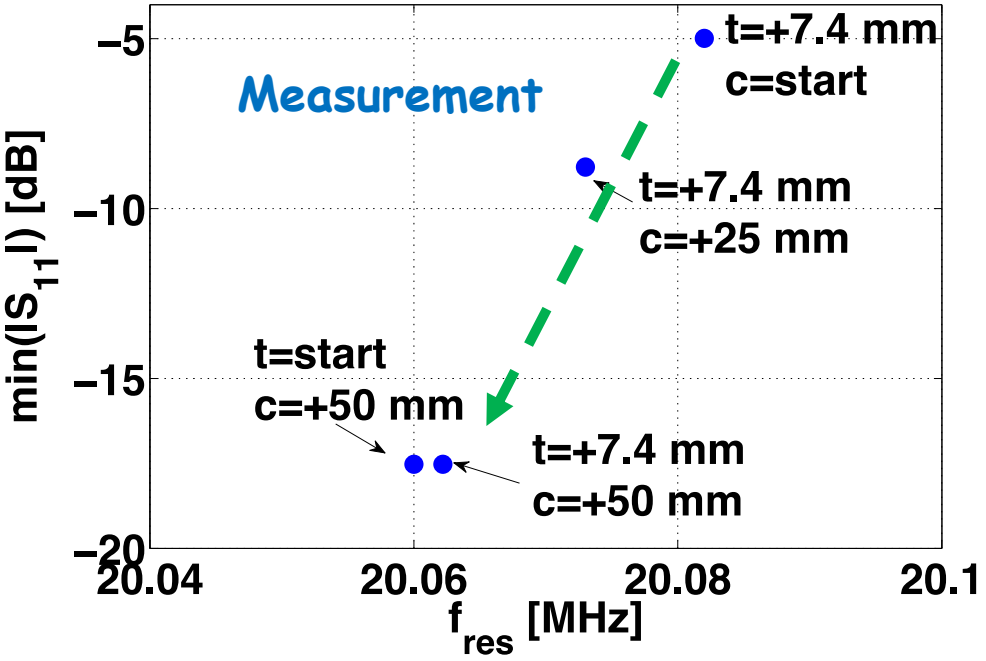


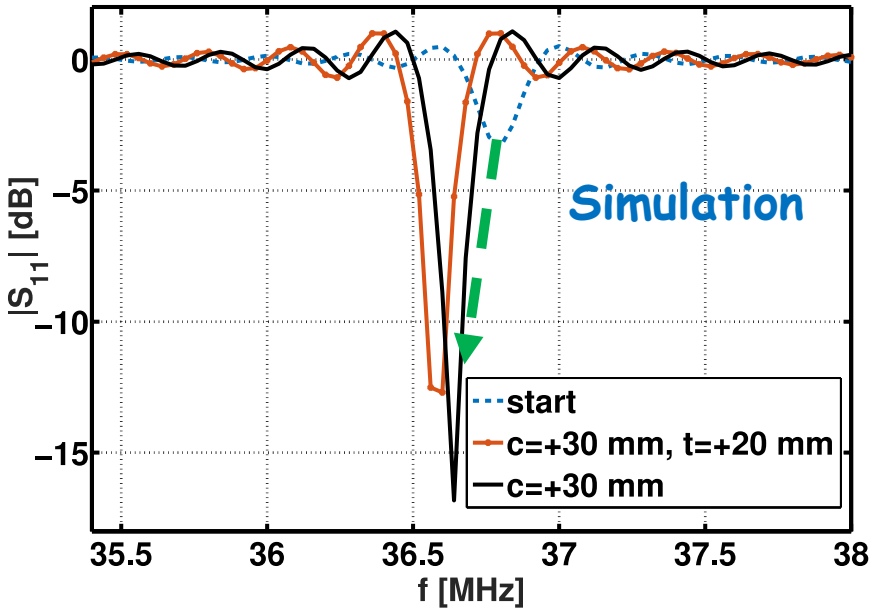
Experimental validation of RF simulation

1) The electric field distribution is compatible with what expected

2) Effective coupling sensitivity by changing coupler position







Upgrade of INFN-LNS Superconducting Cyclotron

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Existing: electrostatic deflector
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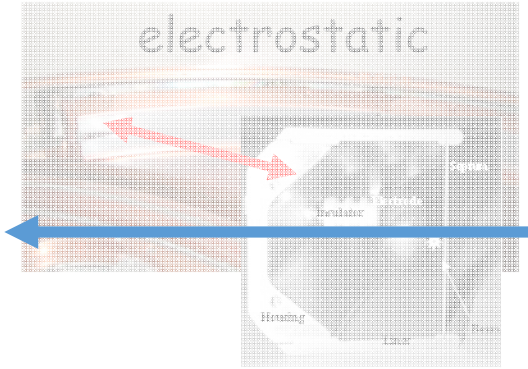

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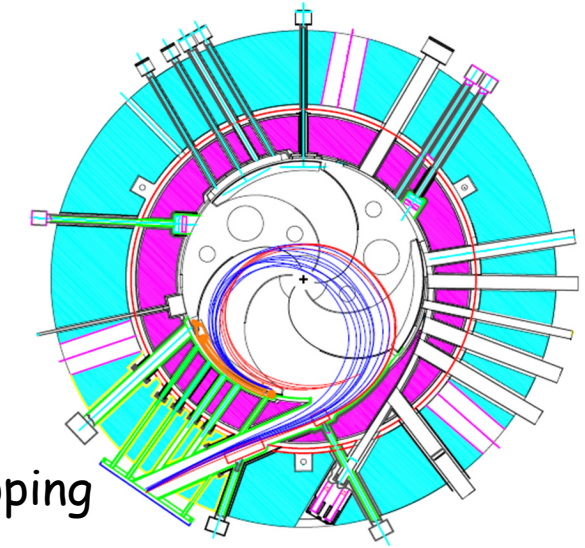

stripping

Radio Frequency cavities simulation

To verify:

- Housing stripping system inside Dee

RF study with different Dee geometry

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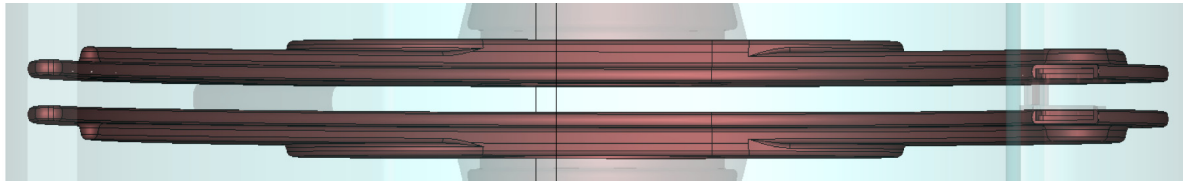
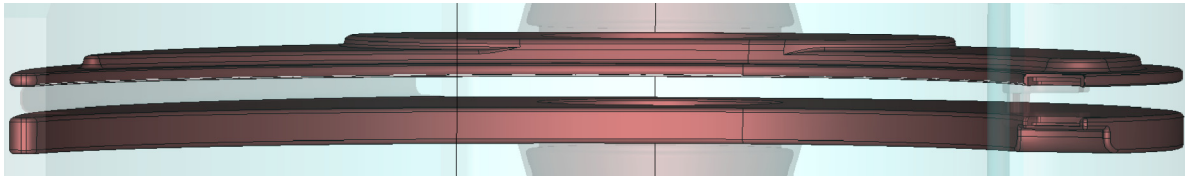


a) current configuration

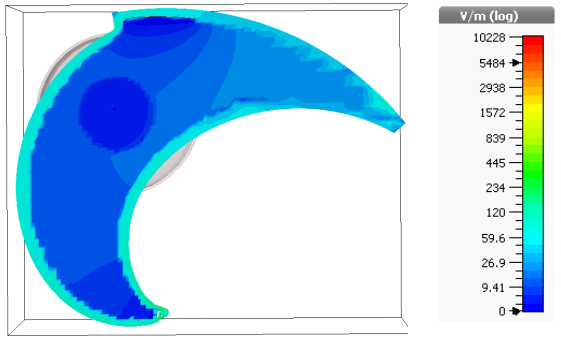


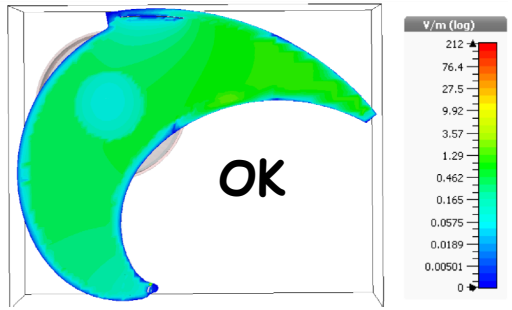
b) one thicker Dee to house **one of the two extraction by stripping system**

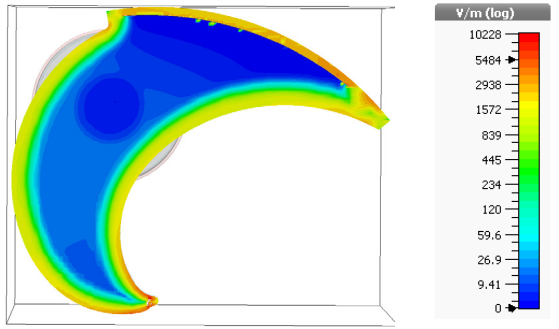
c) symmetric thicker configuration

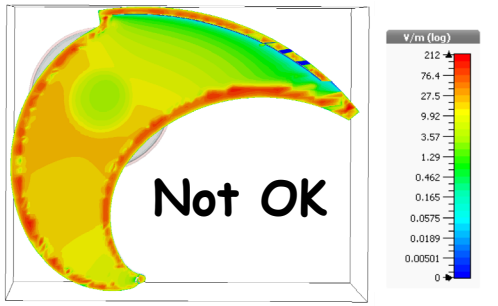
Total electric field in middle plane

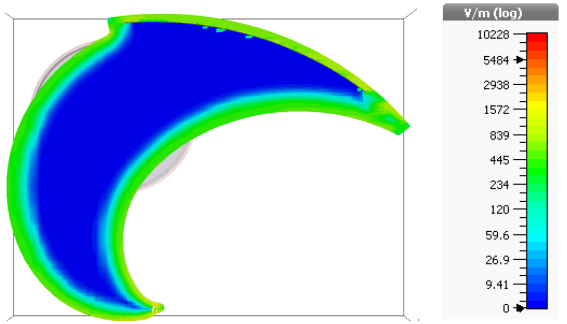
Electric field orthogonal to middle plane

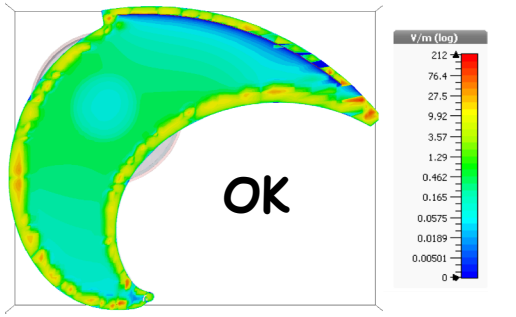












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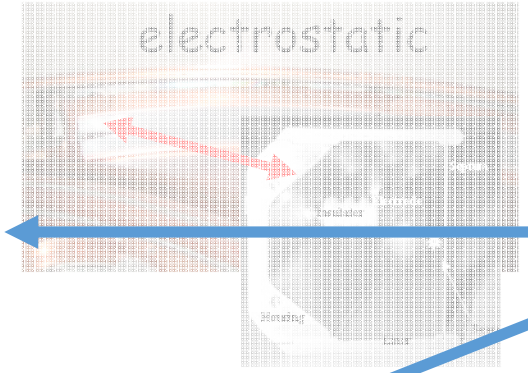

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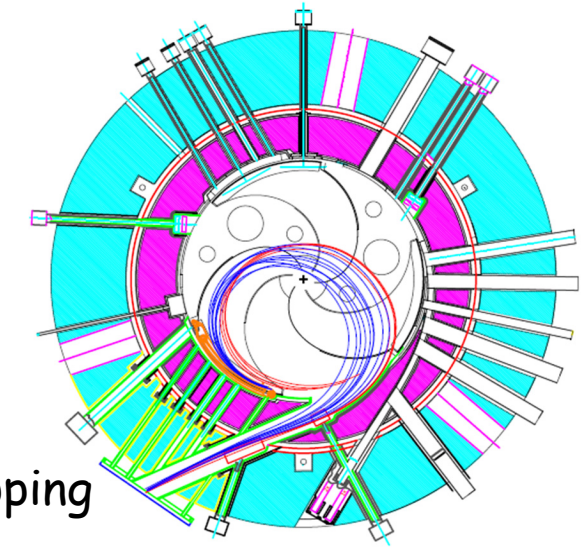
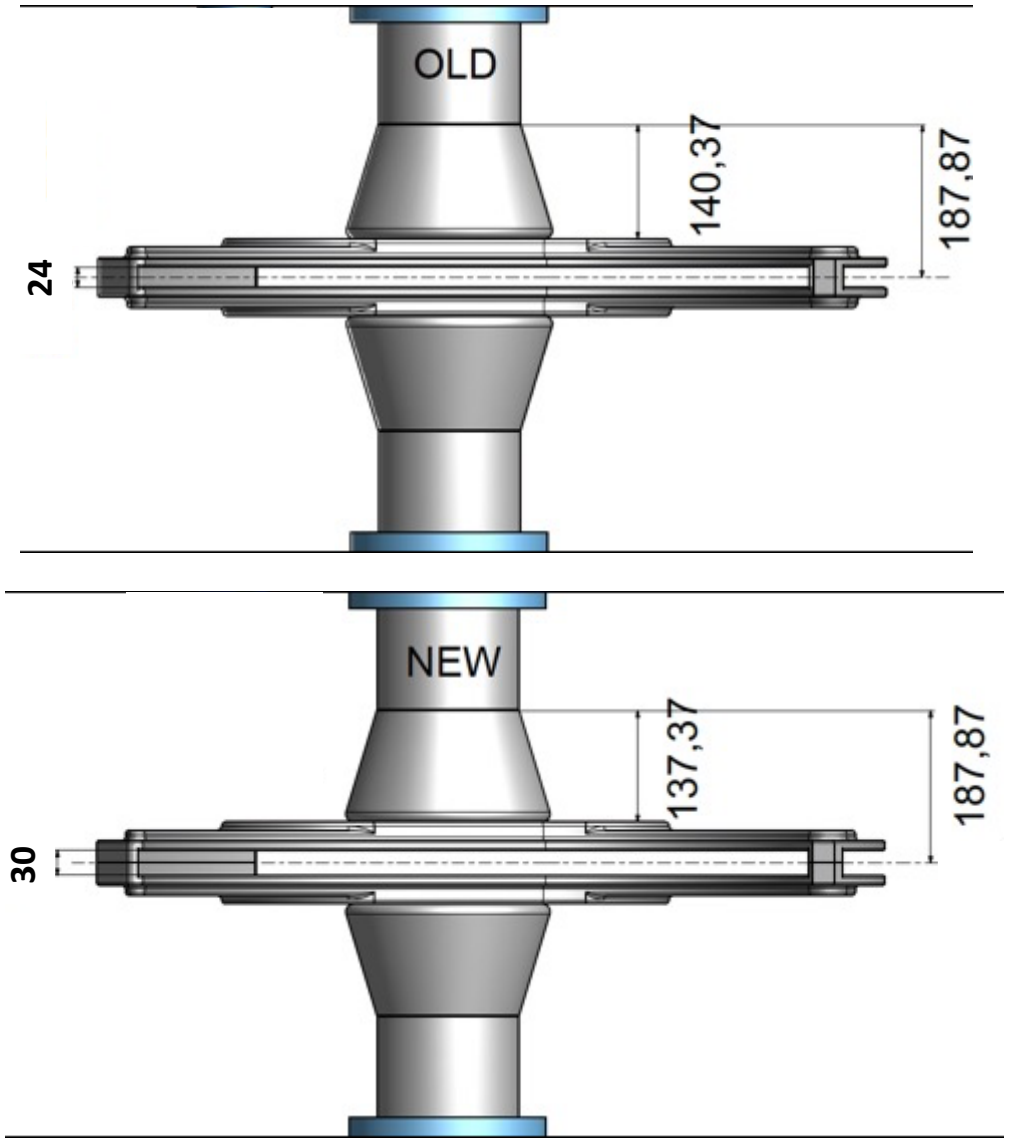
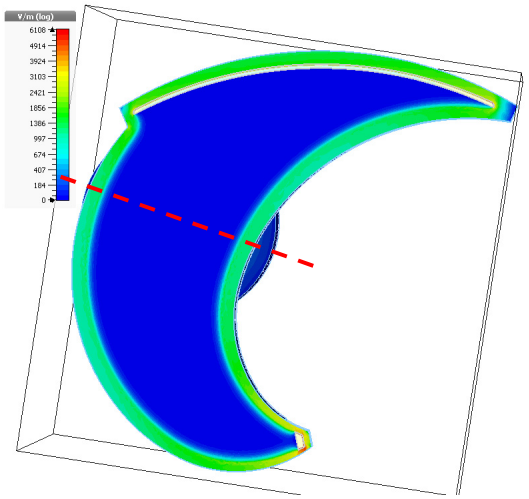


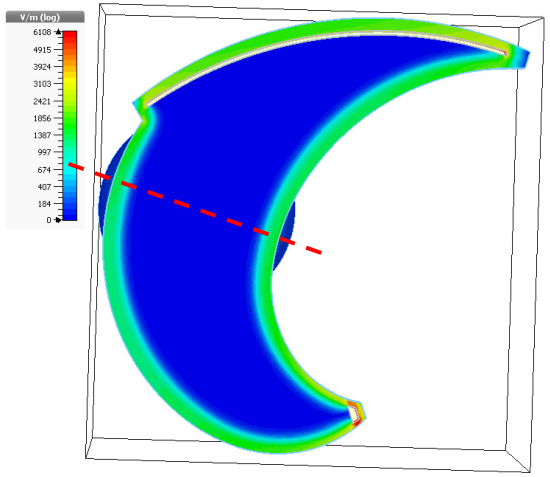
stripping

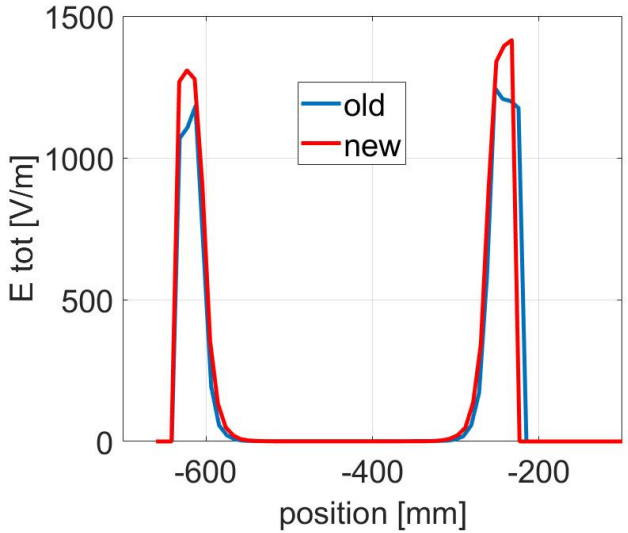
RF study with different gap thickness



Total electric field 10 mm far from middle plane







Same distribution but slightly higher intensity with the new configuration: To be verified with particle dynamics code

Upgrade of INFN-LNS Superconducting Cyclotron

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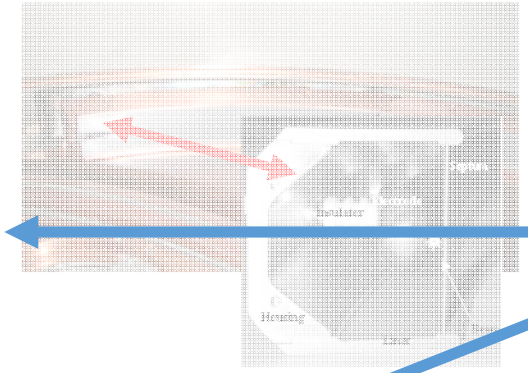

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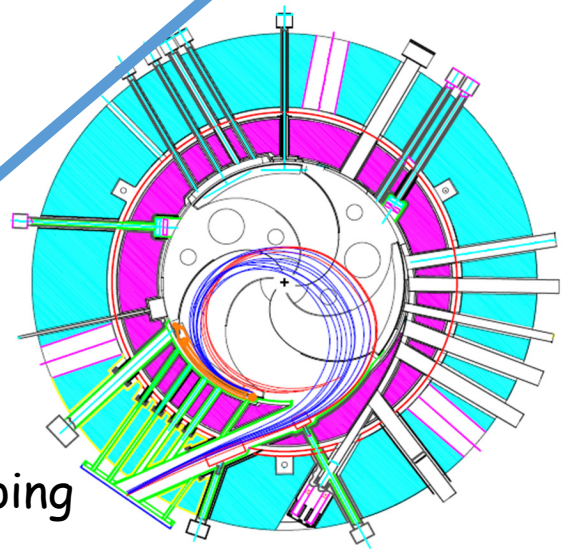

stripping

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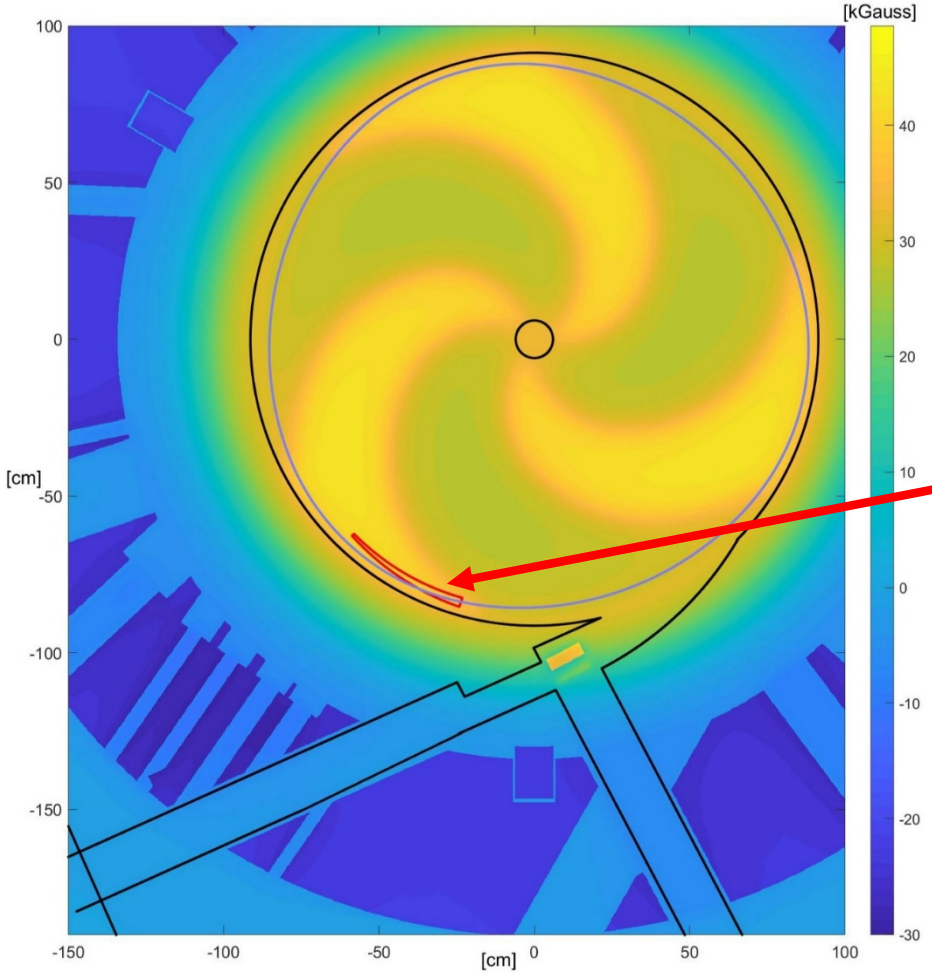
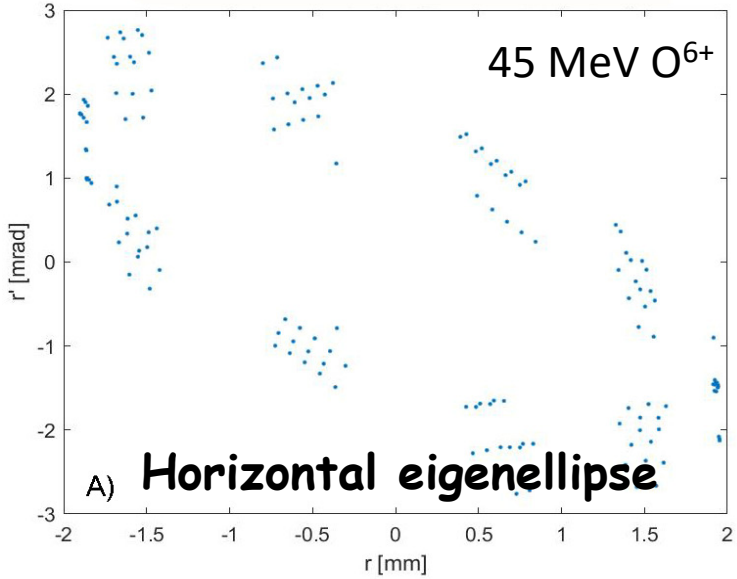
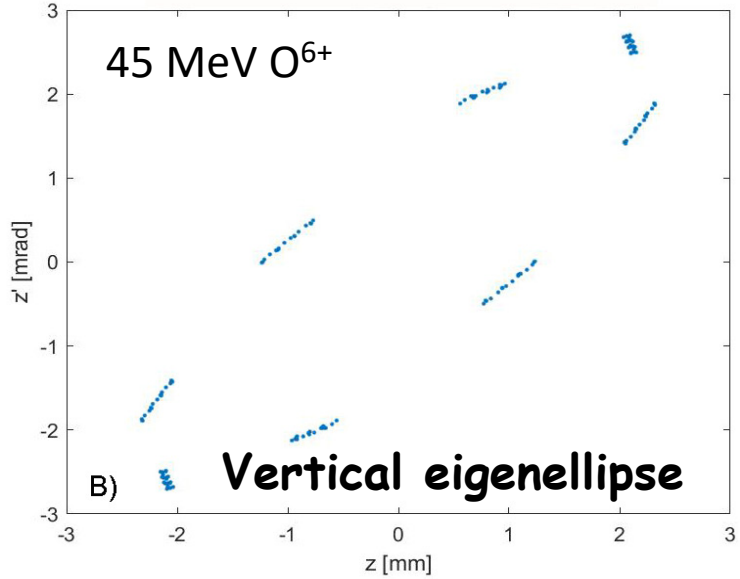
- Extracted energy spread
- Contribution to stripped trajectories

3D magnetic field and eigenellipses (Beam dynamics code)

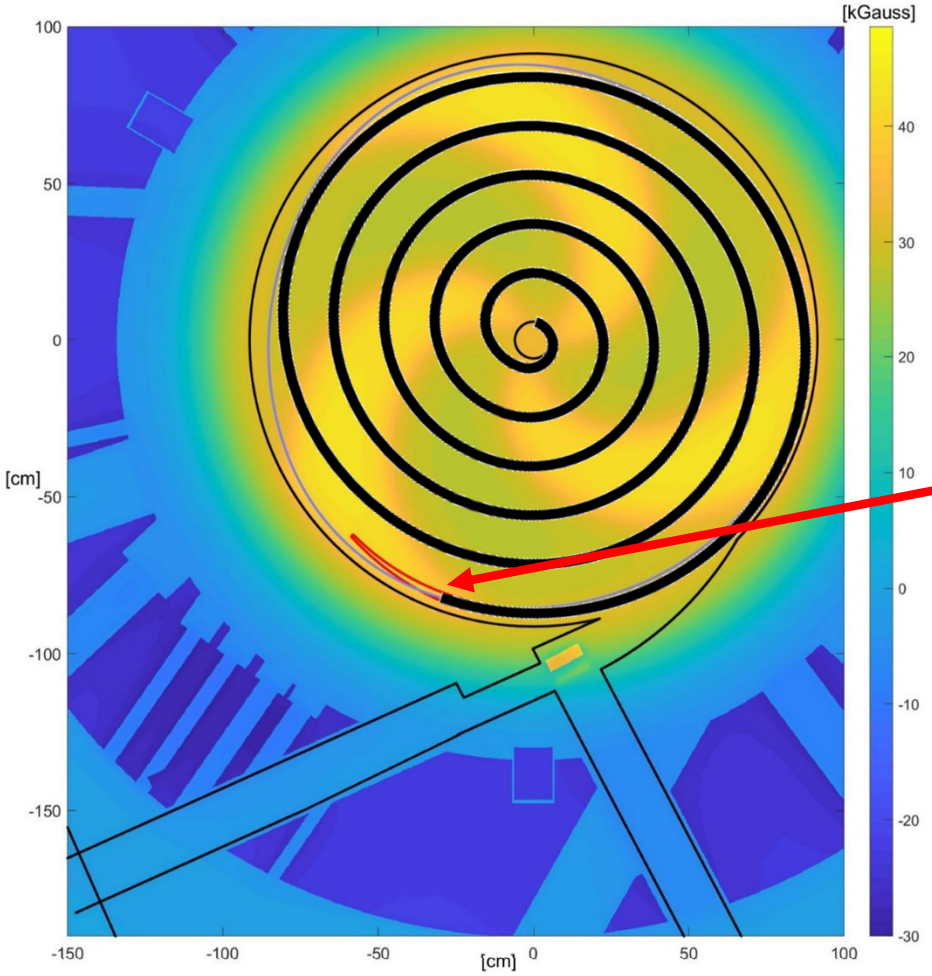


- Measured map on middle plane inside acceleration region was extended out of plane by using Maxwell equations
- 3D Comsol model without trimmer coil used outside acceleration region
- Stationary orbits and eigenellipses computed with custom Matlab beam transport code
- Intersection with stripping foil region





(Beam dynamics code plus RF)



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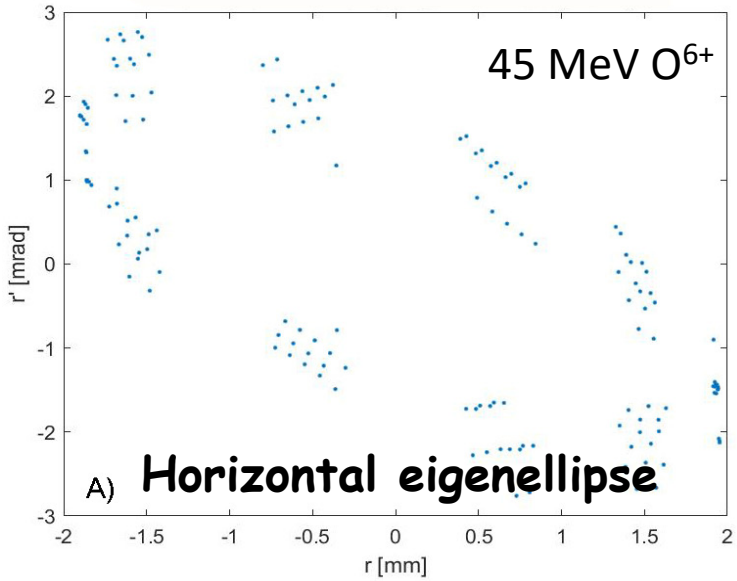
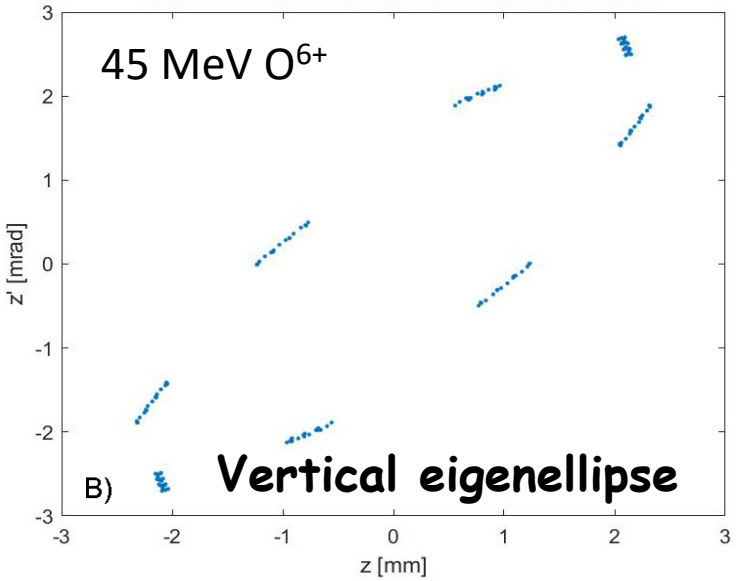
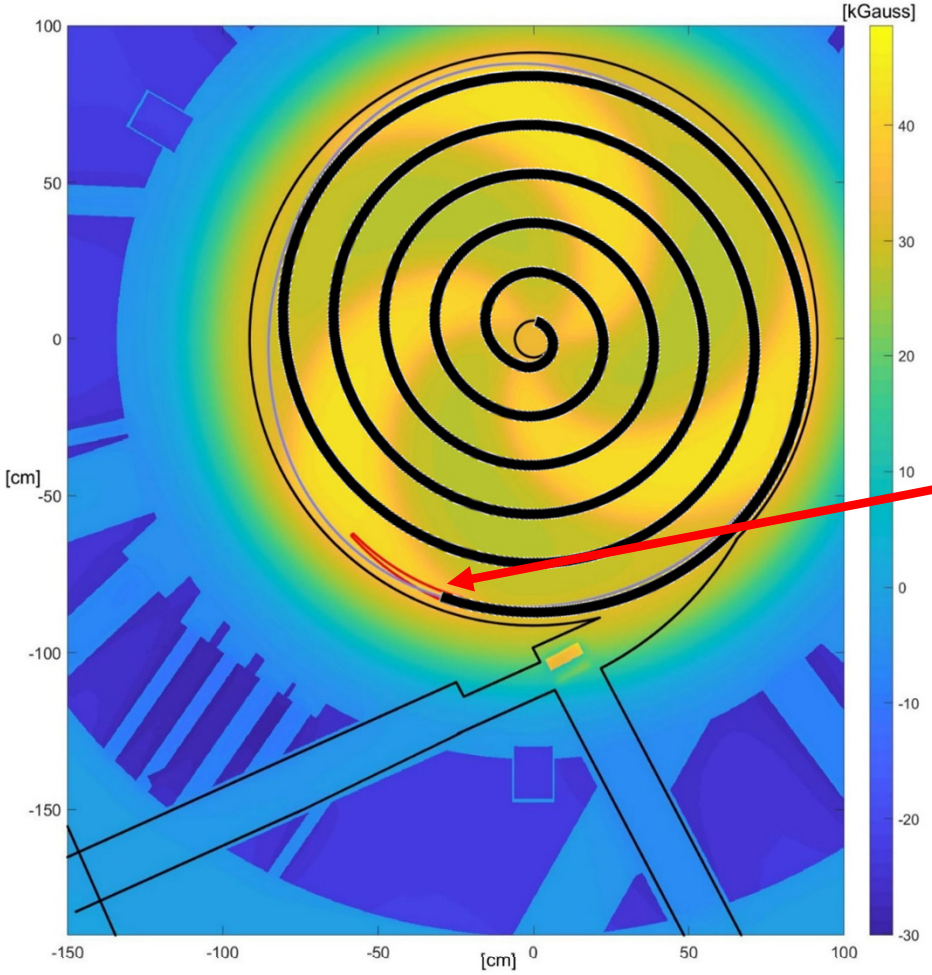


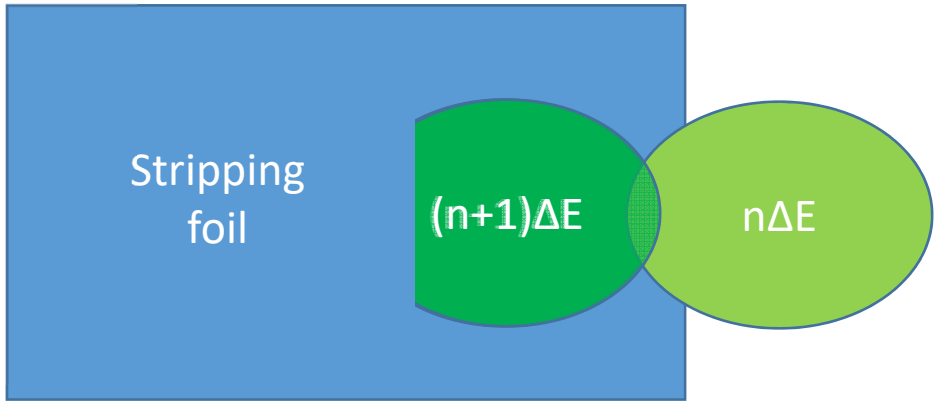


Multi turn extraction

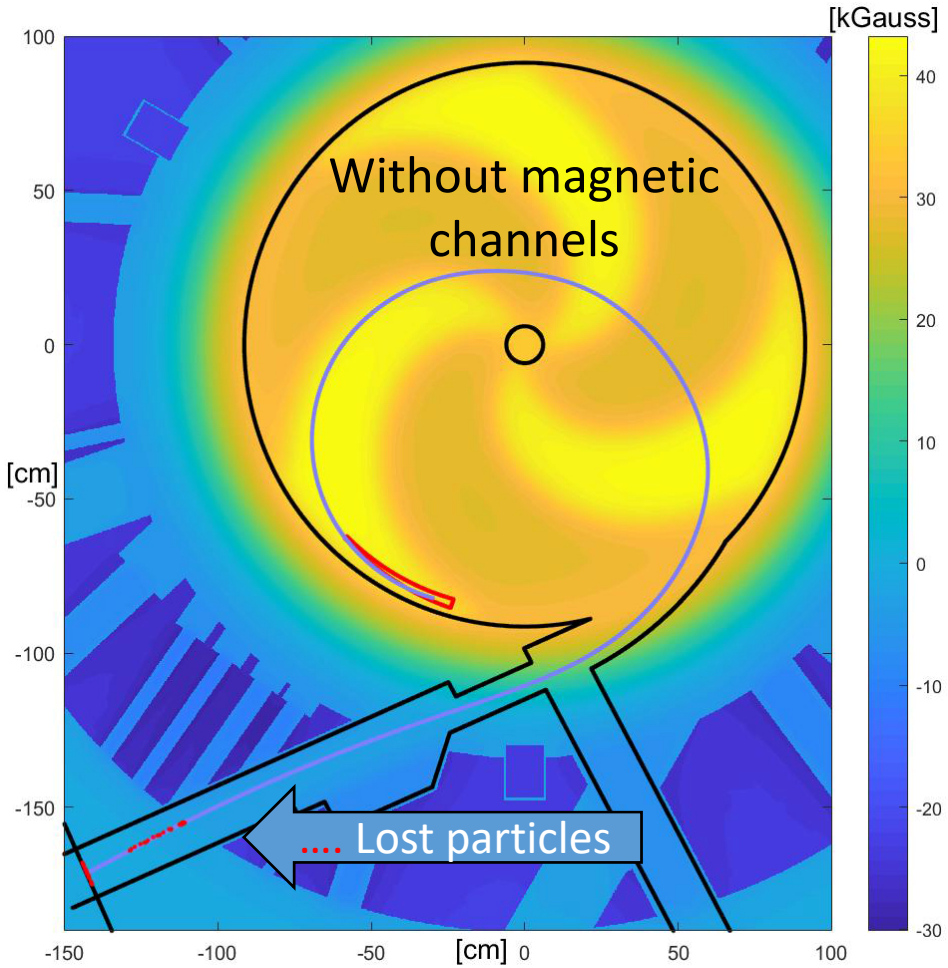
(Beam dynamics code plus RF)



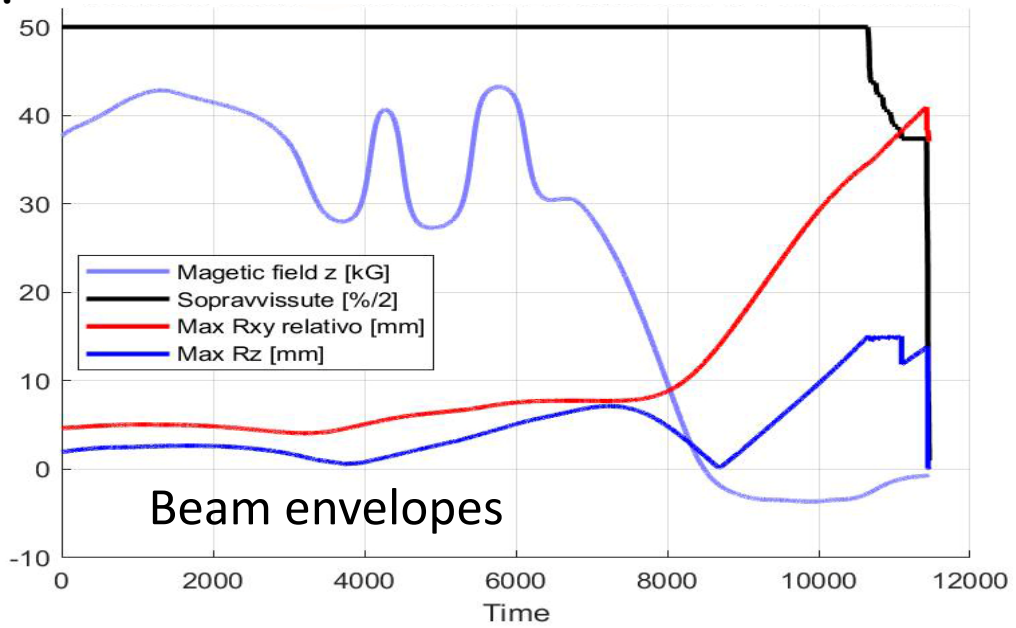
- Measured map on middle plane inside acceleration region was extended out of plane by using Maxwell equations
- 3D Comsol model without trimmer coil used outside acceleration region
- Accelerated orbit, with multi turn extraction and consequently energy spread computation
- Intersection with stripping foil region



Fully stripped trajectory (Beam dynamics code)



- Best starting point inside stripping region is selected
- Lost particles if touching black contour or 15 mm far from middle
- Envelopes of extracted trajectory
- Extracted beam distribution in horizontal and vertical phase-space



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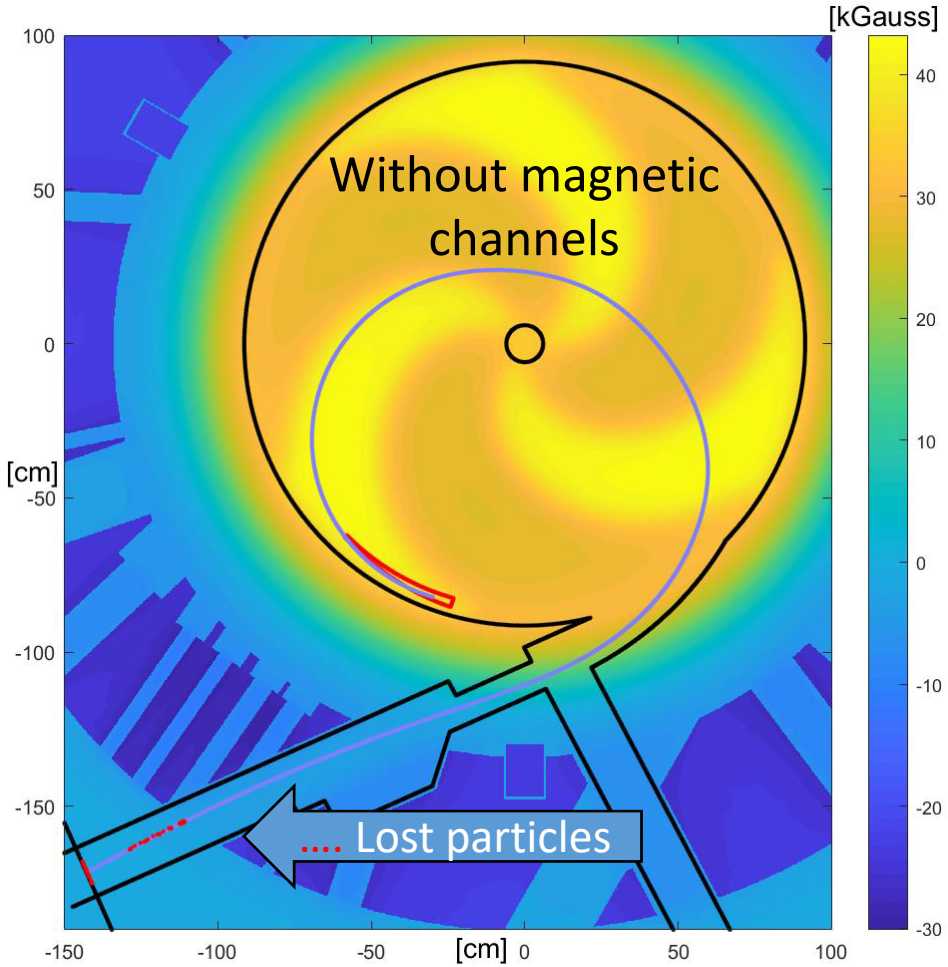

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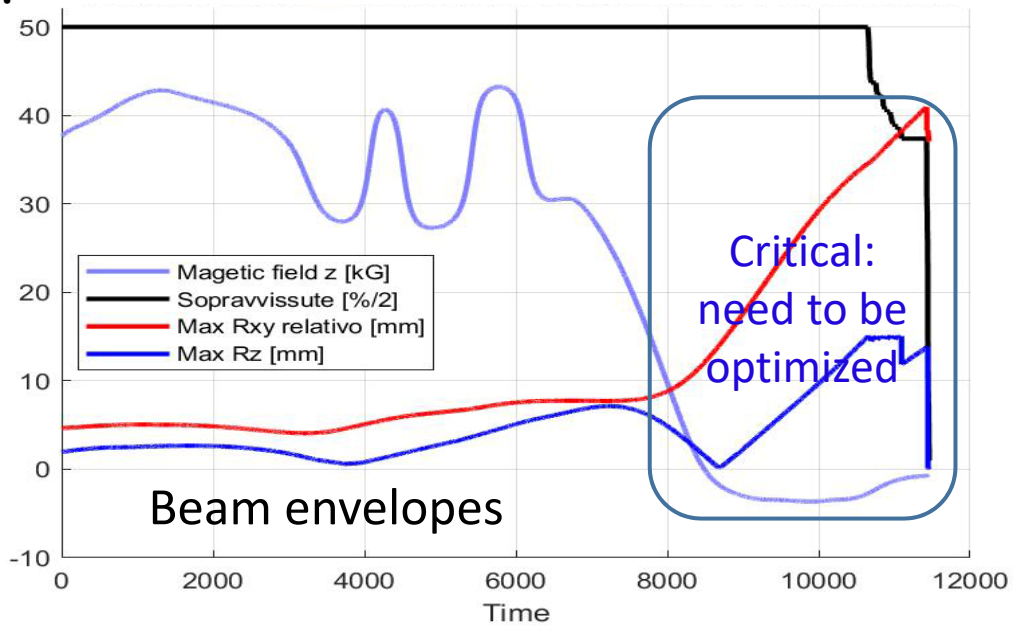
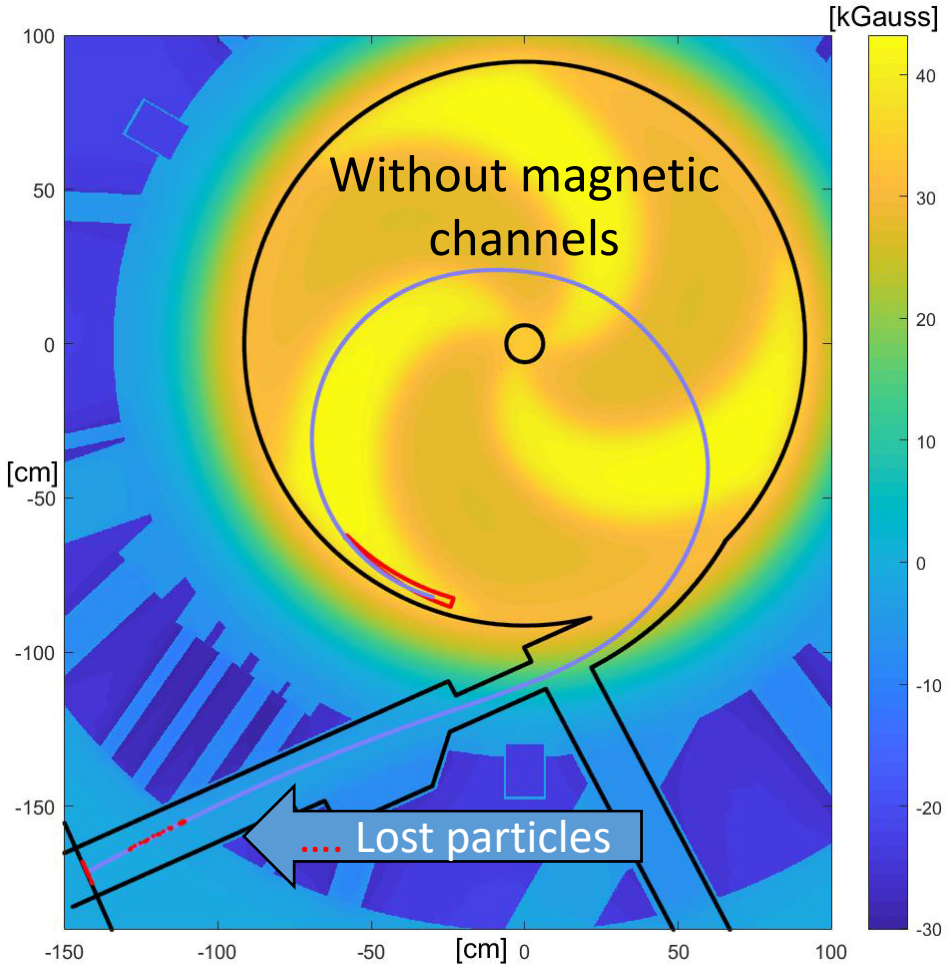


(Beam dynamics code plus RF)



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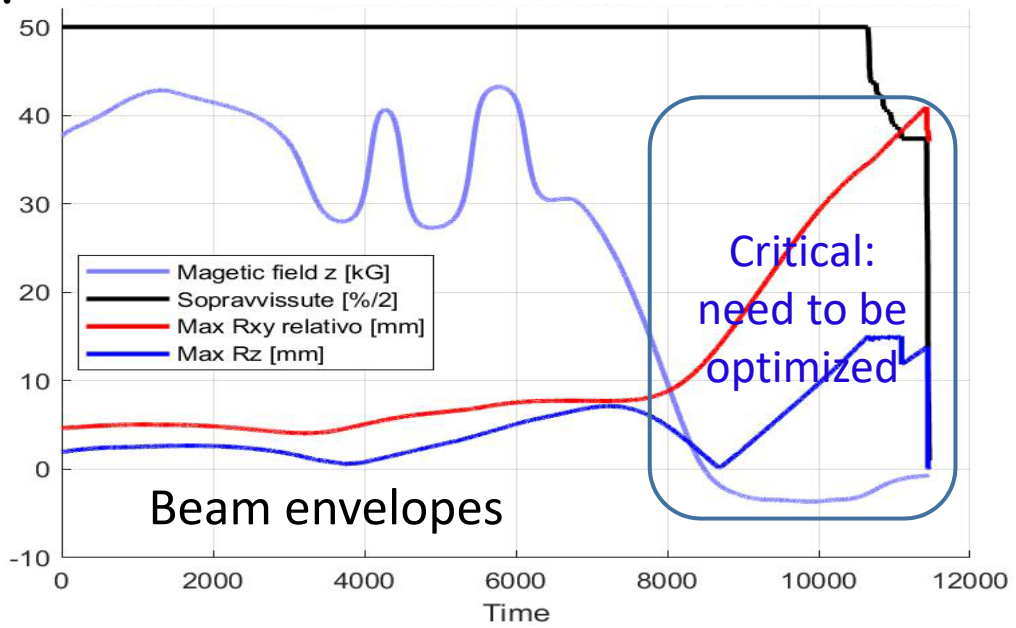
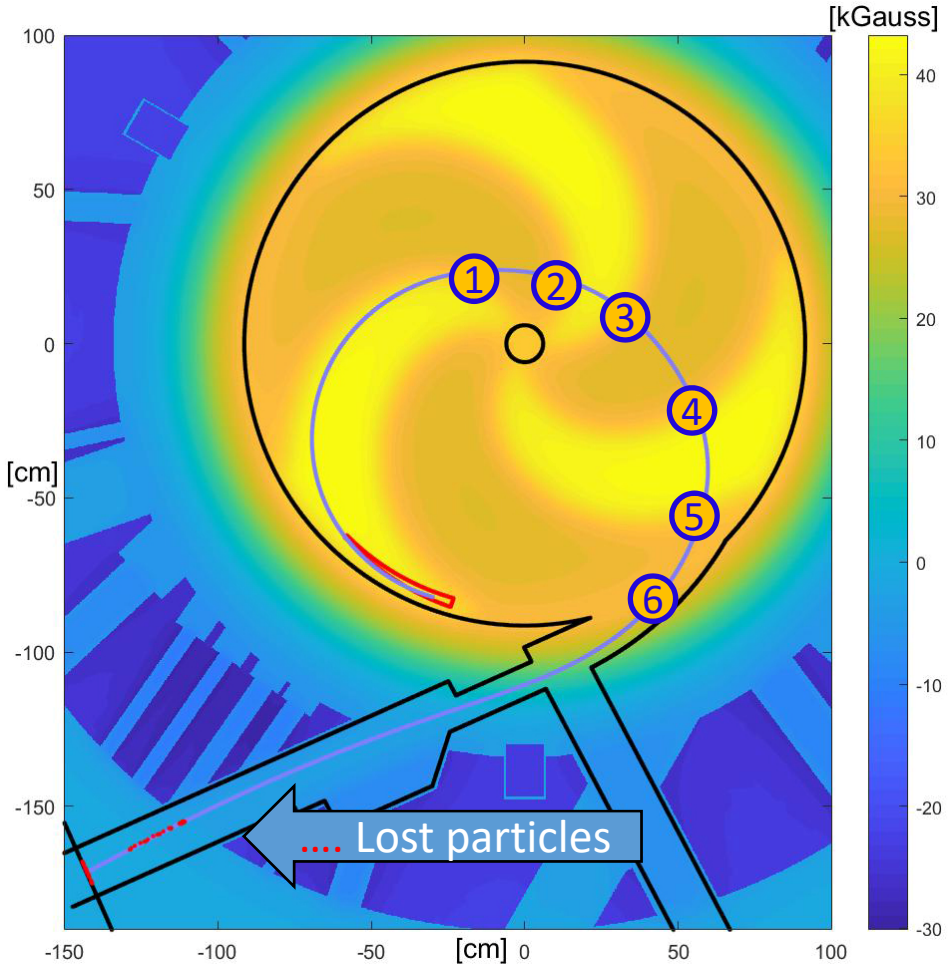
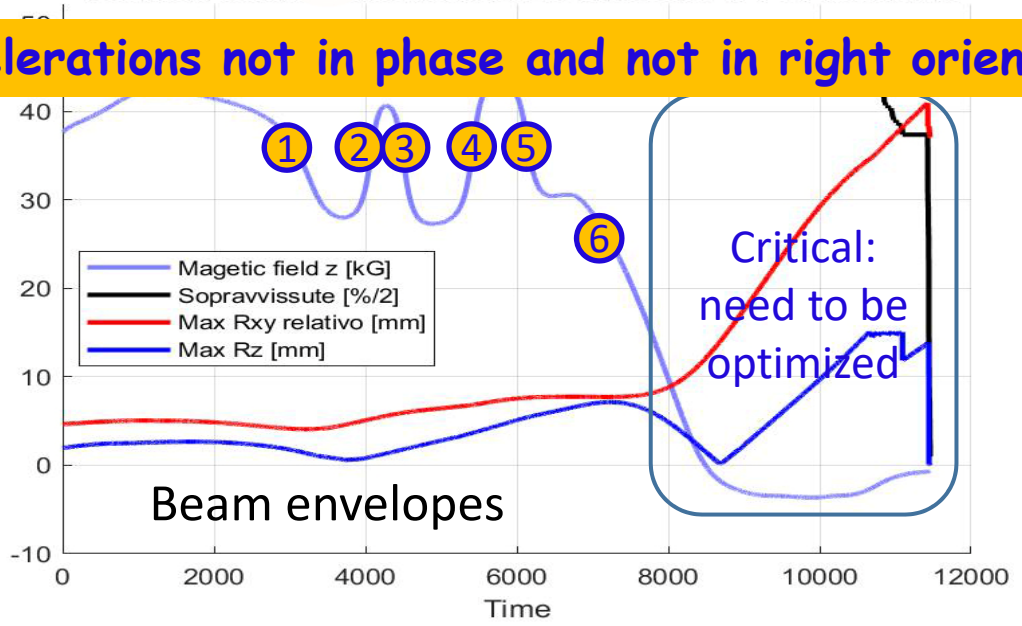
- Envelopes of extracted trajectory
- Extracted beam distribution in horizontal and vertical phase-space



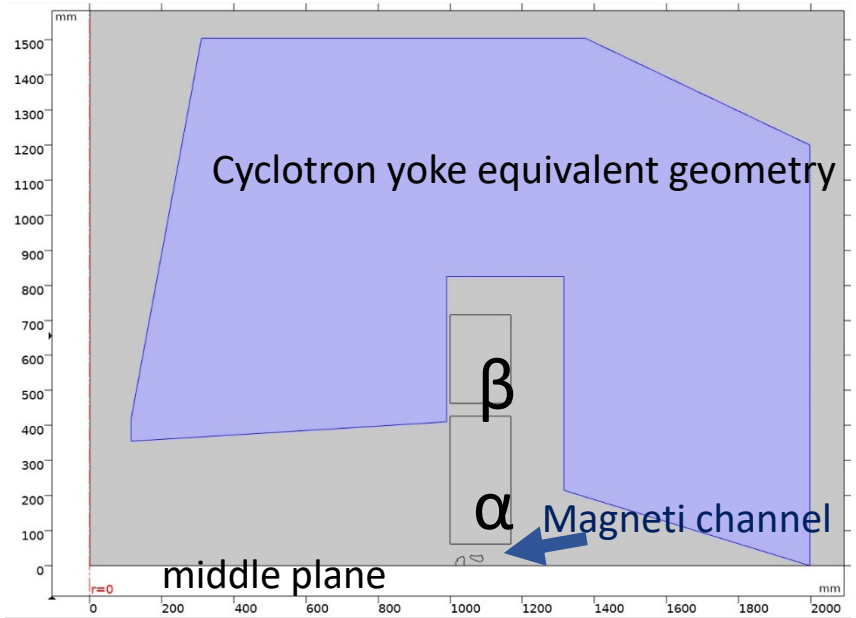
Perturbation of stripped trajectory
(Beam dynamics code plus RF)



- Best starting point inside stripping region is selected
- Lost particles if touching black contour or 15 mm far from middle
- Envelopes of extracted trajectory
- Extracted beam distribution in horizontal and vertical phase-space
- RF accelerations not in phase and not in right orientation

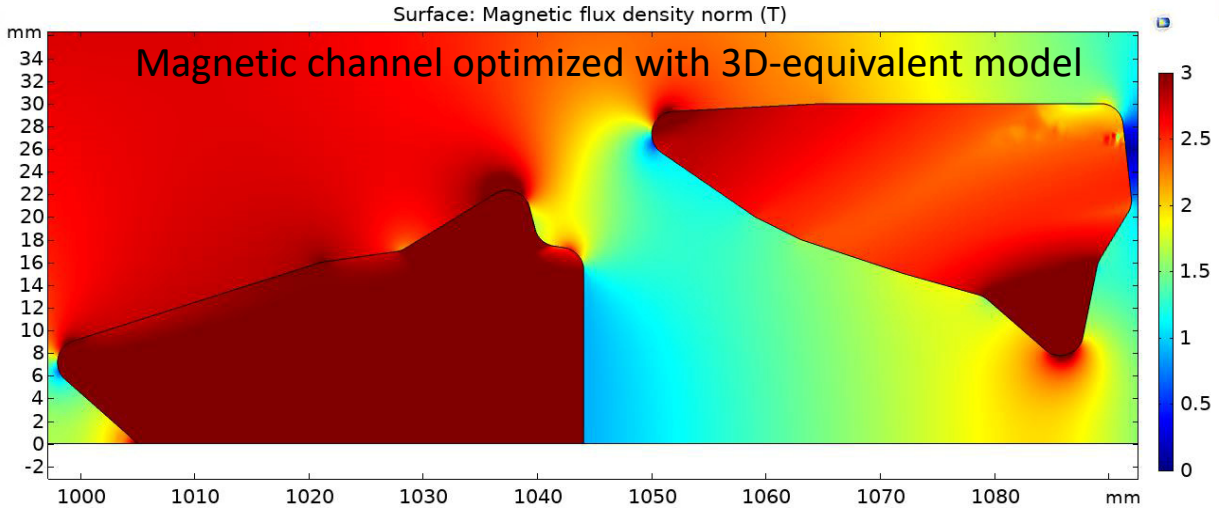


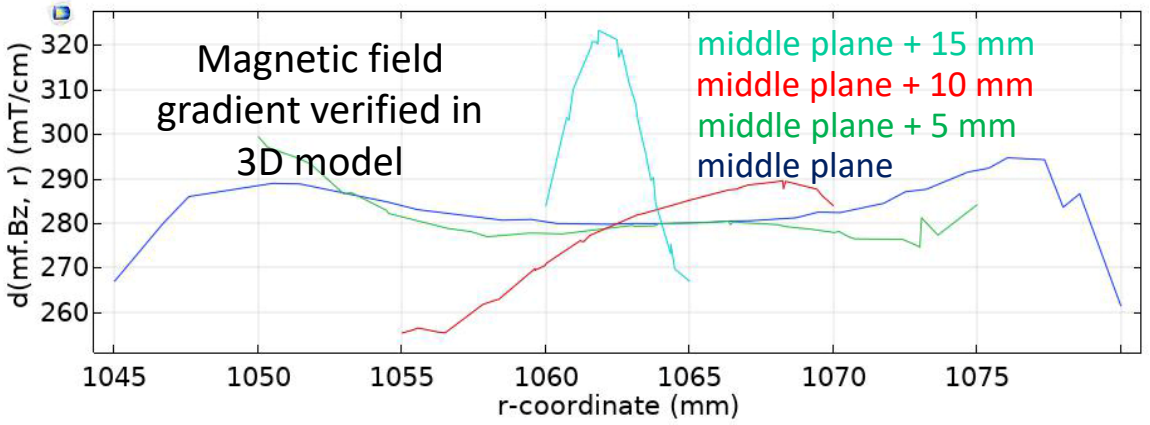
3D-equivalent magnetic environment for magnetic channel optimization



- **3D-equivalent geometrical optimization (genetic algorithm) of first magnetic channel**
- **Huge magnetic field gradient (280mT/cm) obtained by using Cobalt Steel Vanadium Permendur**
- **Excellent uniformity also in the 3D model (inside ±15%)**

MOP014: L. Neri et all., '3D Magnetic Optimization of the New Extraction Channel for the LNS Superconducting Cyclotron'





Improved beam dynamics with optimized first magnetic channel

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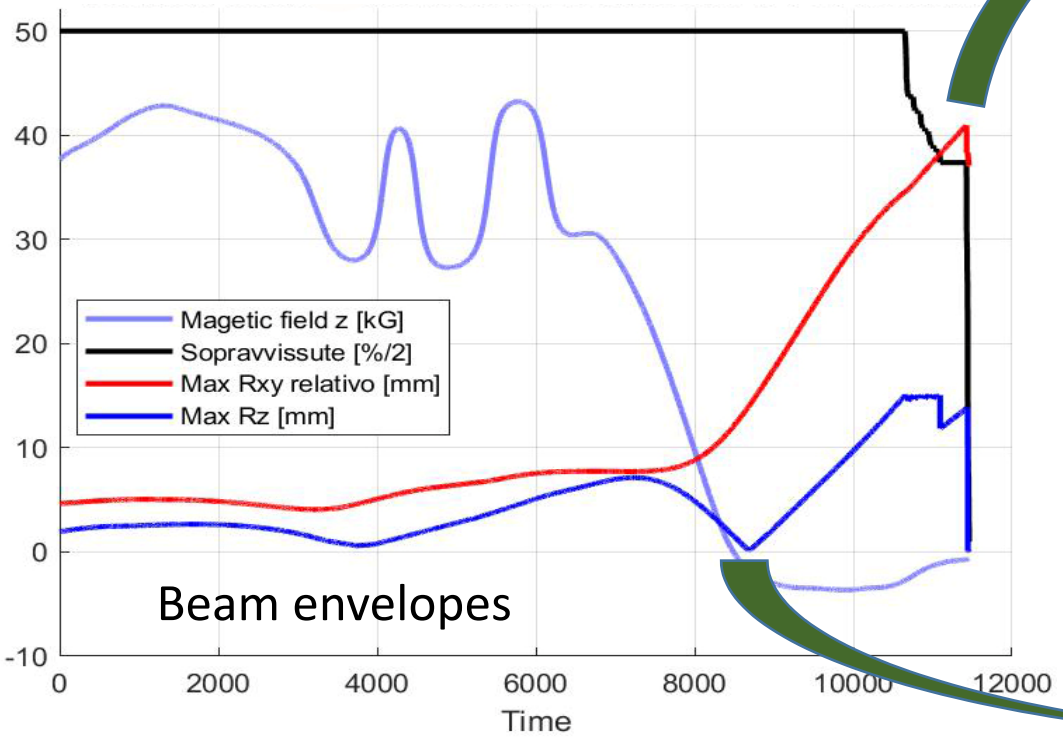
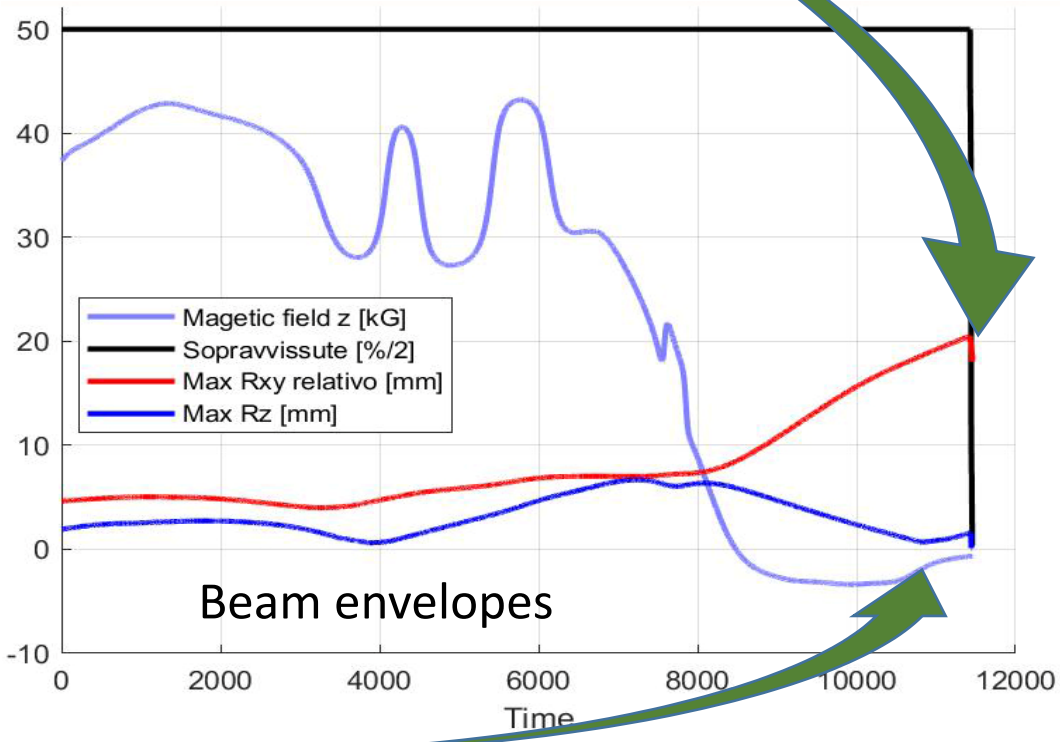
Without magnetic channel



With optimized magnetic channel



MOP014: L. Neri et all., '3D Magnetic Optimization of the New Extraction Channel for the LNS Superconducting Cyclotron'

Improved beam dynamics with optimized first magnetic channel

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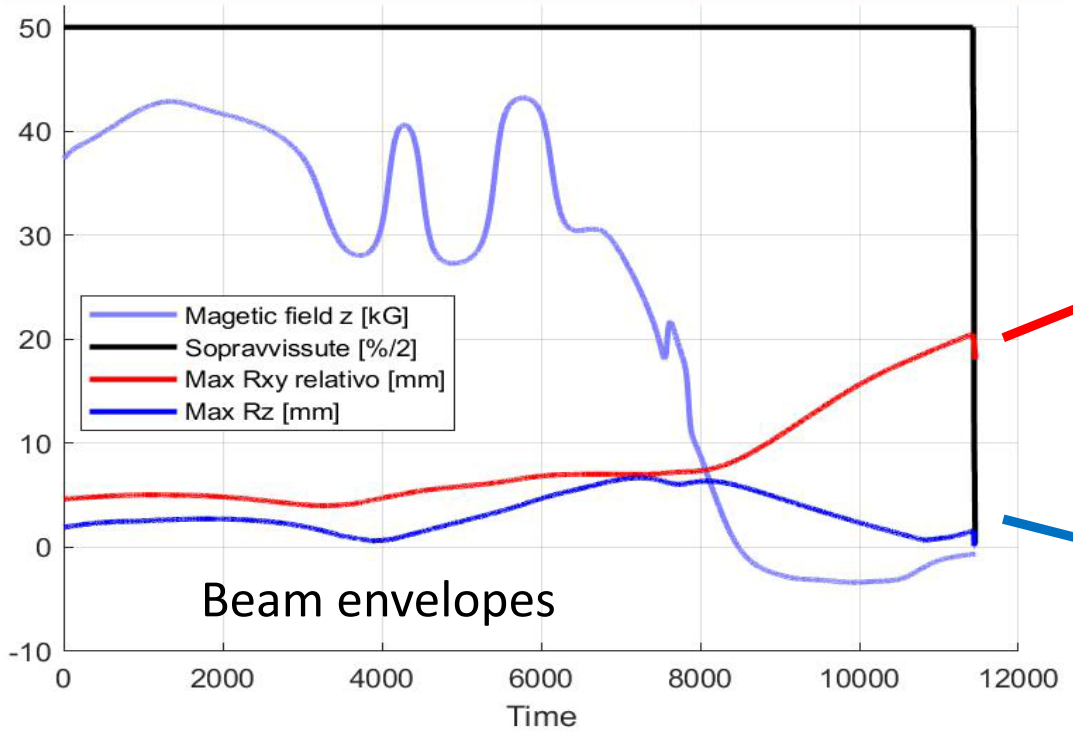
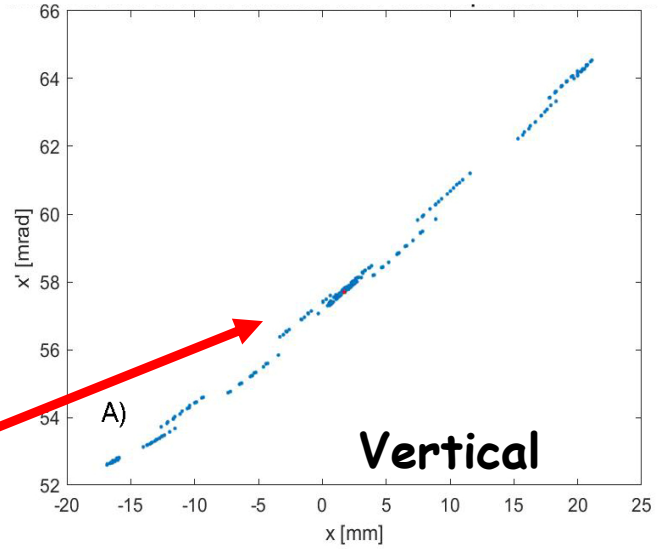
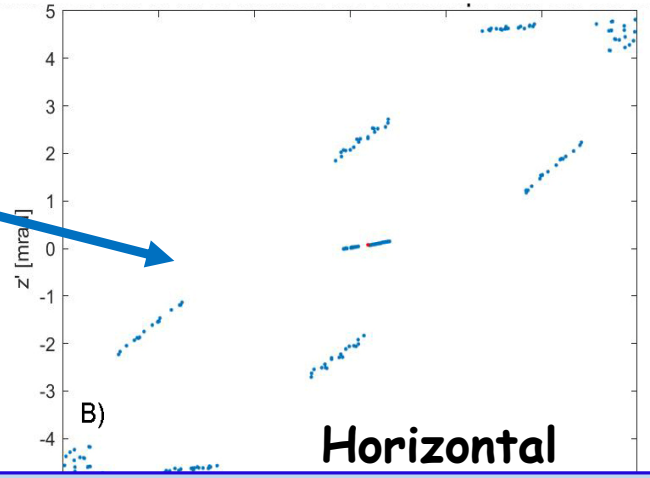
With optimized magnetic channel





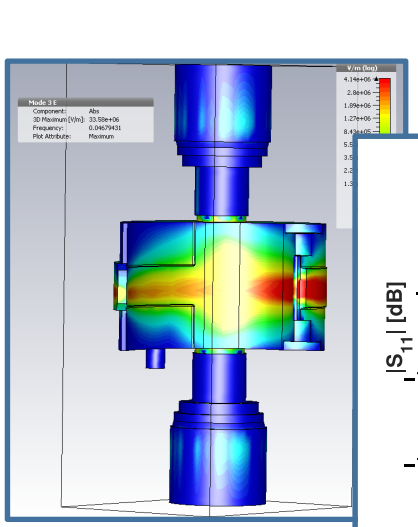


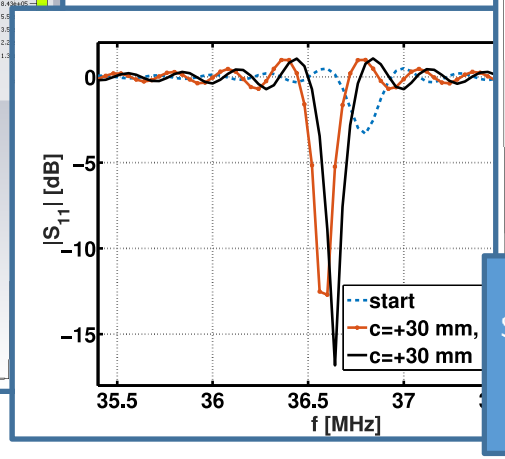
Emittance close to the acceptance of the next optics element

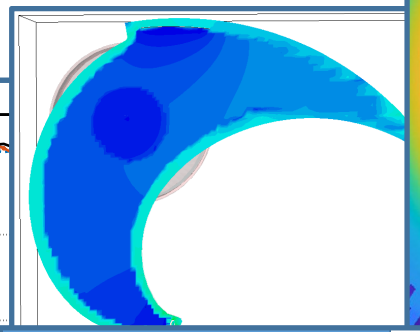
MOP014: L. Neri et all., '3D Magnetic Optimization of the New Extraction Channel for the LNS Superconducting Cyclotron'

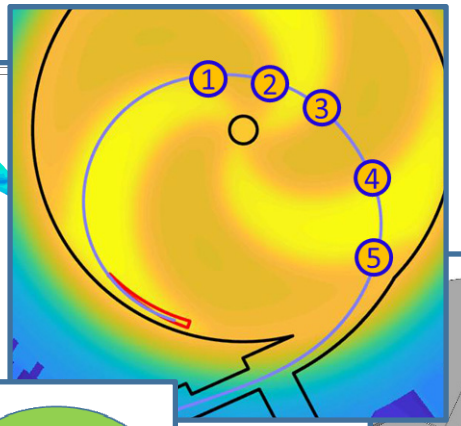
Conclusion

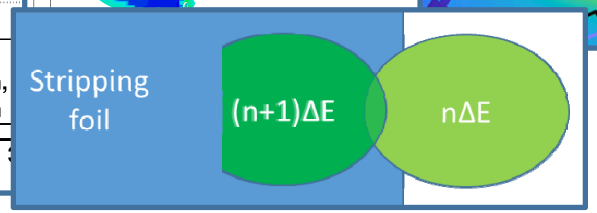
- Upgrade of our cyclotron is well advanced
- RF simulation and beam dynamics code confirms almost all chooses
- Some minor revision, compatible with the procurement status, are ongoing
- RF simulation and beam dynamics code will be merged to achieve the capability to simulate the beam from the injection to the extraction

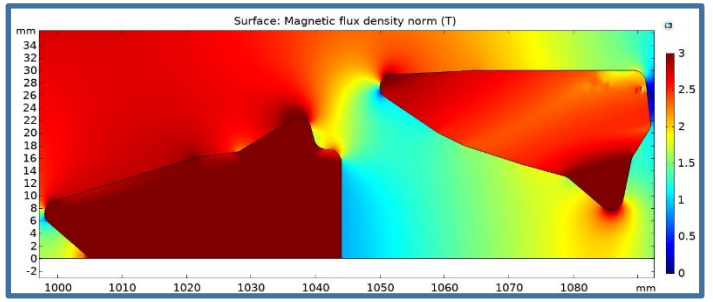


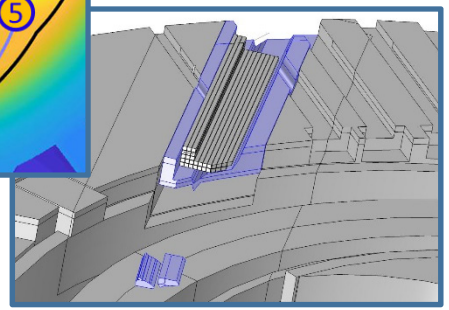


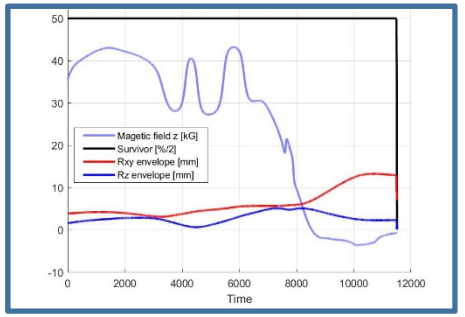












Thanks for the attention

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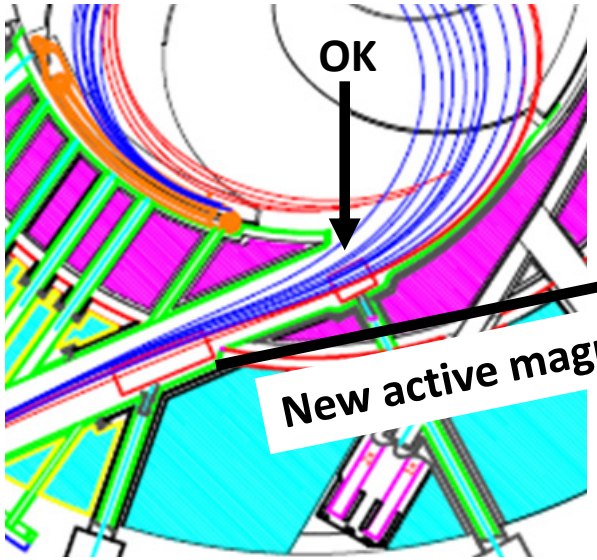
Authors: G. Torrisi, L. Neri, L. Allegra, L. Calabretta, A. Caruso, G. Costa, G. Gallo, A. Longhitano, D. Rifuggiato, (INFN-LNS)

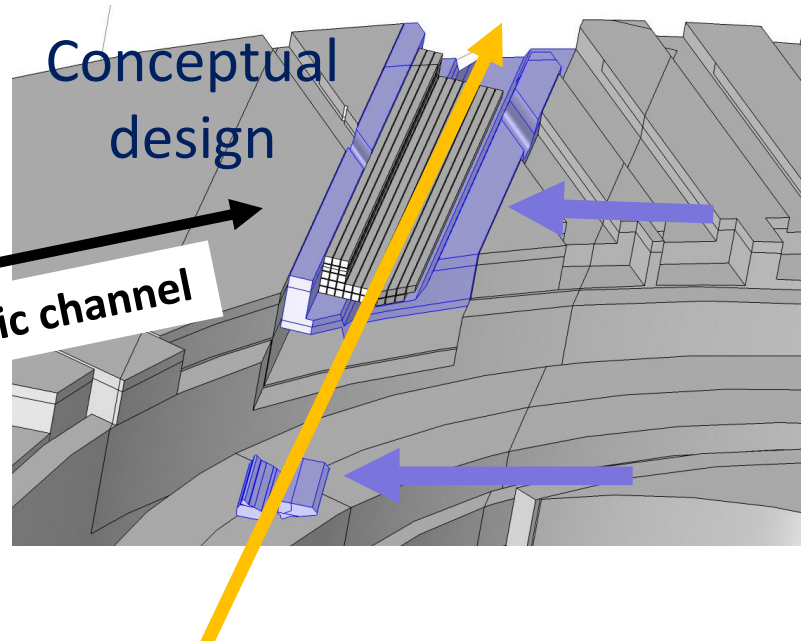
22th International Conference on Cyclotrons and their Applications
September 2019, Cape Town, South Africa

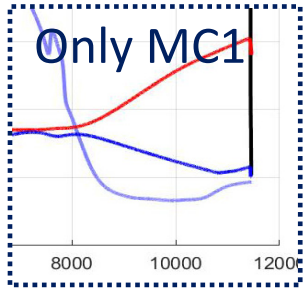
Next actions

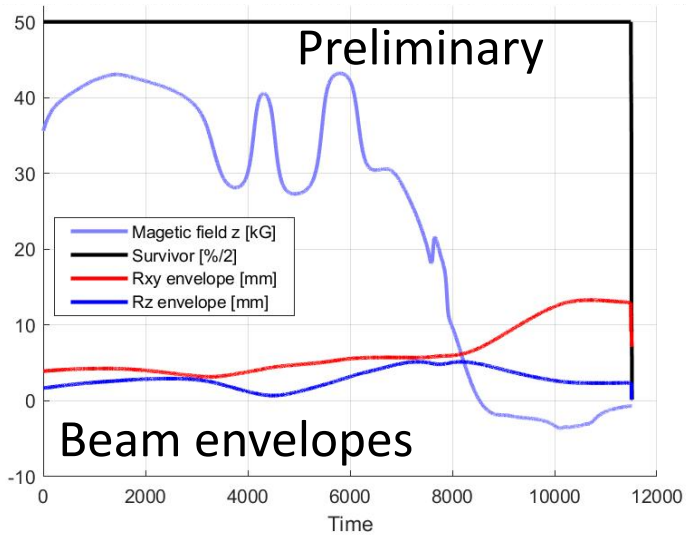
Instead to use a second magnetic channel we are finalizing the design of an **active magnetic channel** composed by a magnetic shielding able to reduce cyclotron stray field and an asymmetric coil able to perform a adjustable gradient that will help in the beam matching with next beam optics element

Cobalt Steel Vanadium permendur:
magnetic channel and magnetic shielding









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