Studies Progress of the High Intensity H_2^+ Cyclotrons for DAEδALUS and IsoDAR Projects

J.J. Yang (CIAE)

For the DAEδALUS Collaboration

Acknowledgements: A. Adelamnn (PSI), J. Alonso (MIT), L. Calabretta (INFN)
A. Calanna (MIT), D. Campo (MIT), J. Conrad (MIT)

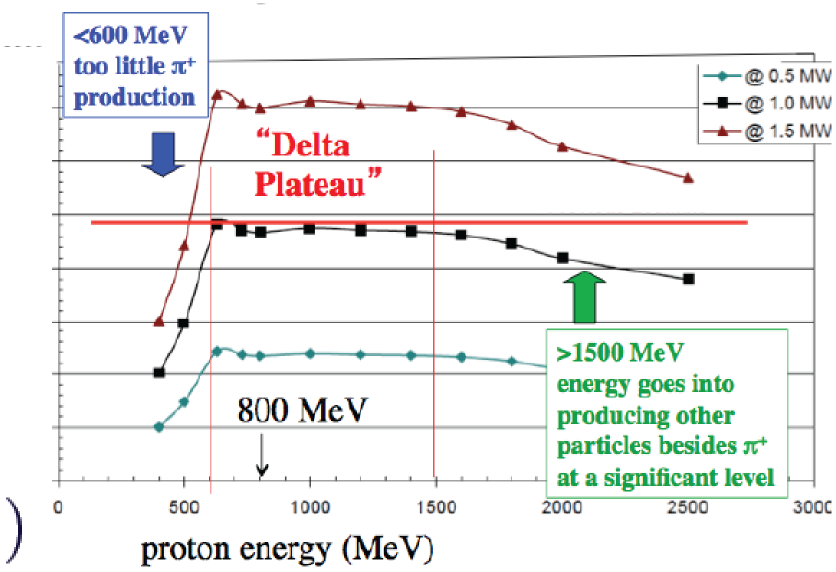
The XV^th NuFact Workshop, Aug. 20, 2013

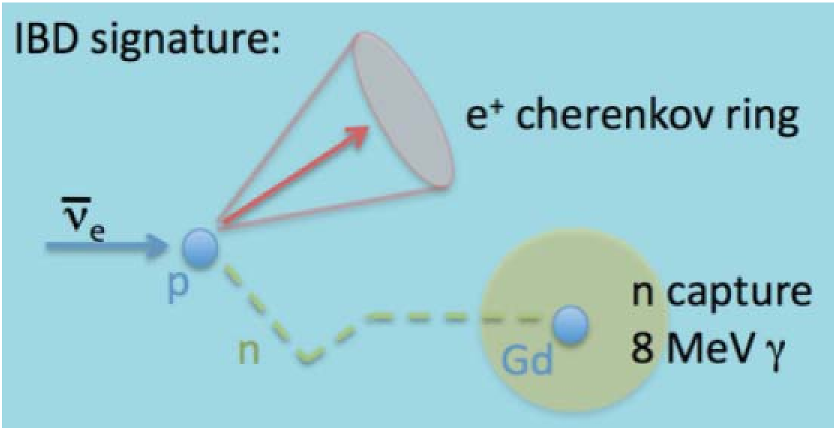
Outline

- DAEδALUS & IsoDAR in Brief
- Cyclotron Design Progress
- Experimental Testing of Design

The DAEδALUS experiment

- 800 p MeV is nicely at the plateau of the delta resonance
  - $p + C \to \pi^+ \to \nu_\mu + \mu^+$
  - $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$
- trade energy versus intensity
- Low $\bar{\nu}_e$ contamination $\mathcal{O}(10^{-4})$
- complementary to LBNE (ν mode)
- Method of detection inverse β-decay: $\bar{\nu}_e + p \to e^+ + n$





The DAEδALUS experiment

Decay-At-rest Experiment for δ_{CP} studies At the Laboratory for Underground Science

What do we want to study: oscillation from $\bar{\nu}_\mu$ to $\bar{\nu}_e$

We want to see whether δ is nonzero

$$\begin{aligned}P_{\mu\to e} &= \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31} \\ &\mp \underline{\sin\delta}\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin^2\Delta_{31}\sin\Delta_{21} \\ &+ \underline{\cos\delta}\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21} \\ &+ \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta_{21} \qquad (1)\end{aligned}$$

where $\Delta_{ij} = \Delta m^2_{ij}L/4E_\nu$. In the second term, the $-(+)$ refers to neutrino (antineutrino) running.

- critical parameter size of θ_{13}, now global average $8.75^\circ \pm 0.43^\circ$
- short base line $\rightarrow$ no dependence on sign of Δm^2_{31}
- CP violation comes in through the inference between Δ_{12} and Δ_{13}

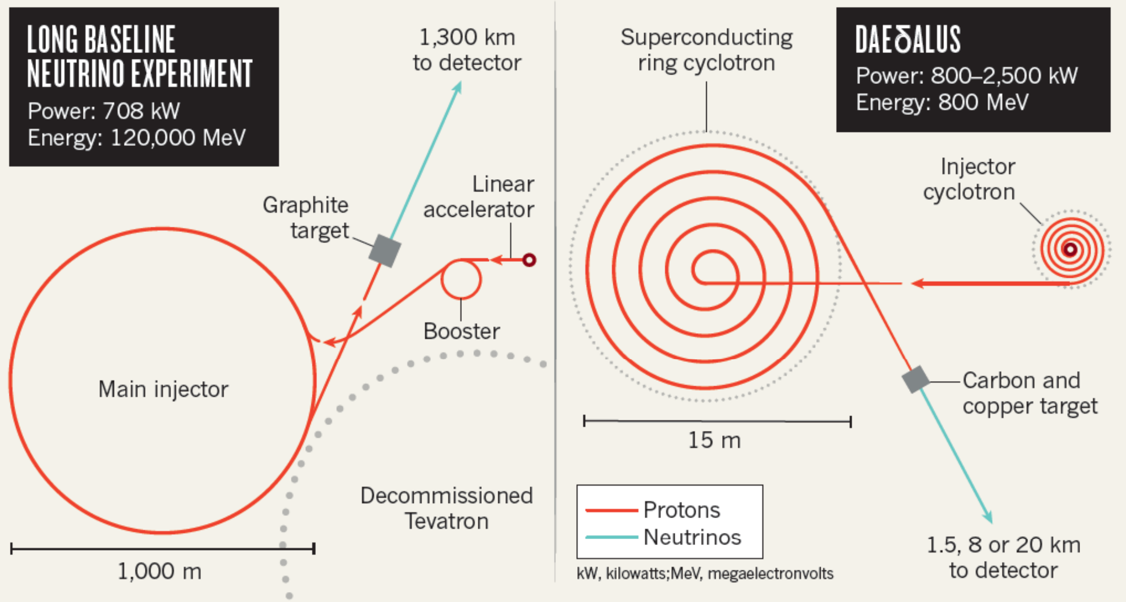
For more physics, refer to [J. M. Conrad, M. H. Shaevitz PRL 104, 141802 (2010)]

The DAEδALUS experiment

NEWS IN FOCUS

CYCLOTRONS RECYCLED

By bringing back cyclotrons, an 80-year-old technology, DAEδALUS could challenge the Long Baseline Neutrino Experiment's attempt to look for fundamental matter–antimatter asymmetries using neutrinos.



PARTICLE PHYSICS

Cyclotrons come full circle

could repurpose the Tevatron's luminous proton beams and establish an 'intensity frontier'.

Fermilab quickly developed plans for a flagship intensity experiment, called the Long Baseline Neutrino Experiment (LBNE). It would send beams of neutrinos and antineutrinos along a 1,300-kilometre underground path to a detector in the Homestake mine near Lead, South Dakota. Neutrinos and antineutrinos are thought to behave the same in nearly every way, but the LBNE would look for crucial differences. It would monitor the way in which the three different types of neutrino morph, or oscillate, into one another as they travel along the beam, and then repeat the experiment, this time with a beam of antineutrinos. Any detected difference would indicate a fundamental asymmetry — helping to explain why the Universe contains so much more matter than antimatter.

In 2012, the DOE asked Fermilab to strip down these ambitious plans (see *Nature* **485**, 16; 2012). Fermilab came back with a design that would cost about $800 million in its first phase. But many physicists are concerned that the scaled-back experiment will be less precise.

DAEδALUS is now emerging as a lower-cost alternative to test for matter–antimatter asymmetry. In this plan, near-stationary protons would be dumped in the centre of a small cyclotron and accelerated by magnetic fields

[E. Reich, Nature, Vol.499, p.391, 25 July (2013)]

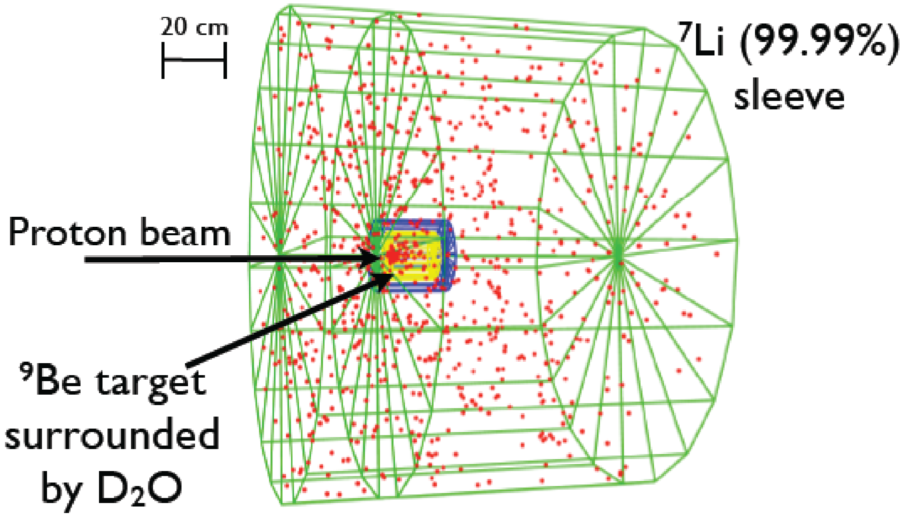
The IsoDAR Experiment

using the Injector cyclotron of DAEδALUS to search sterile neutrino

What do we want to study: $\bar{\nu}_e$ disappearance due to oscillations $\rightarrow$

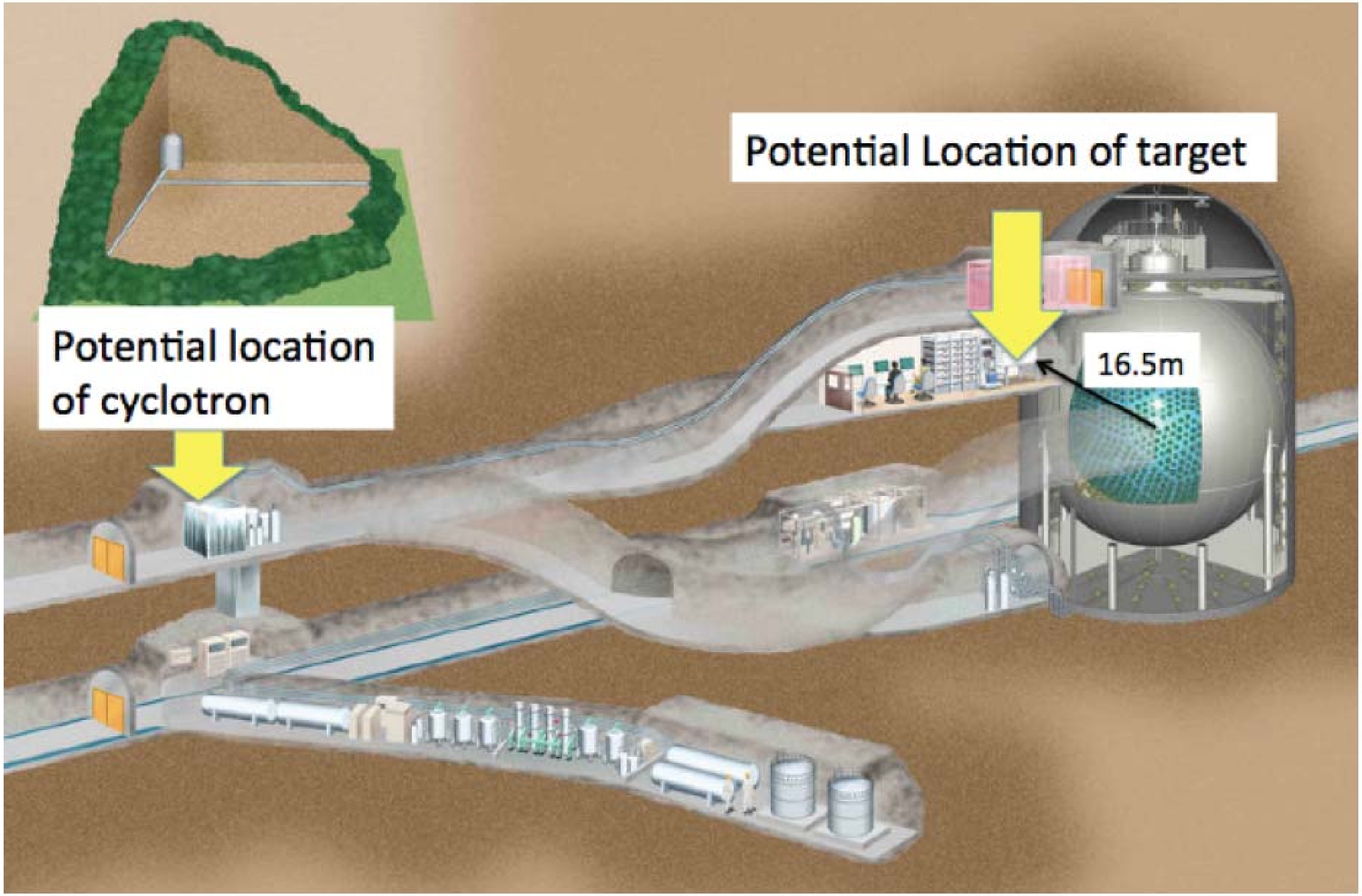
- high sensitive sterile neutrino search (distinguish 3+1, 3+2 models)
- non-standard interaction form ν_e scattering

- p(60 MeV)+^{9}Be$\rightarrow$^{8}Li+2p + n
- n+^{7}Li$\rightarrow$^{8}Li
- β decay: ^{8}Li$\rightarrow$^{8}Be+e$^-$ $\underline{+\ \bar{\nu}_e}$
- $< E_{\bar{\nu}_e} >= 6.4$ MeV
- IBD in liquid scintillator-based detect



[A. Bungau, et al., PRL 109 141802 (2012)]

A Possible Home for IsoDAR is at KamLAND



!!! this is a sketch only !!!

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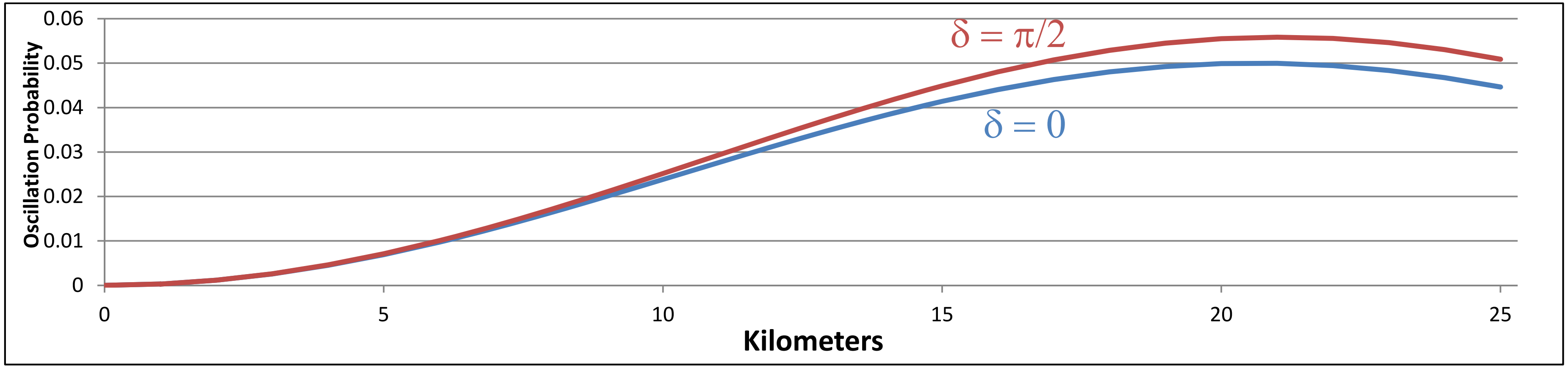
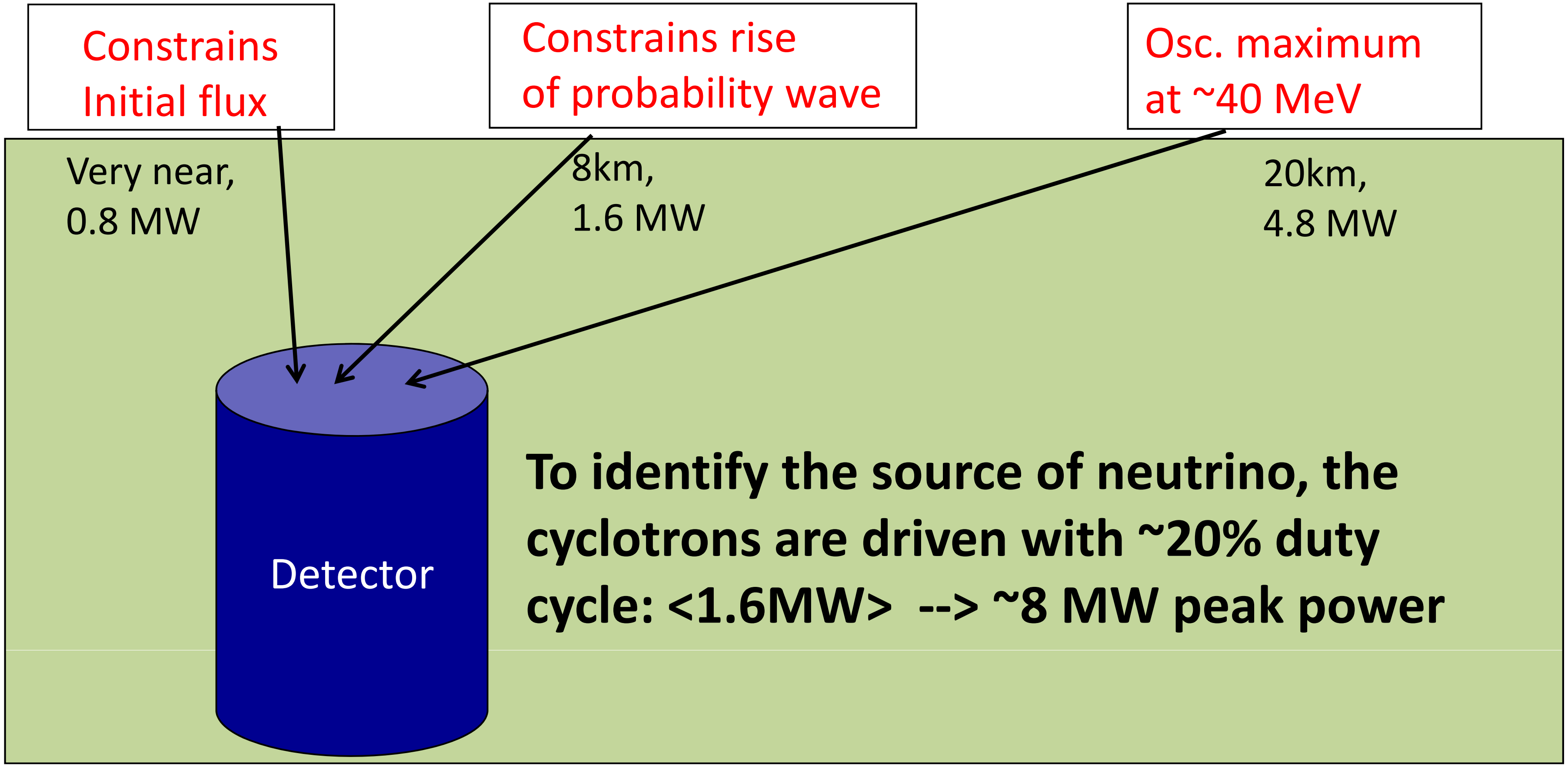
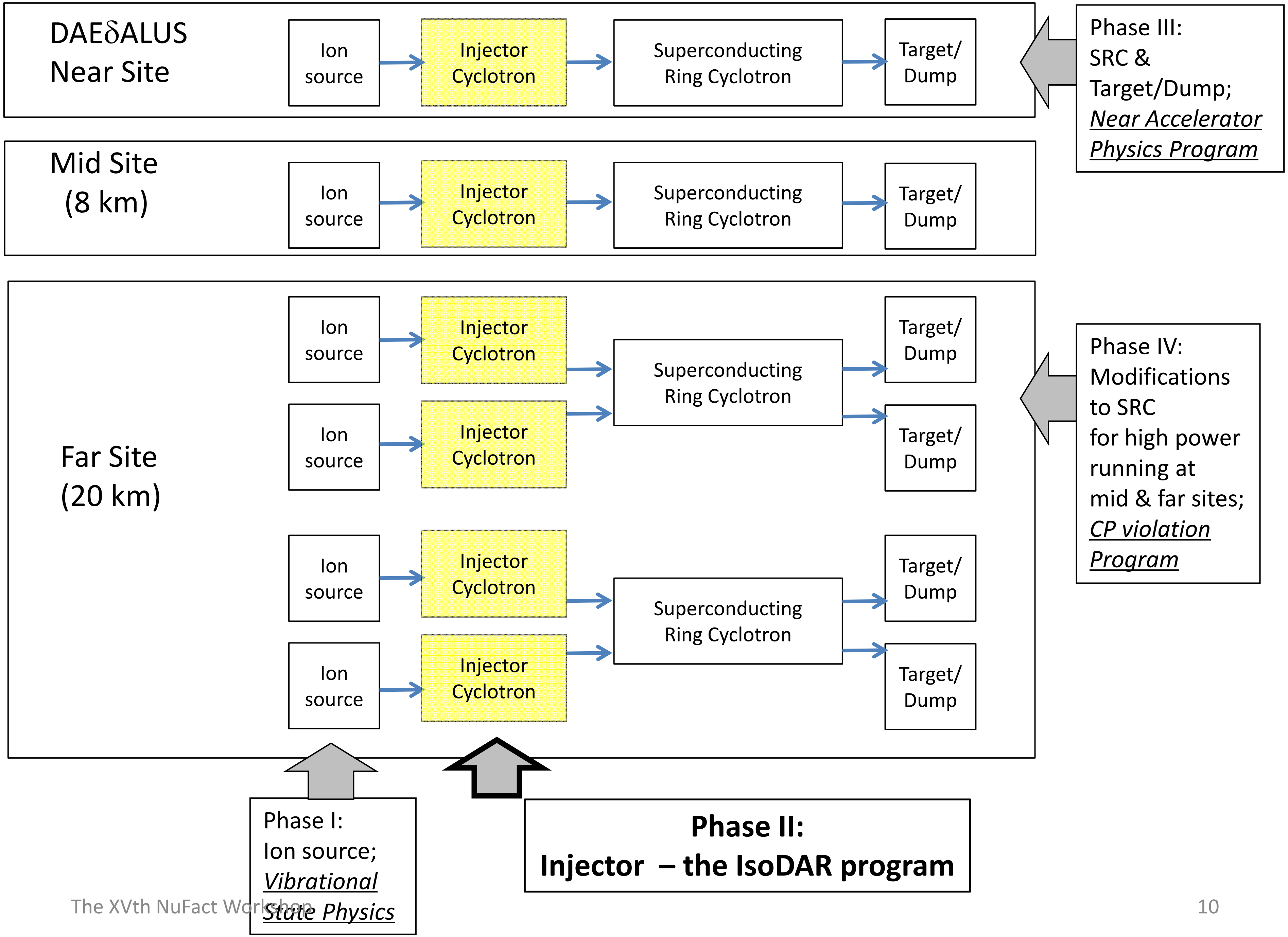
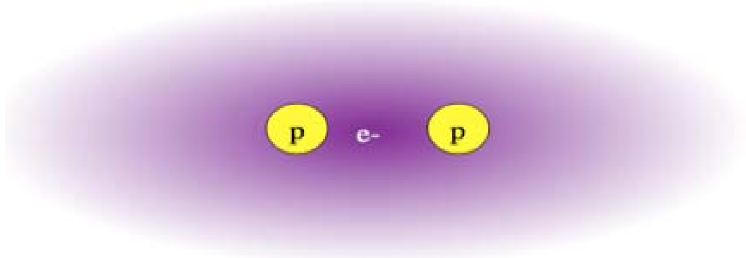

Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
25
Kilometers
δ = π/2
δ = 0


Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV
Very near, 0.8 MW
8km, 1.6 MW
20km, 4.8 MW
Detector
To identify the source of neutrino, the cyclotrons are driven with ~20% duty cycle: <1.6MW> --> ~8 MW peak power

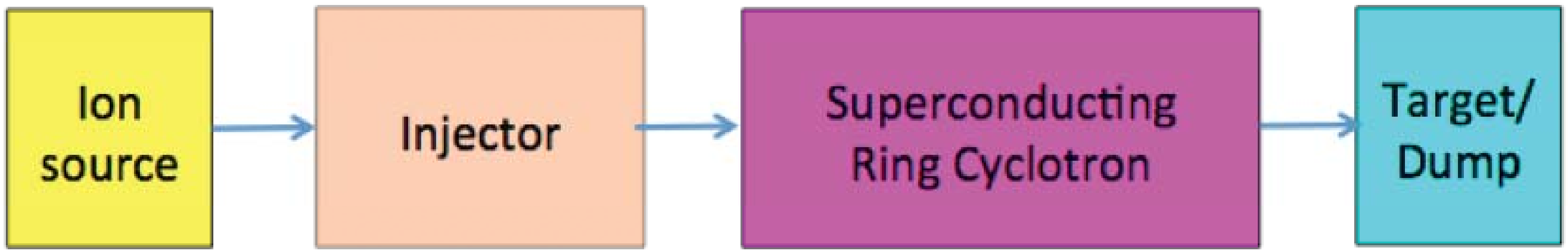

DAEδALUS
Near Site
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Mid Site
(8 km)
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Far Site
(20 km)
Ion source
Injector Cyclotron
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Target/ Dump
Ion source
Injector Cyclotron
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Target/ Dump
Phase III: SRC & Target/Dump; *Near Accelerator Physics Program*
Phase IV: Modifications to SRC for high power running at mid & far sites; *CP violation Program*
Phase I: Ion source; *Vibrational State Physics*
Phase II: Injector – the IsoDAR program

Accelerator Requirement

- 800 MeV p on target
- power on target: 1, 2 and 5 MW on the three sites
- size small
- cost effective
    - construction & operation
    - modules

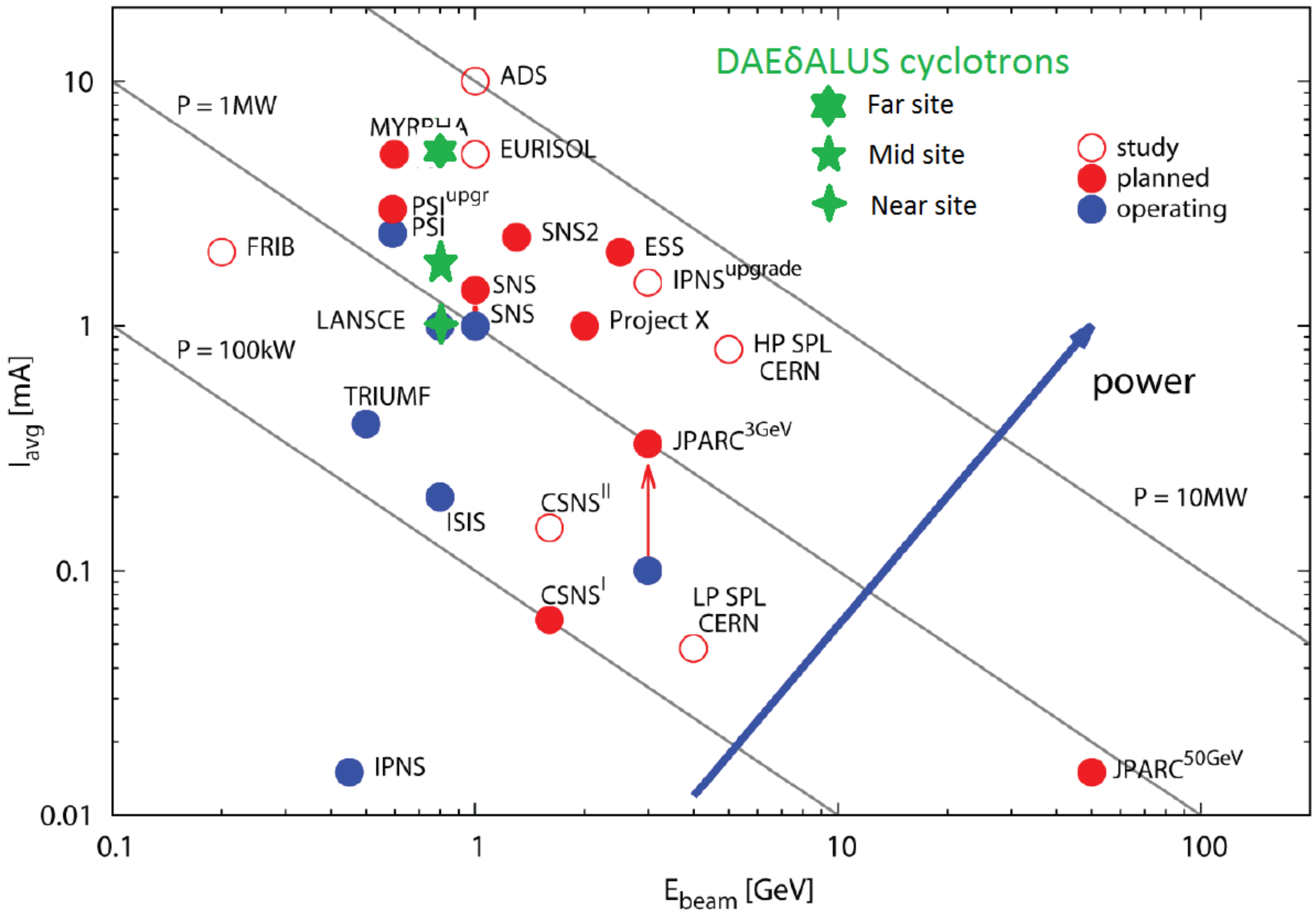


- our approach H_2^+ Cyclotron design (L. Calabretta arXiv:1107:0652)
    - relaxes space charge, 2p per unit of charge 1+
    - allows to extract with a stripping process



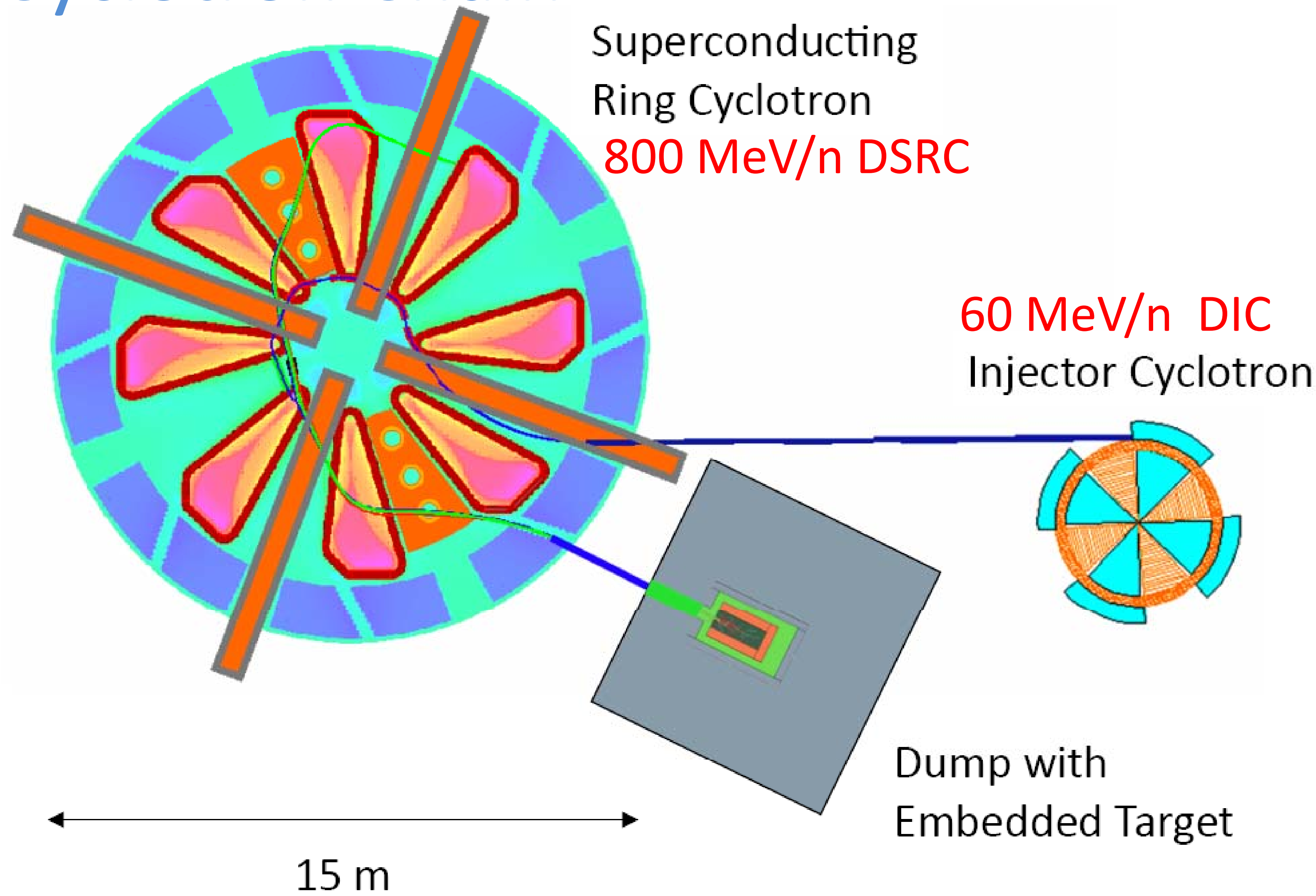
[A. Adelmann et al. arXiv:1207.4895]

Proton Beam Power Requirement



PSI 590MeV cyclotron is current world proton beam power leader with 1.4 MW on target.

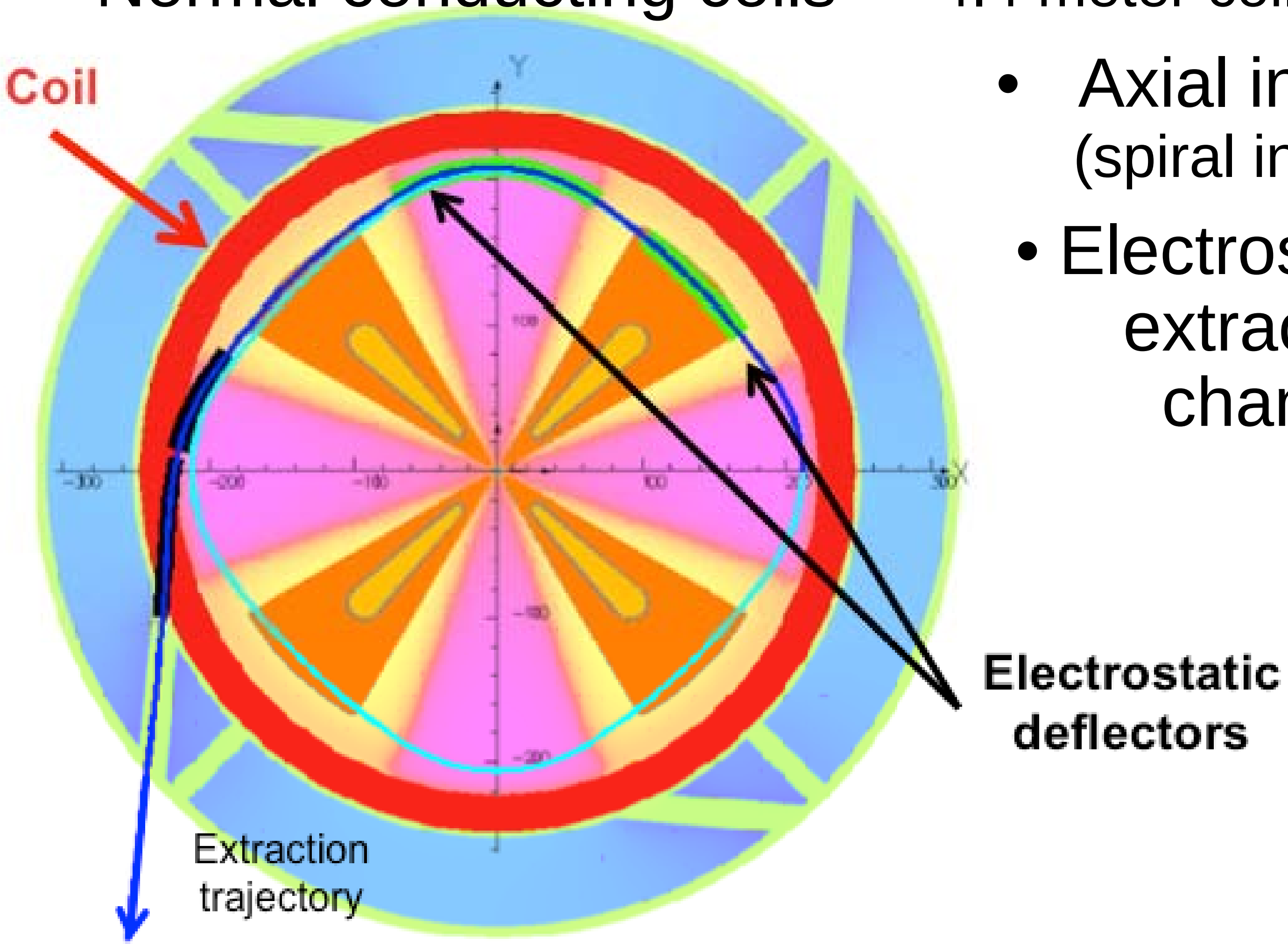
Cyclotron Chain



The result is a decay-at-rest-flux
That can be used for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches

Injector Cyclotron DIC

- 60 MeV/n, peak current 5 mA H_2^+
- Normal conducting coils ~ 4.4 meter coil diameter



- Axial injection (spiral inflector)
- Electrostatic extraction channel

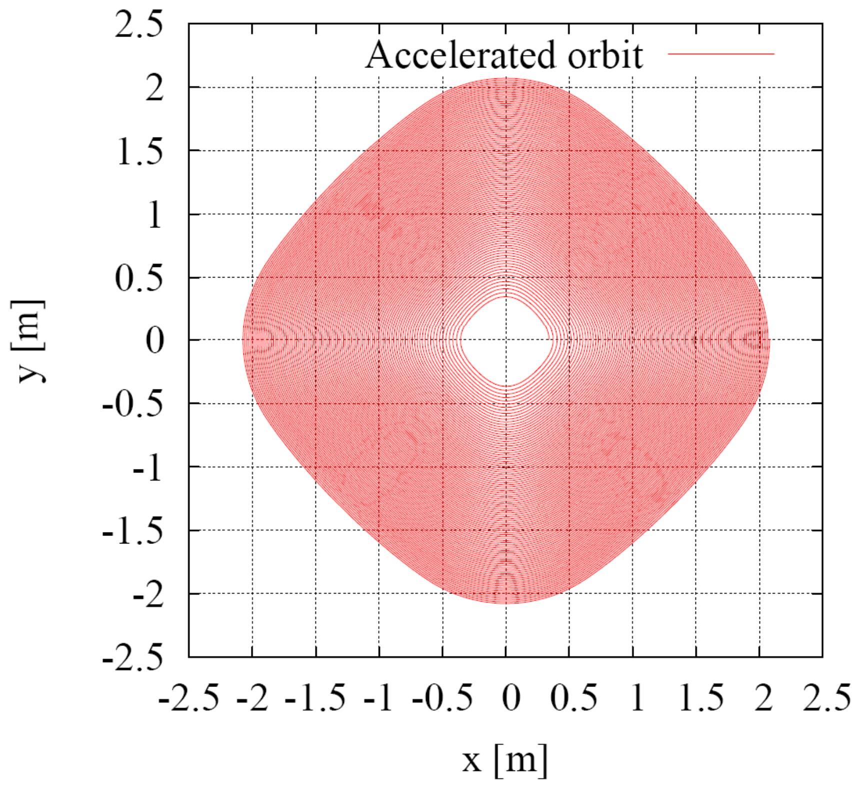
arXiv: 1207.4895

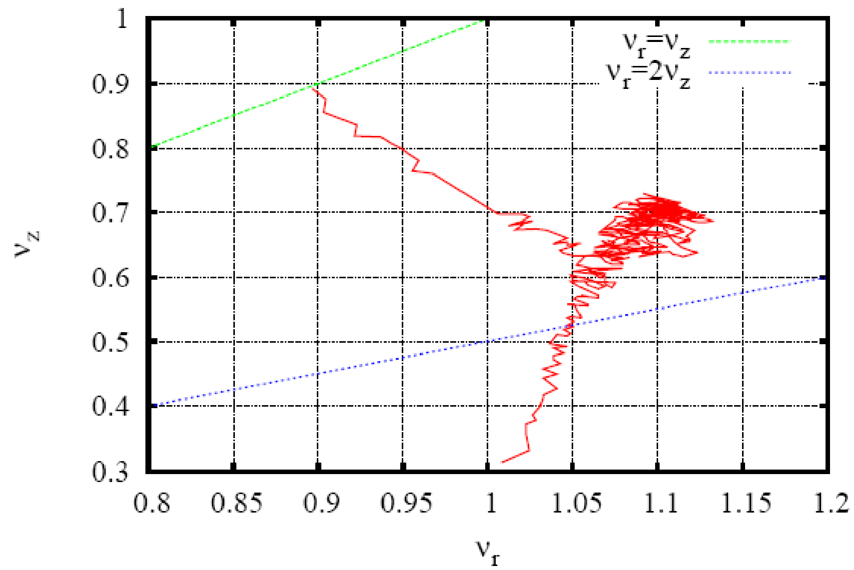
DIC Design Parameters

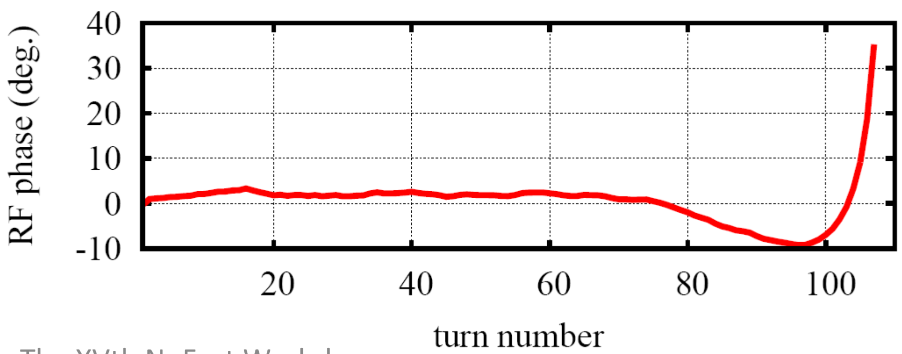
E_{max}	60 MeV/amu	E_{inj}	35 keV/amu
R_{ext}	1.99 m	R_{inj}	55 mm
$< B >$ @ R_{ext}	1.16 T	$< B >$ @ R_{inj}	0.97 T
Sectors	4	Hill width	28 - 40 deg
Valley gap	1800 mm	Pole gap	100 mm
Outer Diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	$\lambda/2$, double-gap
Harmonic	6th	RF-frequency	49.2 MHz
Acc. Voltage	70 - 250 kV	Power/cavity	< 110 kW
ΔE/turn	1.3 MeV	Turns	107
ΔR /turn @ R_{ext}	20 mm	ΔR/turn @ R_{inj}	> 56 mm
Coil size	200x250 mm^2	Current density	3.1 A/mm^2
Iron weight	450 tons	Vacuum	$< 10^{-7}$ mbar

[D. Campo, et. al, IPAC'12]

Basic Facts of the DIC

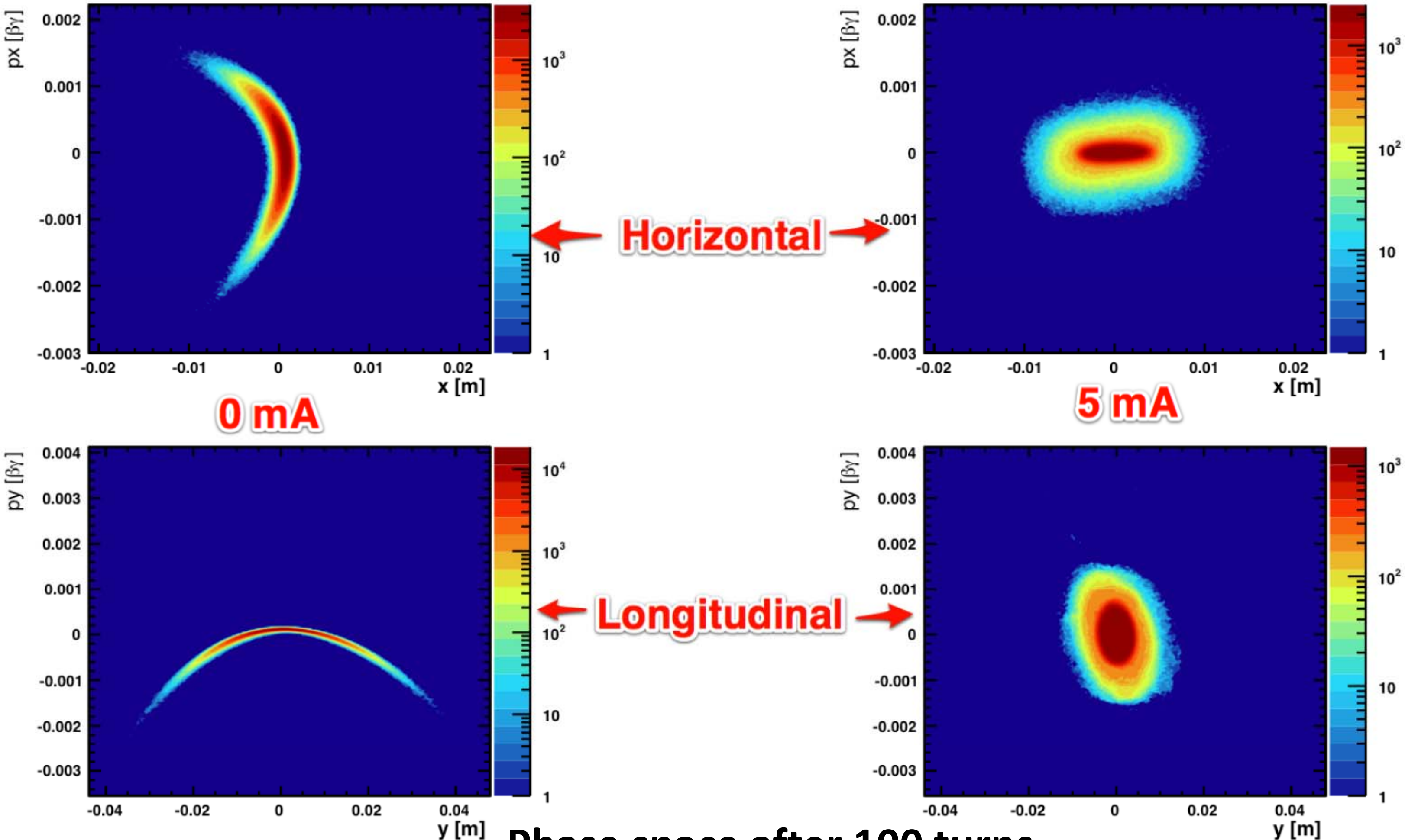






- Compact cyclotron with axial injection @ 35 keV/amu H_2^+
- Reach 61.7 MeV/n in 107 turns with 4 double-gap cavities
- Maximal average radius 2.1 m (3.7 m for PSI Injector 2)
- Single turn extraction with electrostatic deflector
- Integrated phase slipping less than $< 20^\circ$ during accelaration

Space Charge Effects in the DIC



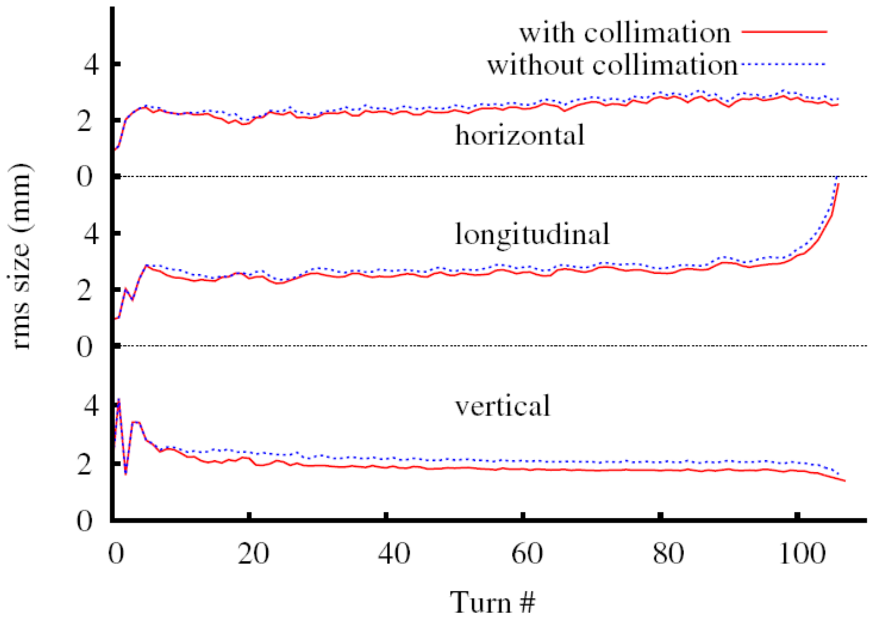
Phase space after 100 turns

Observation: The beam transport in the DIC is space-charge-dominated

Acceleration Simulation in the DIC

OPAL simulation settings

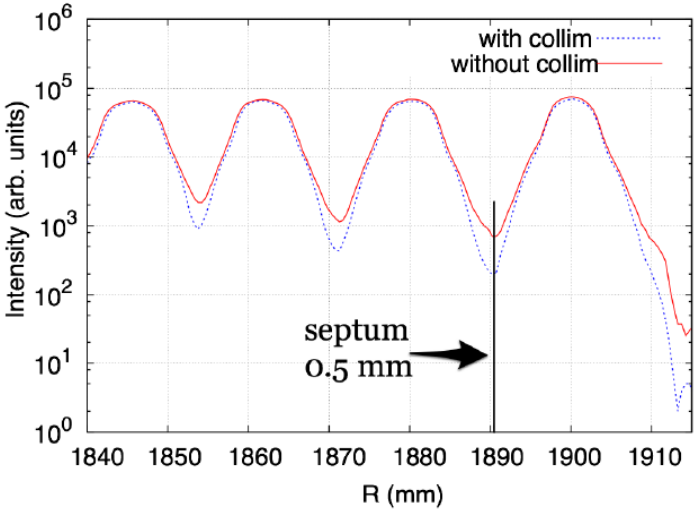
- Start at the exit of central region
- $\epsilon_n(2\sigma)$=0.6 πmm-mrad in the transverse directions
- Assume phase acceptance of $10°$
- Initial energy spread of 0.4% (2σ)
- Different collimation schemes are studied, preferred solution is 4 collimators at 1.9 MeV/n, cutting 10% particles
- Gaussian distribution with 10^6 macroparticles
- 64^3 grid for space charge calculation



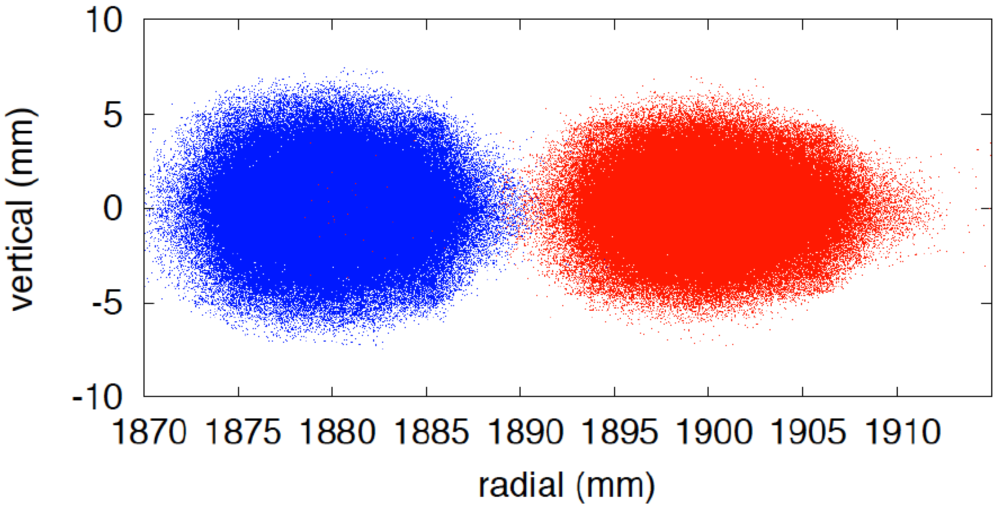
1. Radial size increased slowly
2. Longitudinal size increase slowly $\rightarrow$phase width compressed
3. Phase shift destroys longitudinal space charge focusing at last turns

[J. J. Yang, et al., NIM-A 704, (2013)]

Single-turn Extraction in the DIC



Last 4 turns' radial profile



r-z projection of last 2 turns with collim.

rms parameter	r mm	z mm	$\epsilon_{r,n}$ πmm-mr	$\epsilon_{z,n}$ πmm-mr	θ deg	$\Delta E/E$ %
Inj.	0.84	1.85	0.15	0.15	1.67	0.2
Ext. (collim.)	2.55	1.22	0.37	0.35	1.34	0.16
Ext. (no collim.)	2.75	1.46	0.43	0.49	1.50	0.17

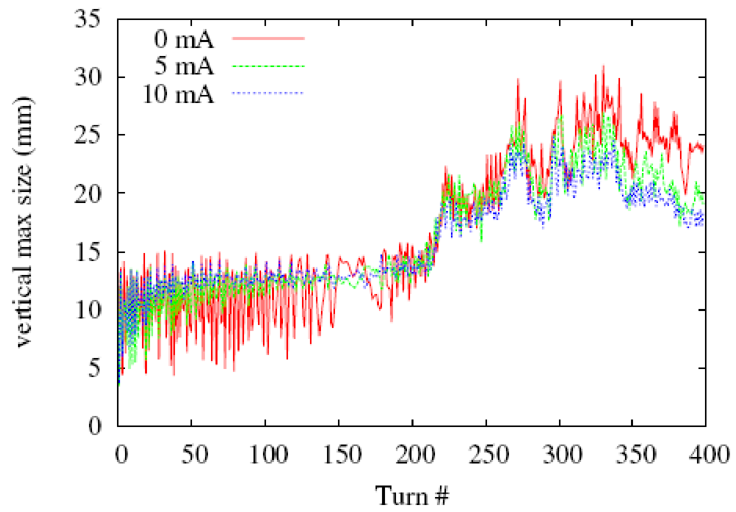
Observation: 5 mA H+2 beam can be extracted with the extraction efficiency of 99.98%, (120W for 100% duty cycle), which is acceptable

DSRC Design Parameters

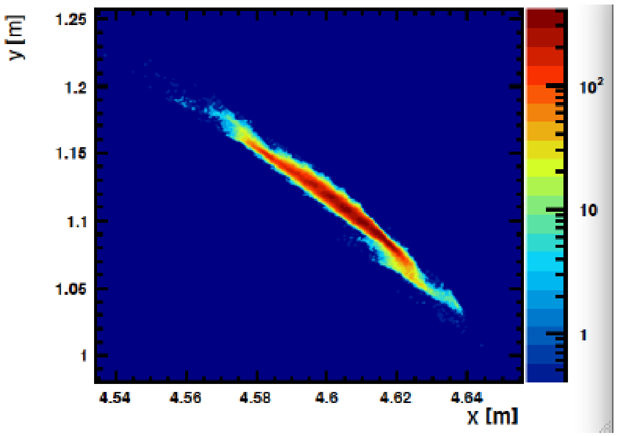
E_{max}	800 MeV/amu	E_{inj}	60 MeV/amu
R_{ext}	4.9 m	R_{inj}	1.8 cm
$< B >$ @ R_{ext}	1.88 T	$< B >$ @ R_{inj}	1.06 T
Sectors	8	Hill width	23 deg
B_{max}	6.05 T	Pole gap	60 mm
Outer Diameter	14 m	Full height	5.6 m
Cavities	6	Cavity type	Single gap (4)
			Double gap (2)
Harmonic	6th	RF-frequency	49.2 MHz
Acc. Voltage	550-1000 kV	Power/cavity	300 kW
ΔE/turn	3.6 MeV	Turns	420
ΔR /turn @ R_{ext}	5 mm	ΔR/turn @ R_{inj}	$>$ 10 mm

[A. Calanna et al., IPAC'12]

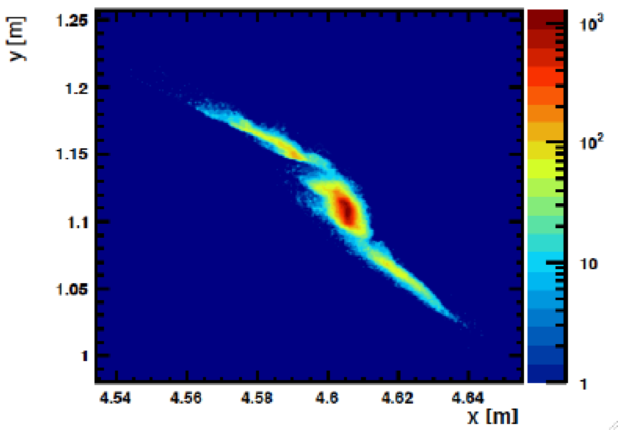
Space Charge Simulation



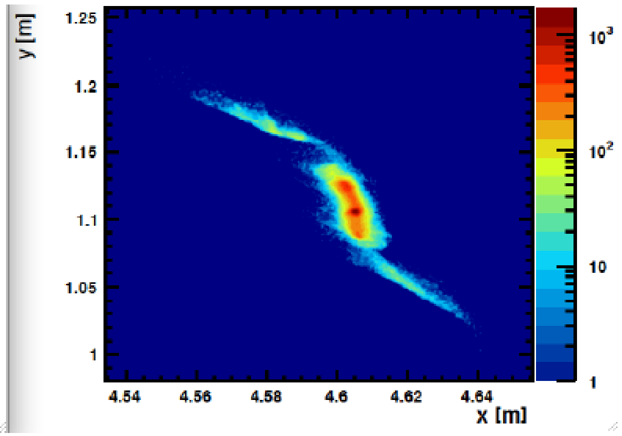
1. Energy reaches 800MeV/n in 400 turns
2. Vertical beam extent < 30 mm (hill gap is 80 mm)
3. Stationary compact shape is not developed, full length ≈ 20 cm !
4. SC force splits beam into 3 sub bunches longitudinally



0 mA



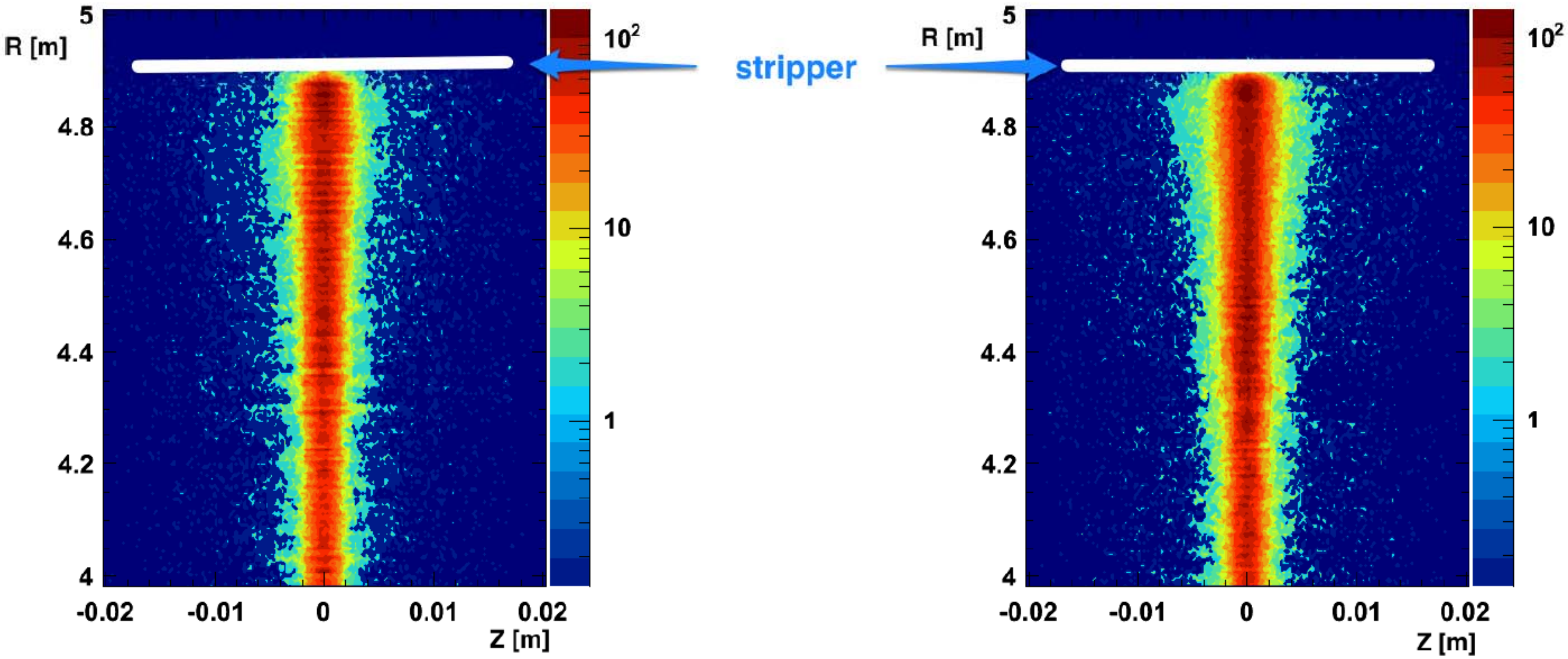
5 mA



10 mA

[J.J. Yang, et al., NIM-A 704, (2013)]

Multi-bunches Simulation



0 mA 5mA

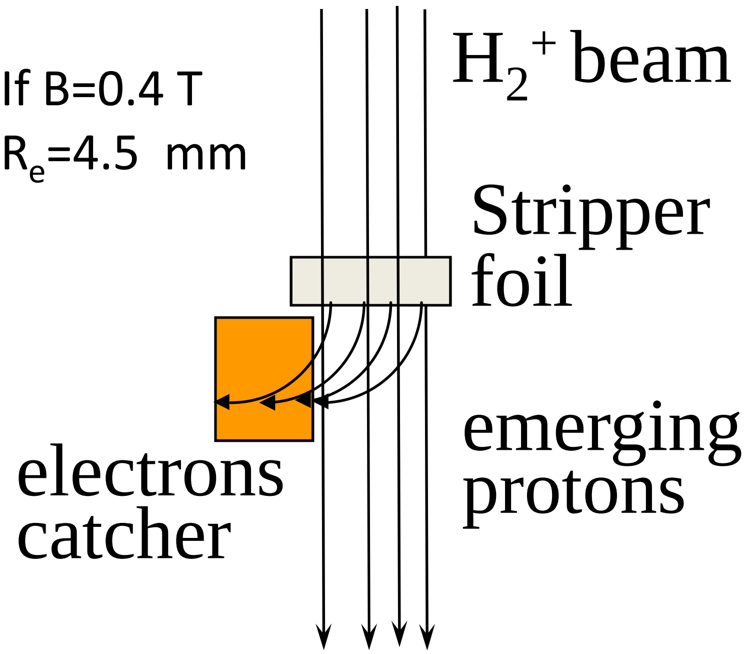
- SC and NB introduce vertical beam halo, but the influence is small
- Beam halos extends vertically to ± 20 mm, still far away from the magnet sector and vacuum chamber (hill gap is 80 mm)

Stripping Process

- Stripper foil: 5 MW beam @ 800 MeV hitting a stripper foil 1 mg/cm^2 thick releases ~ 45 W due to nuclear interaction!
- The electrons removed by the strippers have a full power of 1370 W !
- Electrons are the main source of stripper damage, but can be stopped before strike the stripper

If B=0.4 T

R_e=4.5 mm



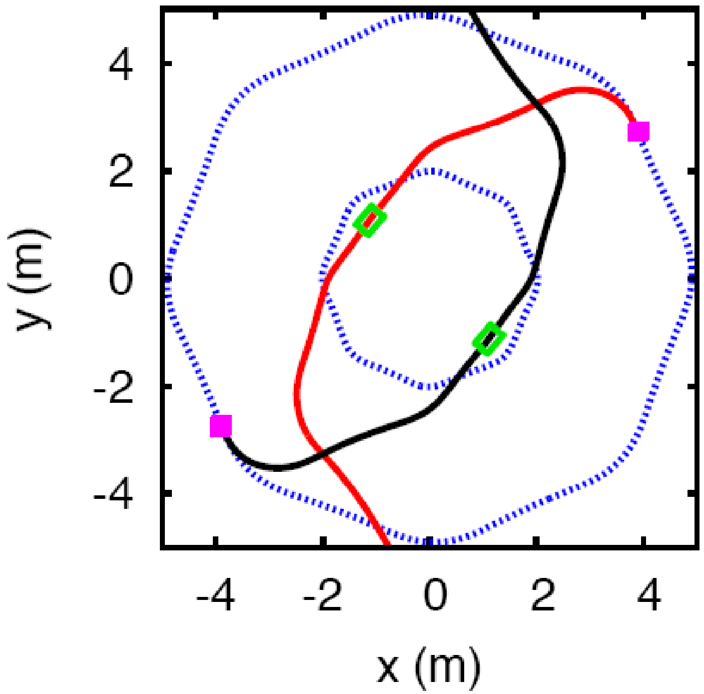
Stripper Thickness can be also thinner than that for H- beam , because:

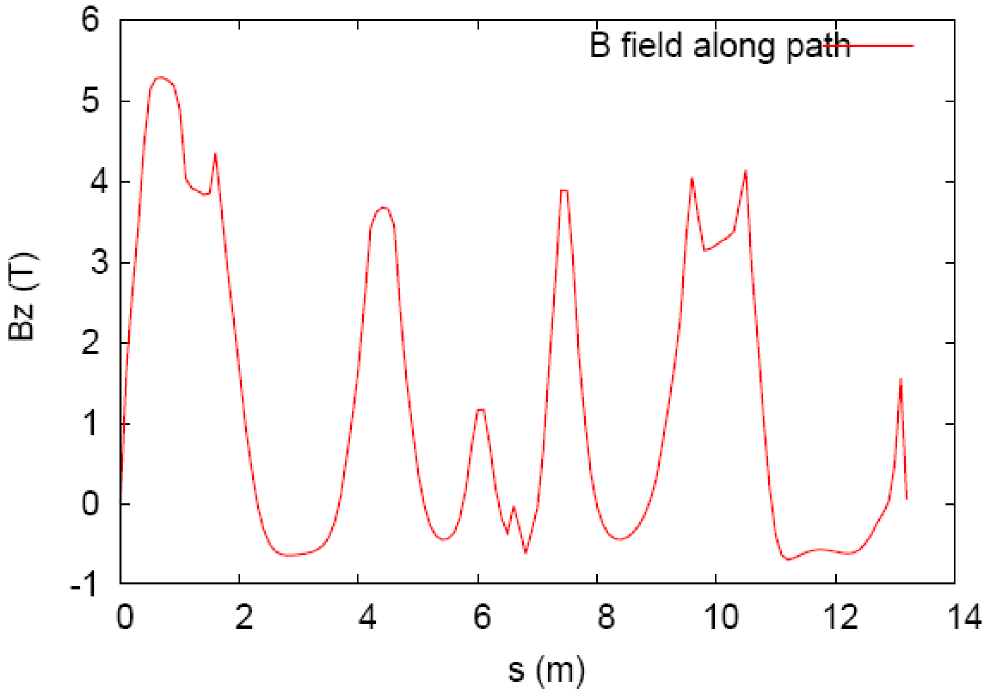
H- =(p+e+e) → p, e, e is a two steps process

H2+ =(p+p+e)→p, p, e is a single step process

[L. Calabretta]

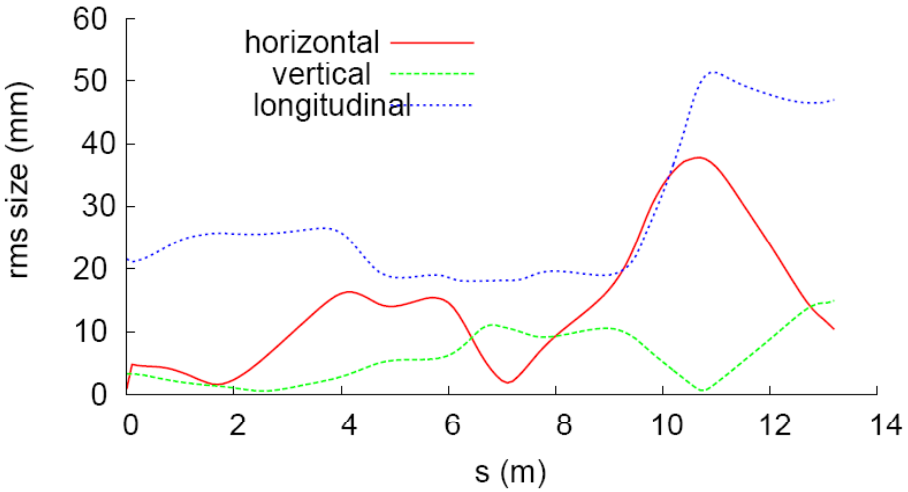
10 mA Proton Beam Extraction





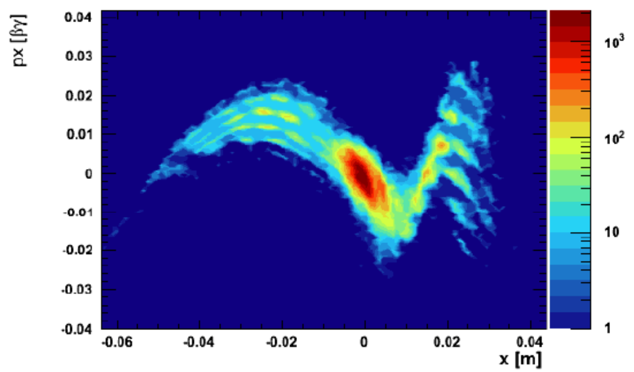
- Protons experiences complicated bending fields including nonlinear fringe fields
- Protons are accelerated and decelerated for 3 times
- Extra dipole field with 1.6 kG/cm is applied at the inner free space to strengthen vertical focusing

10 mA Proton Beam Extraction

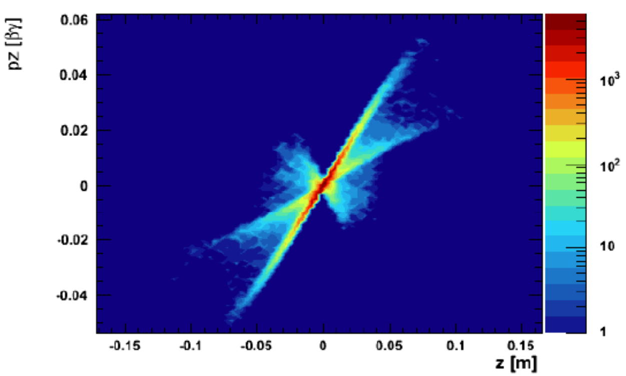


- Vertically well focused with the help of extra dipole field
- Momenta dispersion increase horizontal and longitudinal beam size
- Exotic phase space caused by multi-turn stripping scheme

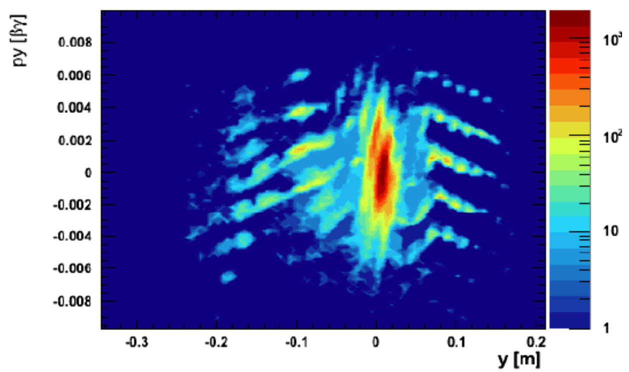
Phase space at the last point:



horizontal

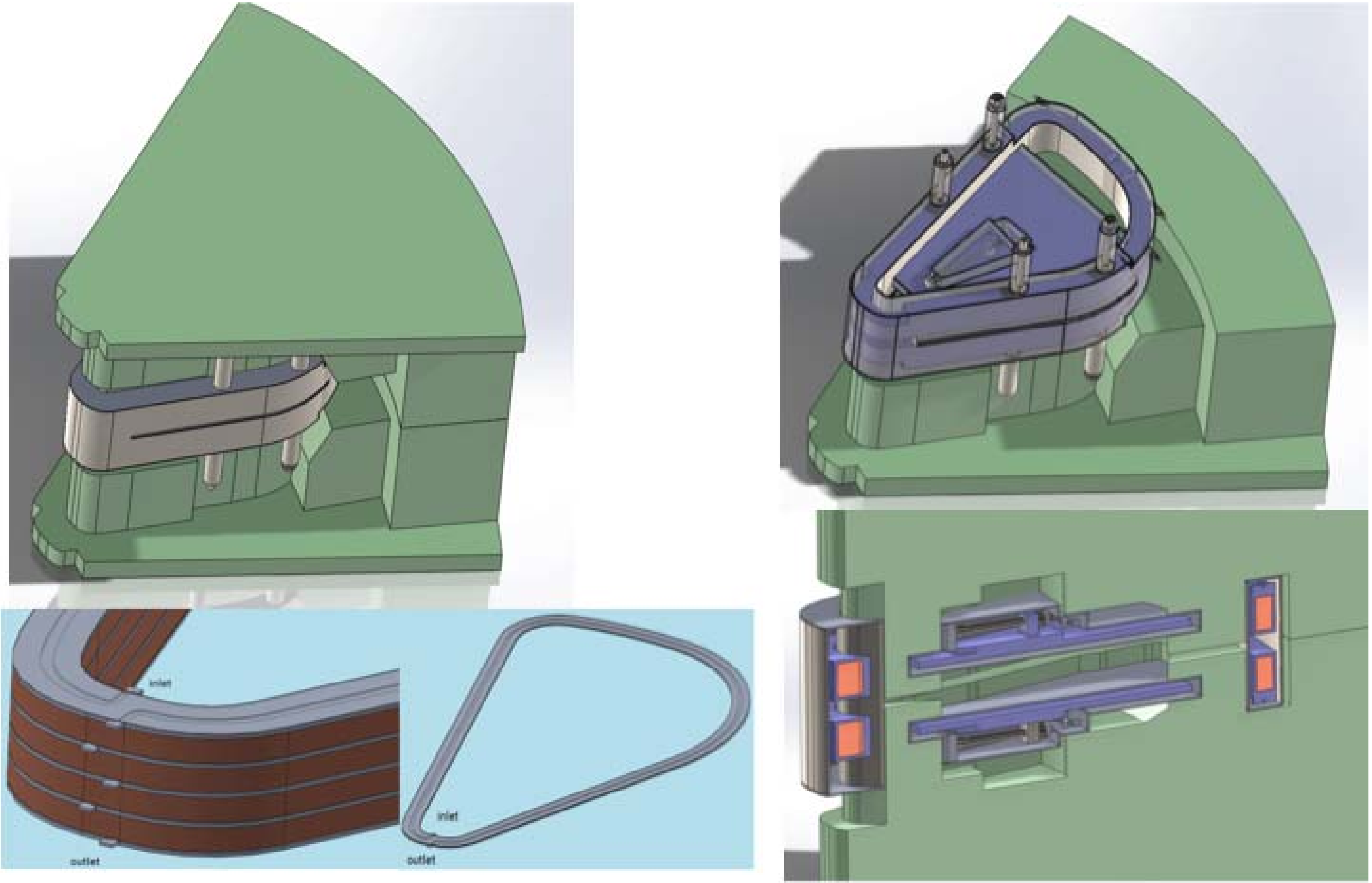


vertical



longitudinal

Preliminary Engineering Design

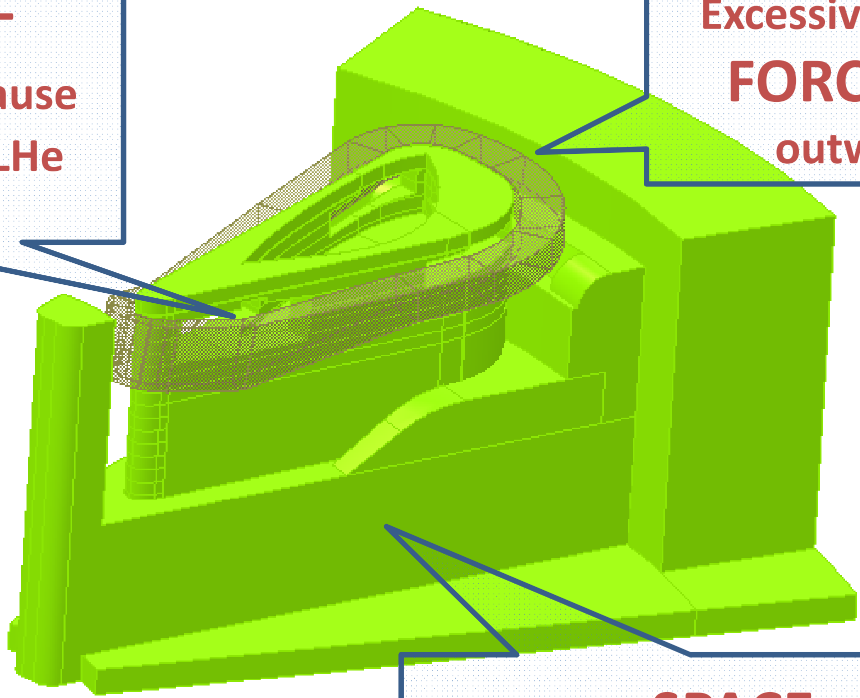


[J. Minervini, et al., arXiv:1209.4886]

Technical Challenges in 8-sector design

the variable **cross-section** that could cause complications on the LHe cooling system

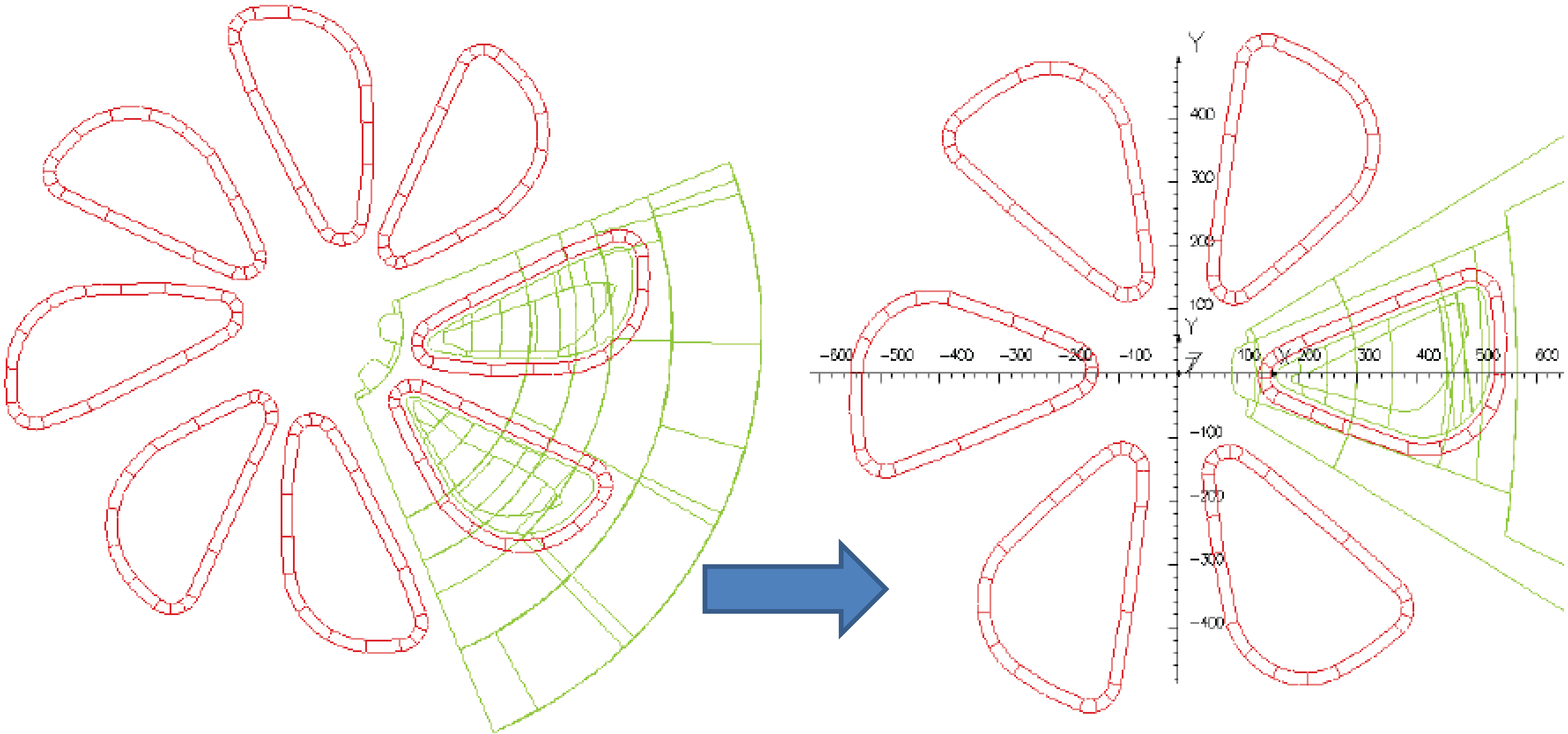
Excessive residual radial **FORCE** that pushed outward the coil



Not enough **SPACE** left between two contiguous sectors to install RF cavities PSI like

[A. Calanna et al., IPAC'12]

The 2nd Design iteration:6 sectors



[A. Calanna et al.]

- Lower costs for magnets building
- More space to accommodate the coil and the cryostat.
- Arrangements with tilted coils are acceptable but add complexity

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BEST Test Stand

What we want to test: the performance of H_2^+ beams during generation, injection and acceleration in a compact cyclotron

1MeV cyclotron

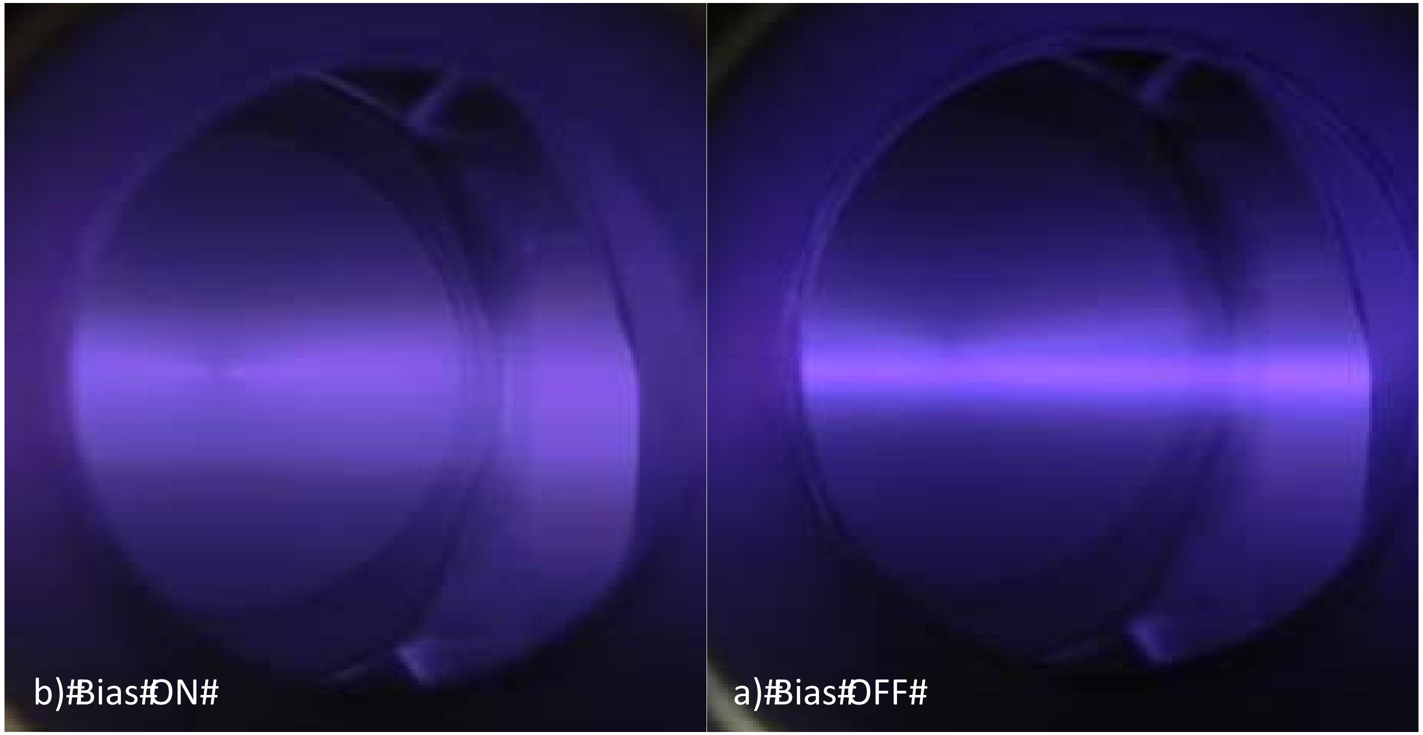
Beam line & analysis system

VIS

- Total length of is about 5 meters.
- Located at Best Cyclotron Systems, Inc. in Vancouver, Canada
- The Catania Versatile Ion Source (VIS) is used, which provides p, H_2^+ and H_3^+ simultaneously
- The fully-operational cyclotron is expected to be available by the end of September 2013.

[L. Calabretta,et al., ICIS'13]

Observation on the Injection Line

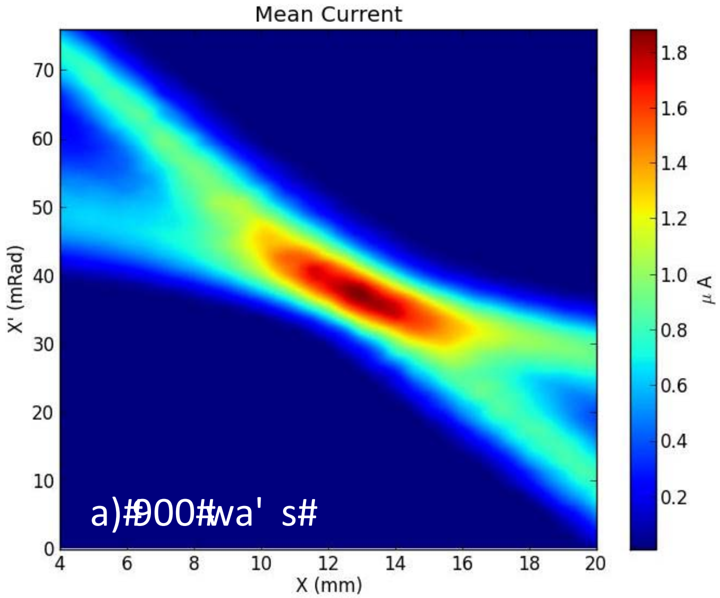


voltage bias on
Beam size ≈ 15 mm

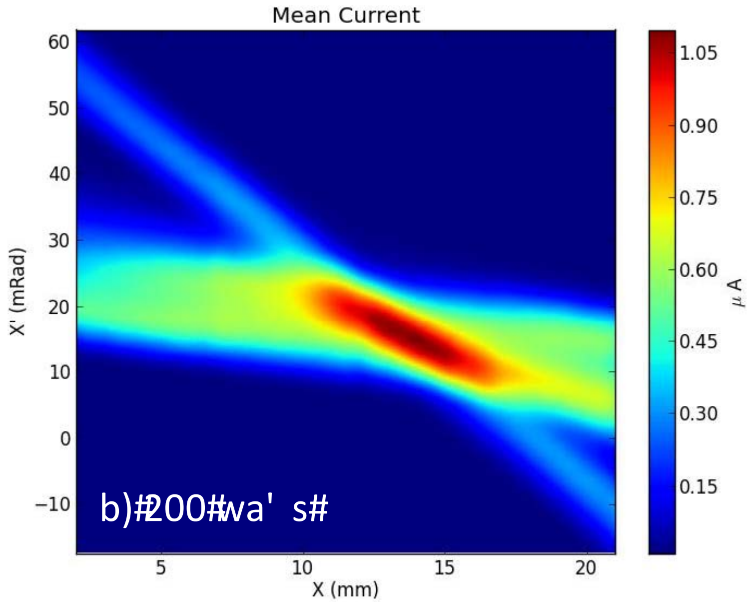
voltage bias off
Beam size ≈ 3 mm

Observation: space-charge compensation in the injection line is important to keep beam sizes low !

Emittance measurement



900 W microwave power

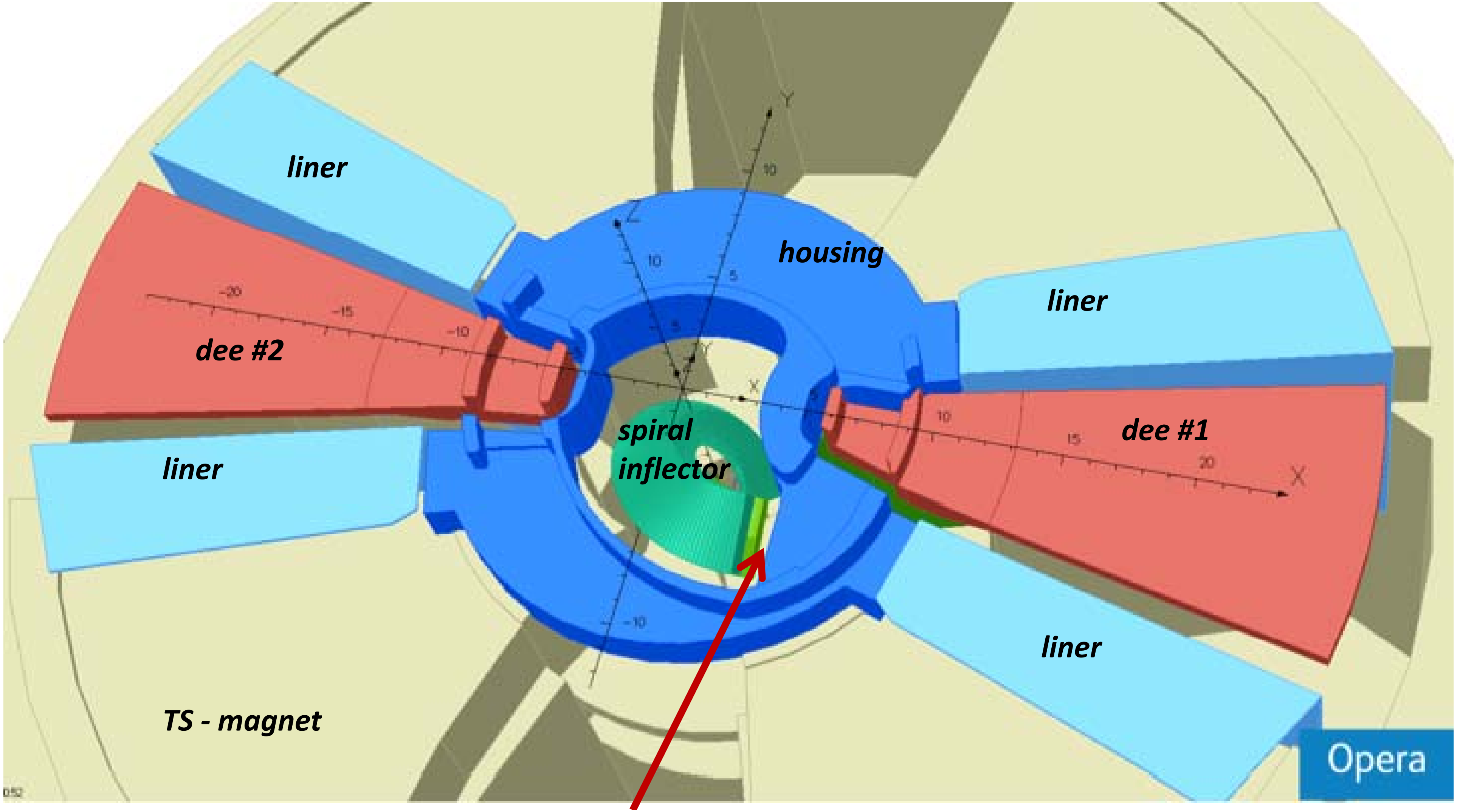


200 W microwave power

Observation:

- Three ellipses related to p, H2+ and H3+ produced from the ion source can be seen
- RMS normalized emittance is about 0.4π mm-mrad

Inflection, Capture & Acceleration



beam injection in the median plane

Next Steps

- Installation of an analysis system to cleanly separate the proton and H_2^+ components
- Tests of the H_2^+ beam inflection, capture and acceleration
- Based on the experience gained from the tests at BEST, a new 7 MeV/n test-stand will be built at INFN-LNS in Catania, which will use an improved ion source, a redesigned transport line and central region.
- Phase II, III, IV ……

Thanks all the DAEδALUS team members !