

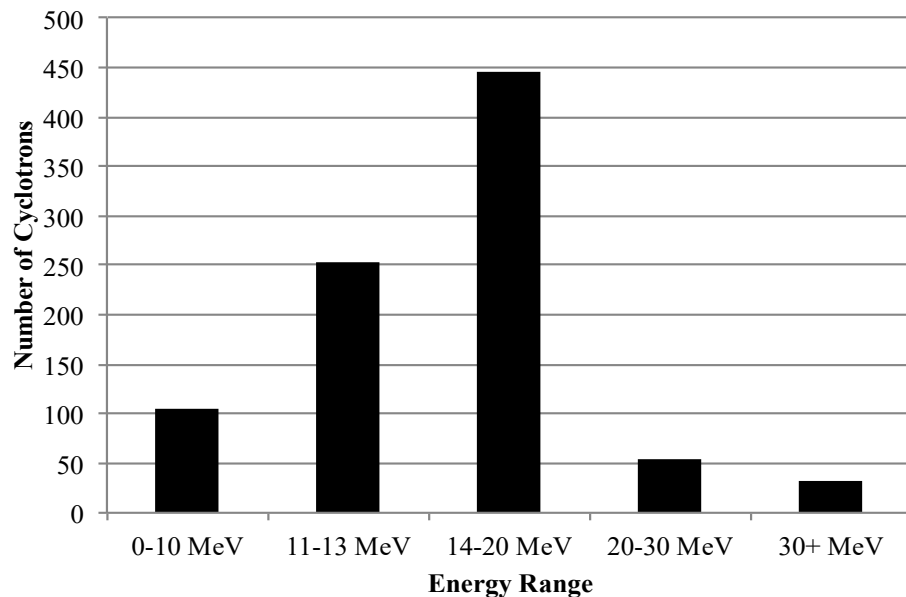
Review of High Power Cyclotrons and their Applications



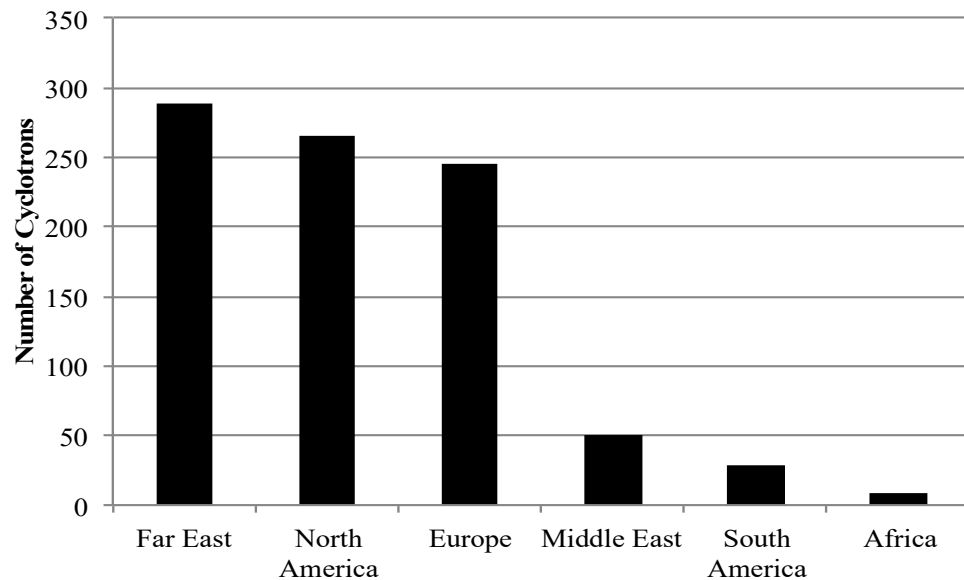
L. Calabretta, D. Rifuggiato, INFN-LNS, Catania
M. Maggiore, INFN-LNL, Legnaro

22nd ICCA, Cape Town, 26 September 2019

Number of commercial cyclotrons for classes of energies.



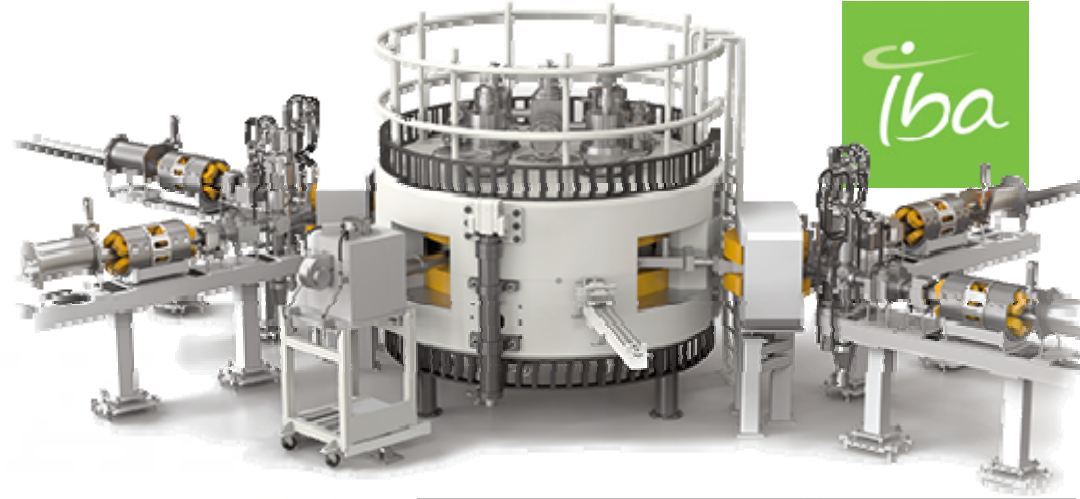
Regional distribution of cyclotrons in the world



Date at 2015

Commercial Cyclotrons for Production of Medical Radioisotopes

More than 1200 cyclotrons
installed in the world

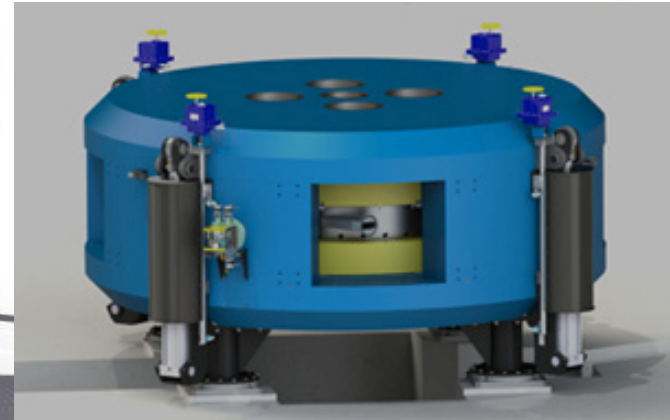


TR 30 MeV



PMB
— FILCEN —

12 MeV



Best Cyclotron Systems



22nd ICCA, Cape Town, 26 September 2019

Commercial Cyclotrons for production of Medical Radioisotopes

Energy range from 7 to 70 MeV. An incomplete list!

ACSI (Advanced Cyclotron System Inc.) Maximum energies are 14/7, 19/8.5, 24/12, 30/15 MeV, p/D

ABT (Advanced Biomarkers Technology) a new small “table-top” cyclotron for 7.5 MeV

BSCI (Best Cycl. Systems Inc.) has a set of 3 cyclotron models to accelerate H⁻ up to 14, 35 and 70 MeV

CIAE (China Inst. for Atomic Energy) plans to build cyclotrons to produce H⁻/D⁻ at 14 MeV and 70 MeV

EUROMEVE constructs the ISOTRACE superconducting cyclotron, previous OSCAR-12, H⁻ up to 12 MeV

GENERAL ELECTRIC has two cyclotrons models to accelerates H⁻ up to 9.6 and 16.5/8.6 MeV

IBA produces cyclotrons able to accelerate H⁻ and D⁻ at energies 10/5, 11, 18/9, 30 and 70 MeV

NIIEFA is a national institution, their cyclotrons delyver H⁻/D⁻ at maximum energy 12/6, 18/9, 30/15 MeV

JSW (Japan Steel Works) has 5 cyclotrons models for H/D up to 16/8, 17/10, 20/10, 22/11, 30/15 MeV

Samyoung Unitech Co., previous **KIRAM**, has 2 cyclotron models to deliver proton at 13 and 30 MeV

SCANDITRONIX Medical AB, has 6 cyclotrons MC17, MC30, MC32NI, MC40, MC50, MC60, K130

SHI (Sumitomo Heavy Industries) cyclotron models HM7, HM10, HM12, HM12S, HM18, to deliver H/D

SIEMENS Medical Systems produce the ECLIPSE. It is capable to deliver proton beam at 11 MeV.

RADIOISOTOPES FOR MEDICAL APPLICATION PRODUCED BY CYCLOTRONS

Radioisotope	Half life	Nuclear Reaction	Energy [MeV]	Use
Carbon 11	20.4 m	$^{14}\text{N}(p,\alpha)^{11}\text{C}$	12	PET
Nitrogen 13	9.96 m	$^{13}\text{C}(p,n)^{11}\text{N}$	5-10	PET
Oxygen 15	2 m	$^{15}\text{N}(p,n)^{15}\text{O}$	10-15	PET
Fluorine 18	110 m	$^{18}\text{O}(p,n)^{18}\text{F}$	8-17	PET
Sodium 22	2.6 y	$^{22}\text{Ne}(p,n)^{22}\text{Na}$	11-17	PET
Cobalt 57	272 d	$^{\text{nat}}\text{Ni}(p,x)^{57}\text{Co}$	>20	Other
Copper 64	12.7 h	$^{64}\text{Ni}(p,n)^{64}\text{Cu}$	5-20	SPECT
Copper 67	62 h	$^{68}\text{Zn}(p,2p)^{67}\text{Cu}$	>40	SPECT
Gallium 67	78.3 h	$^{68}\text{Zn}(p,2n)^{67}\text{Ga}$	20-40	SPECT
Germanium 68 → Gallium 68	271 d 68 m	$^{\text{nat}}\text{Ga}(p,x)^{68}\text{Ge}$ $^{68}\text{Ge} \rightarrow ^{68}\text{Ga}$	15-30	PET
Rubidium 82	4.6 h	$^{85}\text{Rb}(p,4n)^{82}\text{Sr}$ $^{82}\text{Sr} \rightarrow ^{82}\text{Rb}$	50-70	PET
Palladium 103	17.5 d	$^{103}\text{Rh}(p,n)^{103}\text{Pd}$	10-15	Other
Cadmium 109	461 d	$^{109}\text{Ag}(p,n)^{109}\text{Cd}$	5-10	γ -camera
Indium 111	2.83 d	$^{\text{nat}}\text{Cd}(p,n)^{111}\text{In}$	5-15	Other
Iodine 123	13.2 h	$^{124}\text{Xe}(p,pn)^{123}\text{Xe}$ $^{123}\text{Xe} \rightarrow ^{123}\text{I}$	25-35	Other
Iodine 124	4.2 d	$^{124}\text{Te}(p,n)^{124}\text{I}$	10-15	PET
Rhenium 186	90.6 h	$^{186}\text{W}(p,n)^{186}\text{Re}$	18	Therapy
Thallium 201	73.5 h	$^{203}\text{Tl}(p,3n)^{201}\text{Pb}$ $^{201}\text{Pb} \rightarrow ^{201}\text{Tl}$	27-35	SPECT

The $^{68}\text{Ge} / ^{68}\text{Ga}$ generator is a very effective PET diagnostic tool!

- ^{68}Ge parent isotope (270 day half-life)
- Decays to ^{68}Ga positron emitter,

68 minute half-life

- ^{99}Mo 66 hour half-life, less than 3 days
- $^{99\text{m}}\text{Tc}$ daughter **6 hour half-life**

White paper available:

- <https://arxiv.org/abs/1807.06627>

Visual advantage of 68Ga vs. 99mTc

- natural Ga Target contain 60% and 40% of 69Ga and 71Ga respectively.
69Ga(p,2n)68Ge, 71Ga(p,4n)68Ge cross section about 150 mbarn for both reaction, peaks at 50 MeV and 25 MeV respectively.
- 5 curies of 68Ga parent /week /1 mA
- 50 curies of 68Ga parent /week /10 mA
- Could eliminate need for rapid supply chain

[^{99m}Tc]Tc-MDP



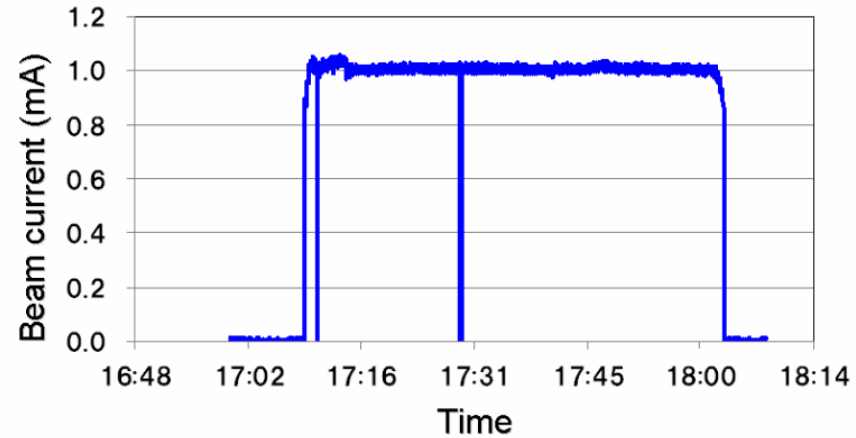
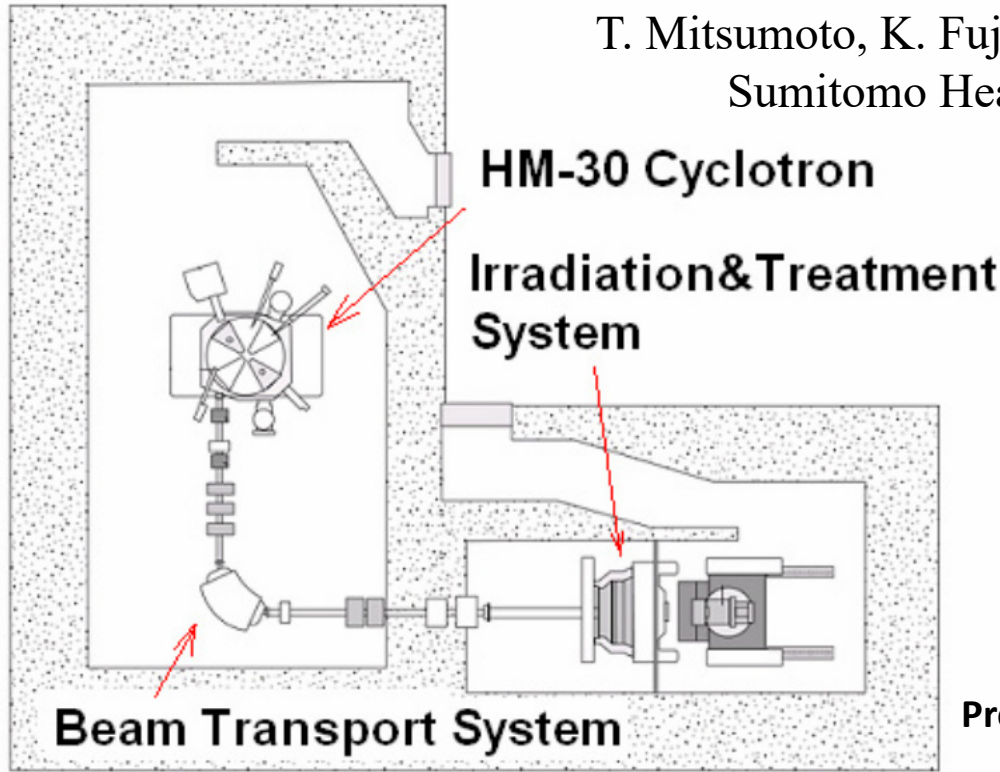
[⁶⁸Ga]Ga-NO₂AP⁸⁰



Courtesy of J. Alonso, MIT

BNCT SYSTEM USING 30 MEV H- CYCLOTRON

T. Mitsumoto, K. Fujita, T. Ogasawara, H. Tsutsui, S. Yajima,
Sumitomo Heavy Industries, Ltd., Tokyo, Japan



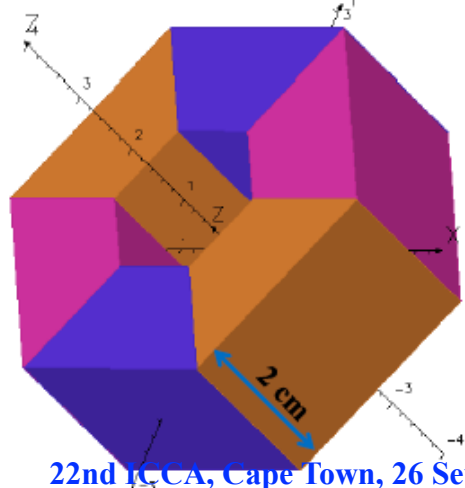
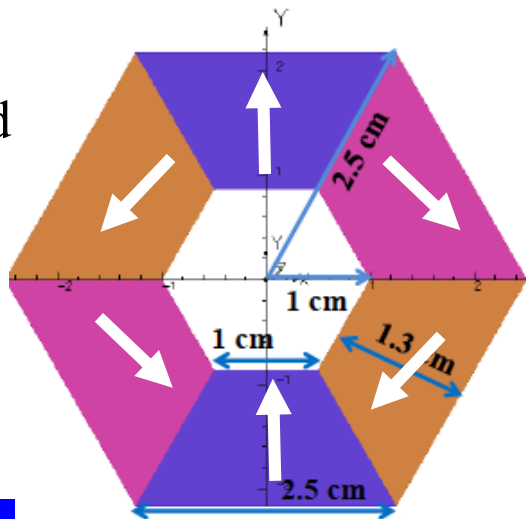
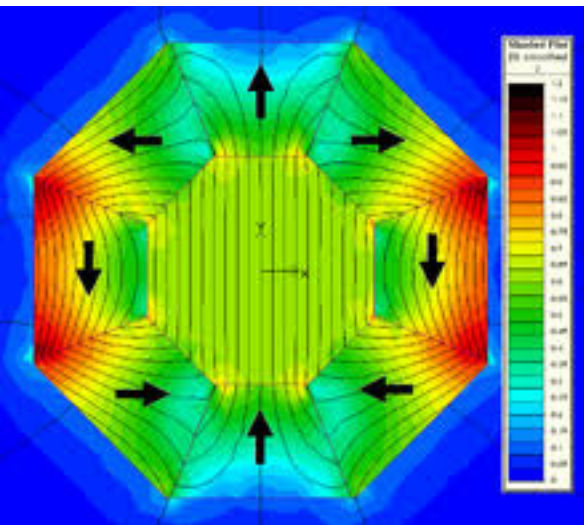
News – May 2019

Product Sumitomo Heavy Industries, Ltd. has started to a comprehensive review of the SAKIGAKE Designation System in order to speedily evaluate the efficacy of accelerator based BNCT systems in Japan.

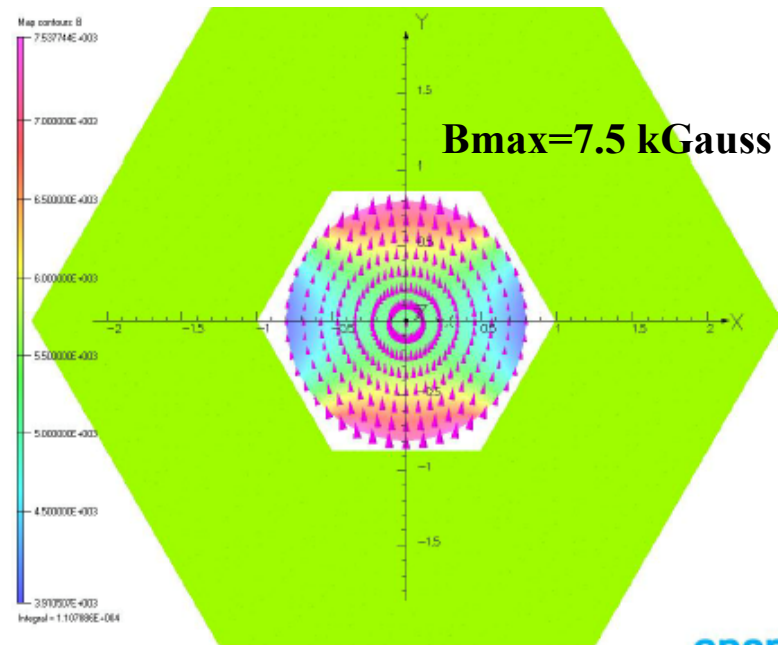
Layout of the cyclotron BNCT system at KURRI

How to increase beam current in the present and future cyclotrons?

Uniform field inside Halbach Magic ring



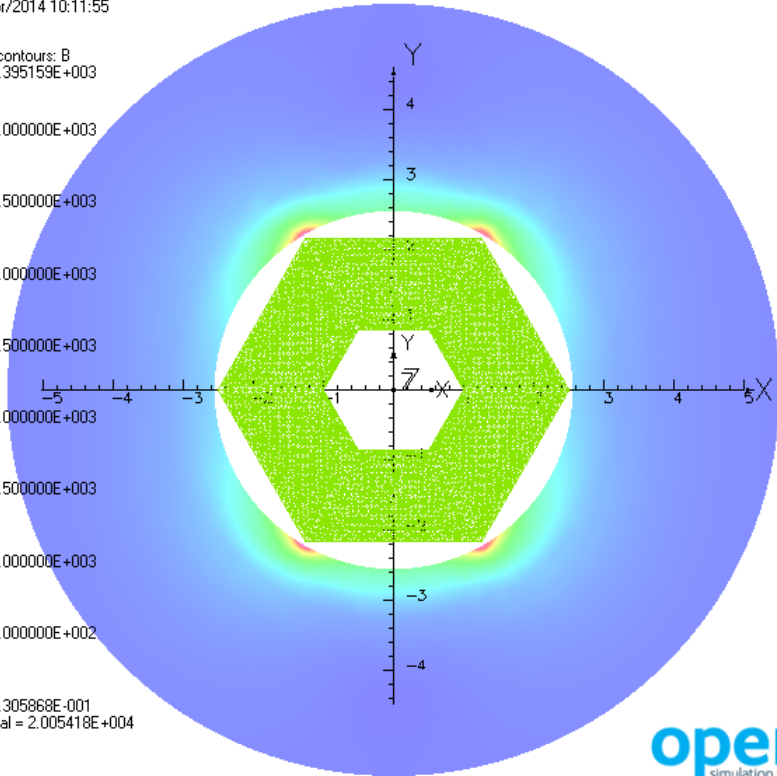
Permanent magnets to produce a spiral inflector with larger diameter hole and without electric field that have negative effects on space charge compensation



Bmax at center 7.5 kGauss

3/apr/2014 10:11:55

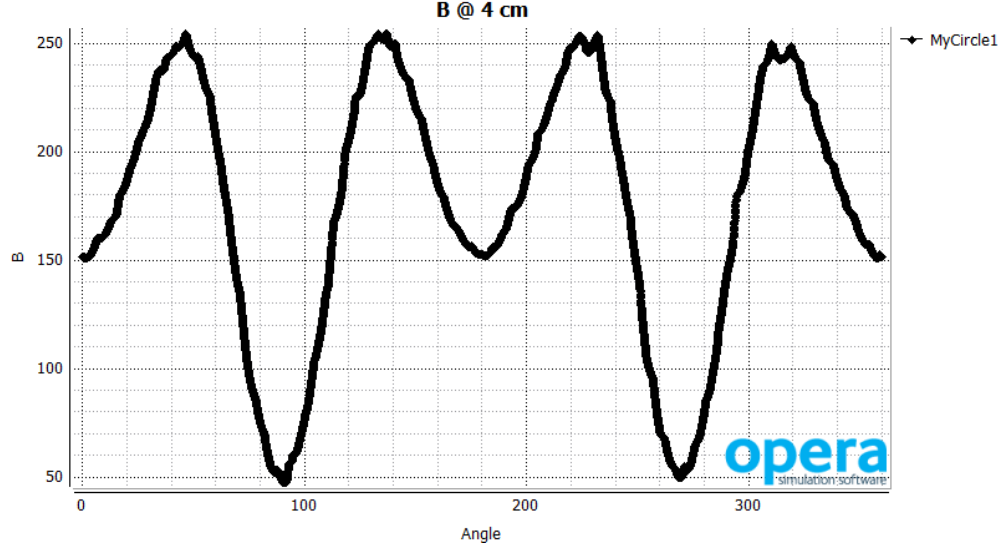
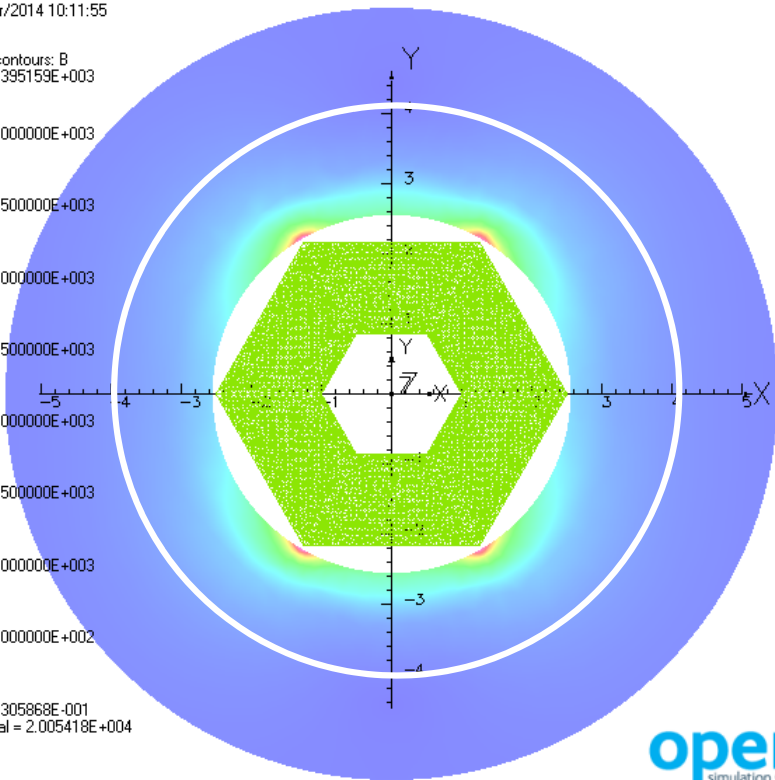
Map contours: B
4.395159E+003
4.000000E+003
3.500000E+003
3.000000E+003
2.500000E+003
2.000000E+003
1.500000E+003
1.000000E+003
5.000000E+002
8.305868E-001
Integral = 2.005418E+004



Bmax at center 7.5 kGauss

3/apr/2014 10:11:55

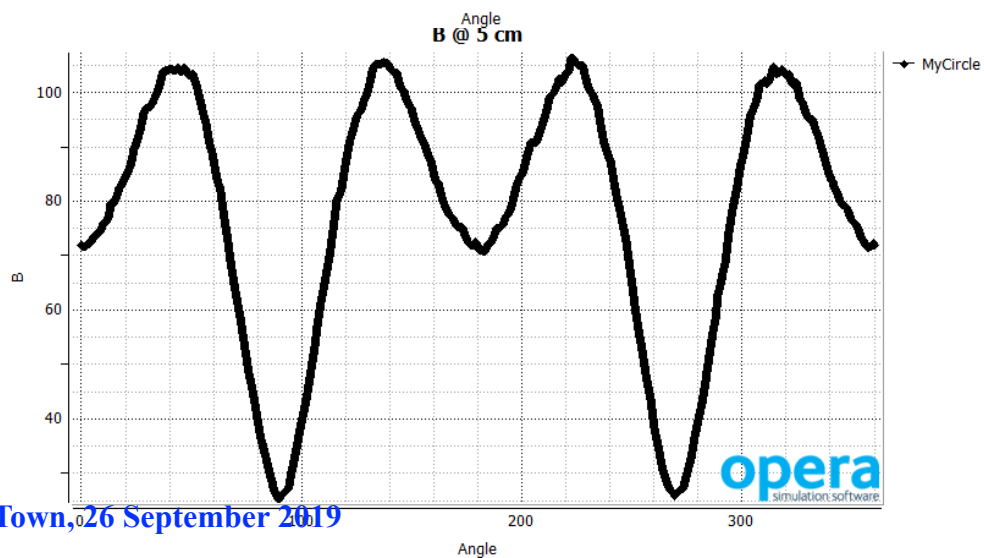
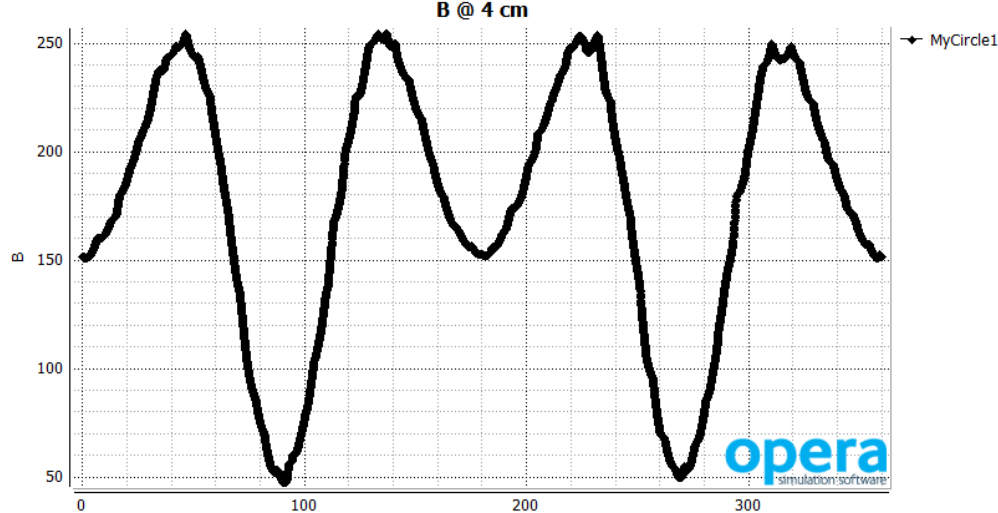
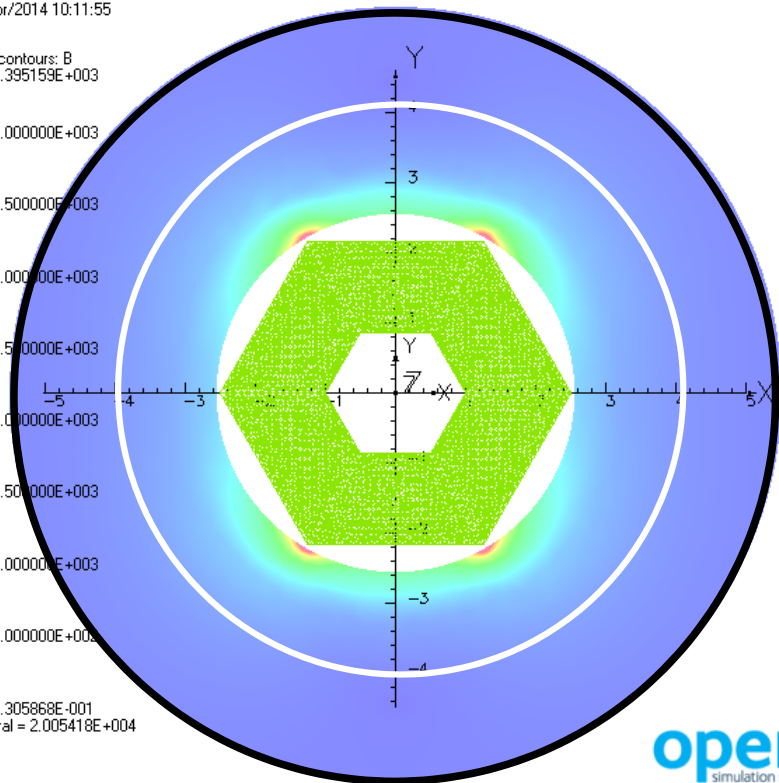
Map contours: B
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2.500000E+003
2.000000E+003
1.500000E+003
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5.000000E+002
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Integral = 2.005418E+004



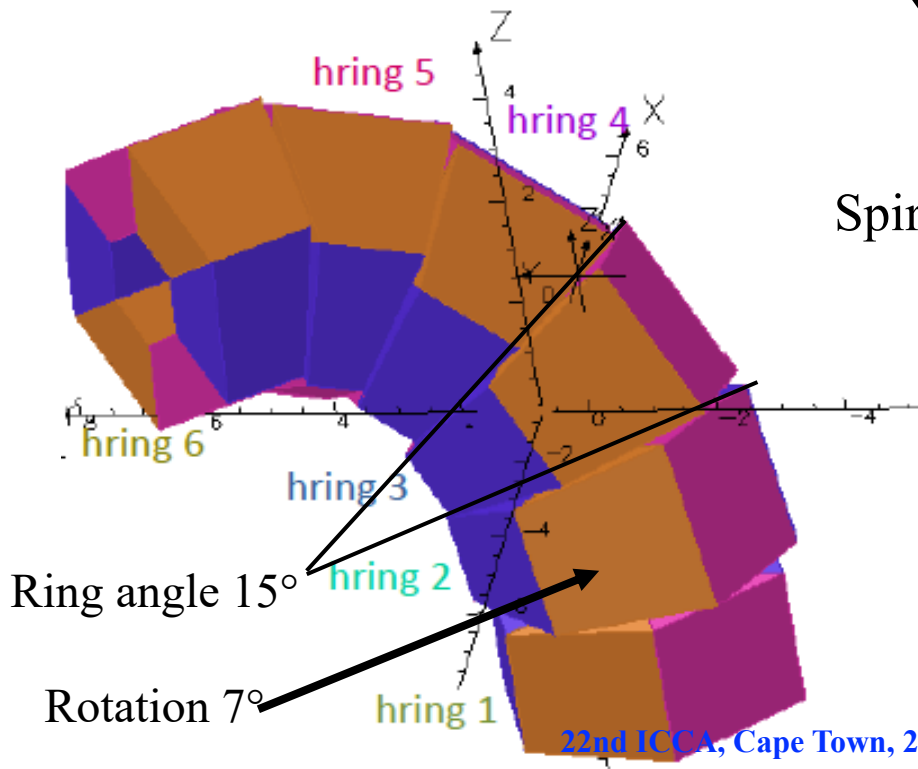
Bmax at center 7.5 kGauss

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Map contours: B
4.395159E+003
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1.000000E+003
5.000000E+002
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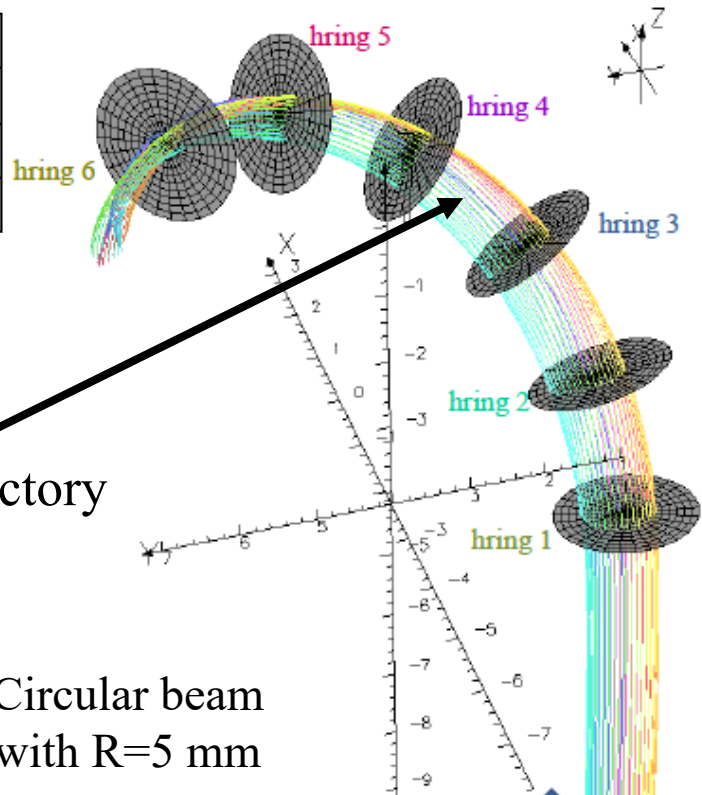


Particle	H ₂ ⁺	Injection energy	30 keV/n
Bo	1.075 T	Electrode gap	15 mm
Tilt angle	16 deg	Electrode voltage	± 11 kV
Electric radius	8.1818	Full path length	12.8519 cm

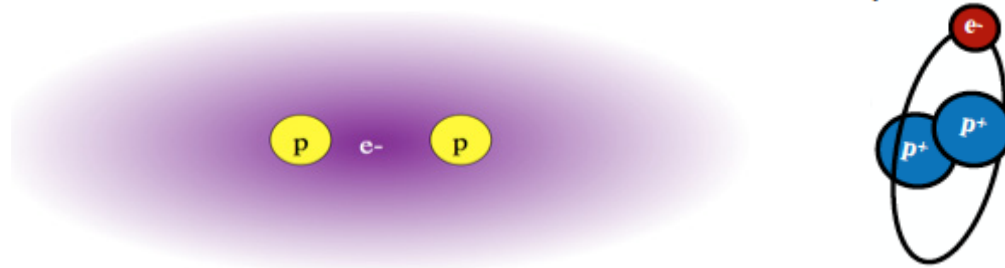


Spiral trajectory

Circular beam with R=5 mm

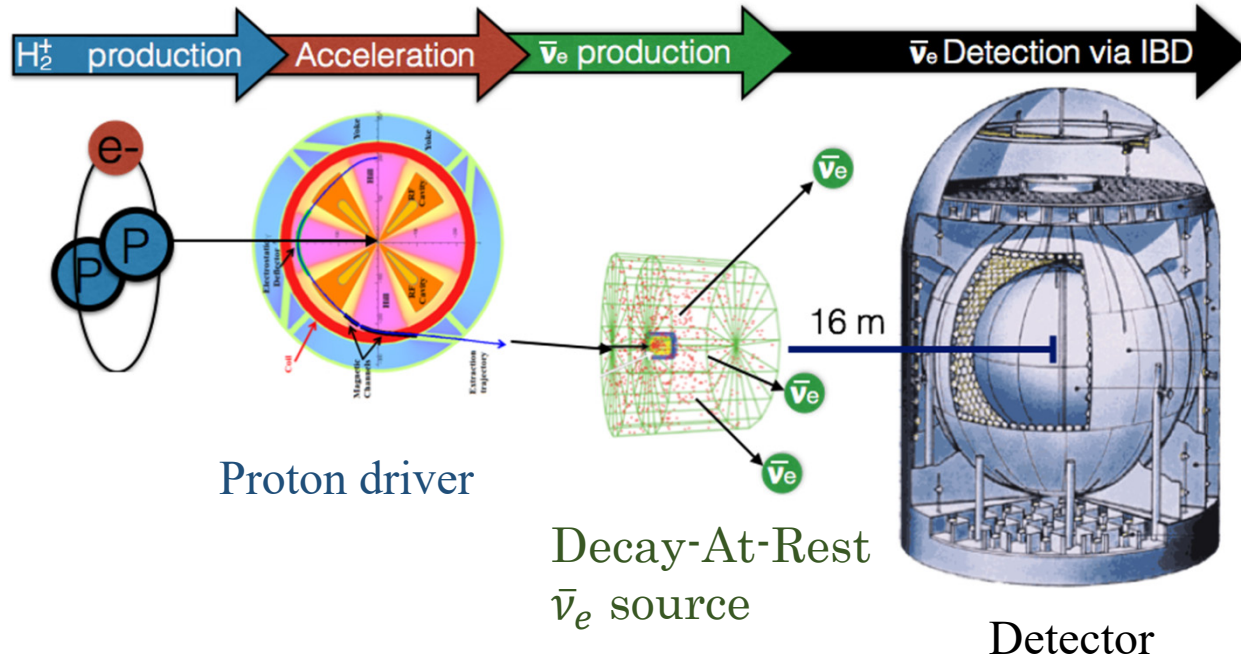


- 1997 At ECPM in Groeningen (NL), Calabretta and Rifuggiato presented “A Superconducting Cyclotron for H_2^+ with extraction by stripping”



- 1998 At Int. Cycl. Conf. in Caen (F),
 - Calabretta and Rifuggiato presented: Superconducting Cyclotrons for acceleration of H_2^+ ;
 - Fietier and Mandrillon presented: High intensity cyclotrons for driving hybrid nuclear systems.

Isotope Decay-At-Rest (IsoDAR) setup



A high intensity proton beam is used to produce neutrinos near a ton scale detector.

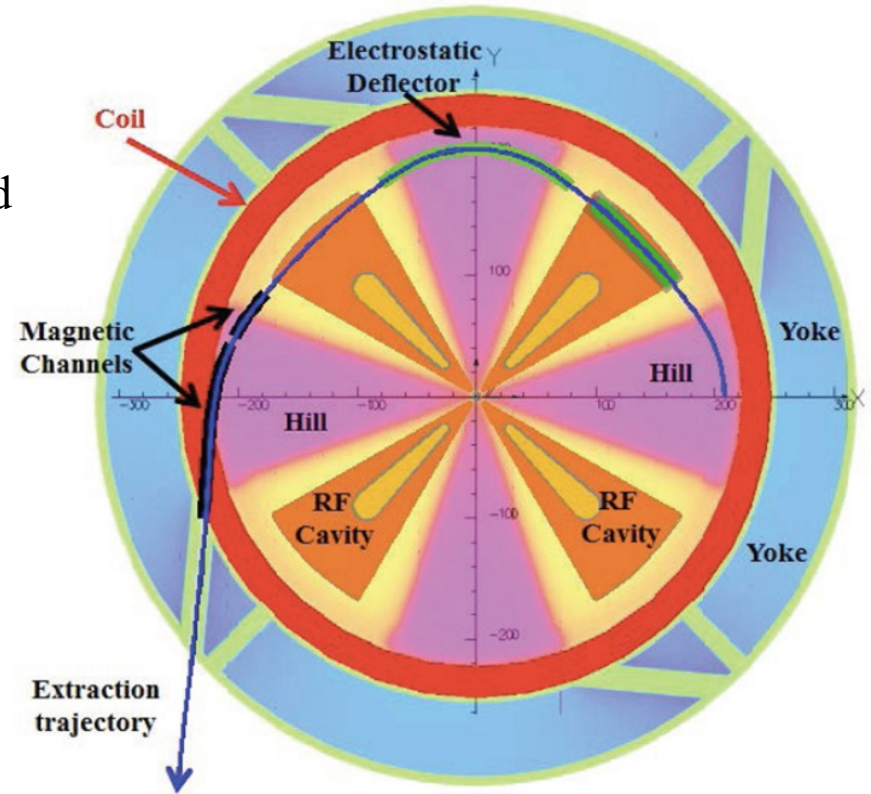
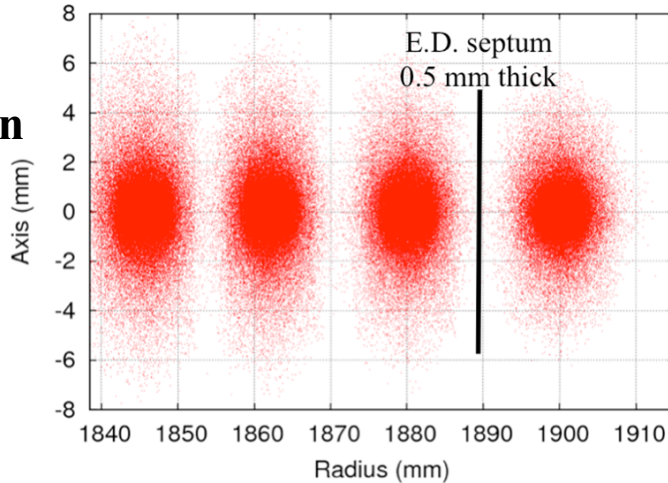
Physics:

- **Sterile neutrino search**
- **neutrino-electron scattering**

IsoDAR Cyclotron

- Extraction by electrostatic deflector
- Use stripper foils to remove the beam halo and minimize the septum heating & activation

OPAL simulation

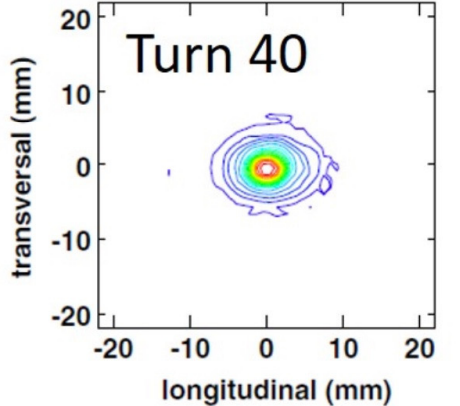
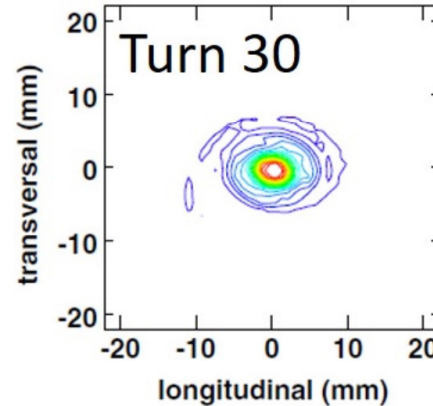
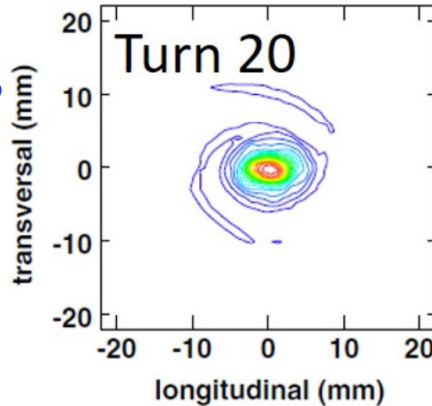
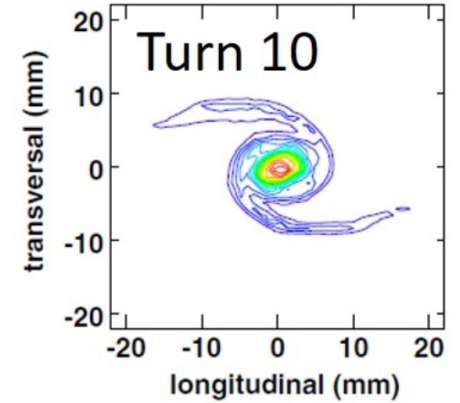
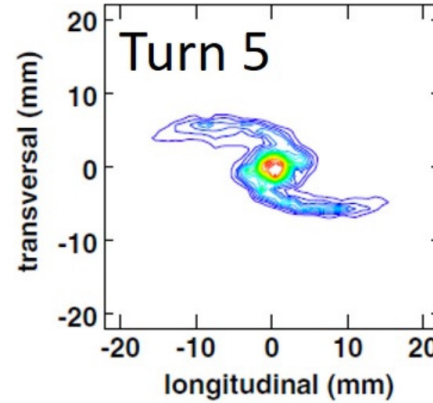
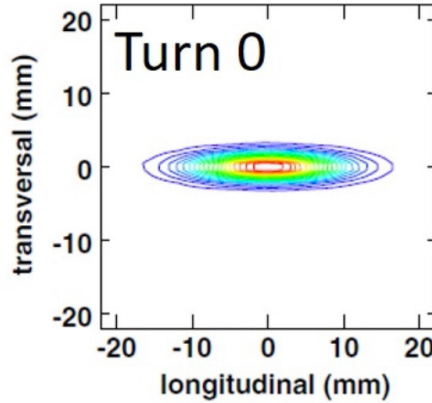


- $\sim 50 \mu\text{A}$ of protons extracted to protect septum
- Up to 4 stripping locations to remove the beam halo
- Protons can be used to produce medical radioisotopes in parasitic mode

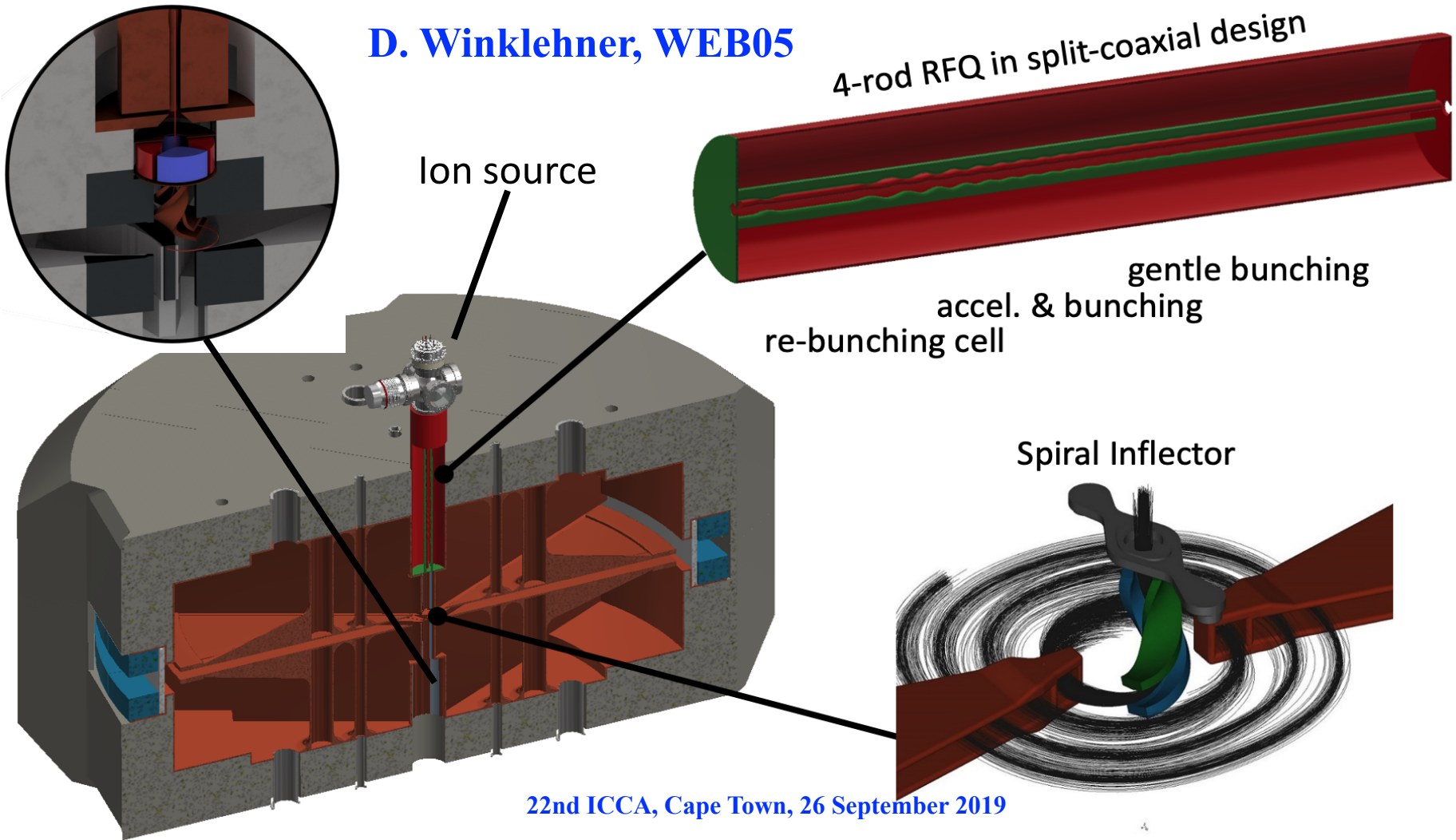
Space-Charge Dynamics: Vortex motion

OPAL simulations

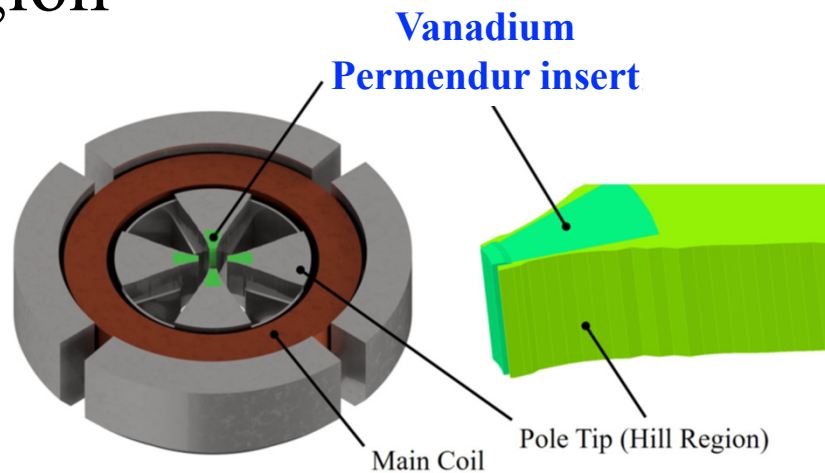
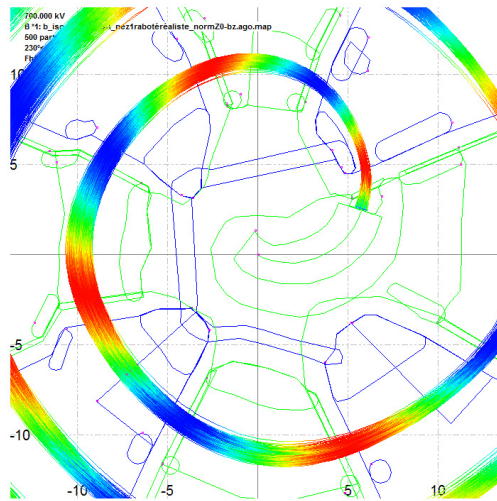
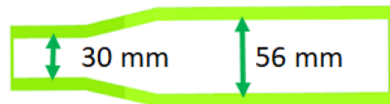
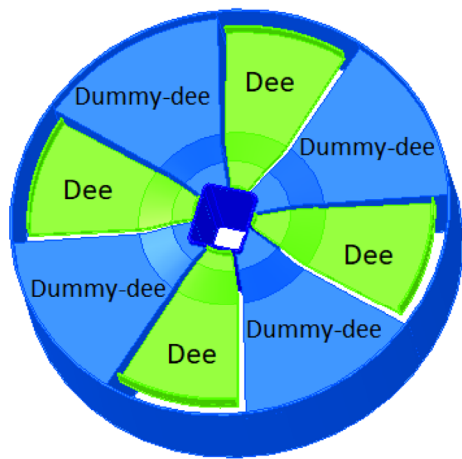
made by:
Andreas Adelman,
Jianjun Yang



D. Winklehner, WEB05



IsoDAR Central Region



AIMA simulations using approximated input
M. Conjat, P.Mandrillon

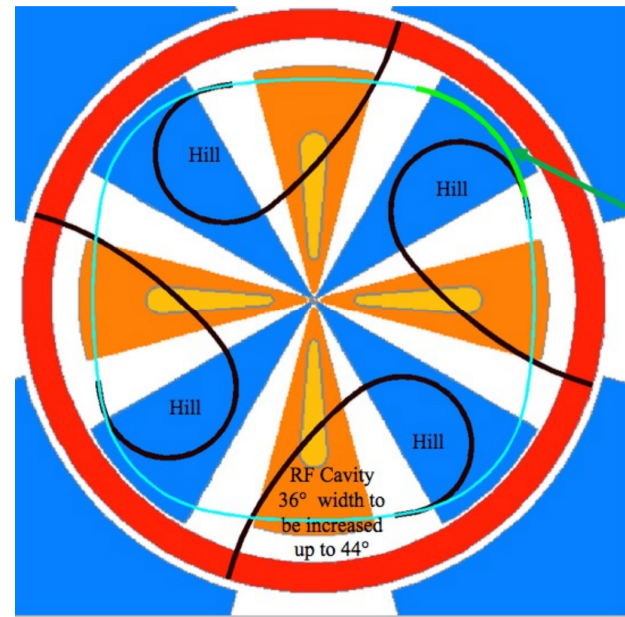
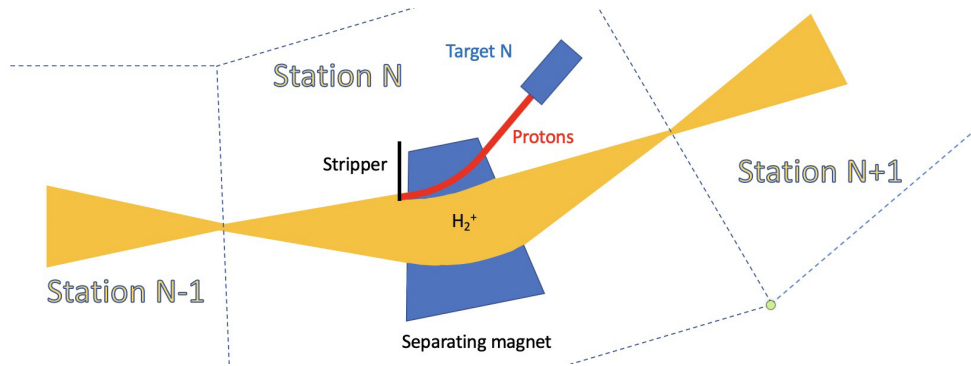
- Collimators to scape halo particles
- **Vanadium Permendur** inserts increase the vertical focusing

60 MeV protons

We could use IsoDAR Cyclotron also as a dedicated machine for radioisotope production and deliver

4 x150 kW beams

Extract the 150 kW proton beam by stripping is feasible if the magnetic field in the stripper area is \leq 500 Gauss (Re>12 mm (slide 28?). Field can be lowered from 3 to 0.5 kG using Permanent Magnets.



The main benefits of higher current for isotope production are:

- higher production rates for lower-cross section isotopes**
- production of larger amounts of long-lived isotopes**

IsoDAR Cyclotron can accelerate also fully stripped light ions as D, He⁺⁺ C⁶⁺ up to energy of 60 MeV/amu.

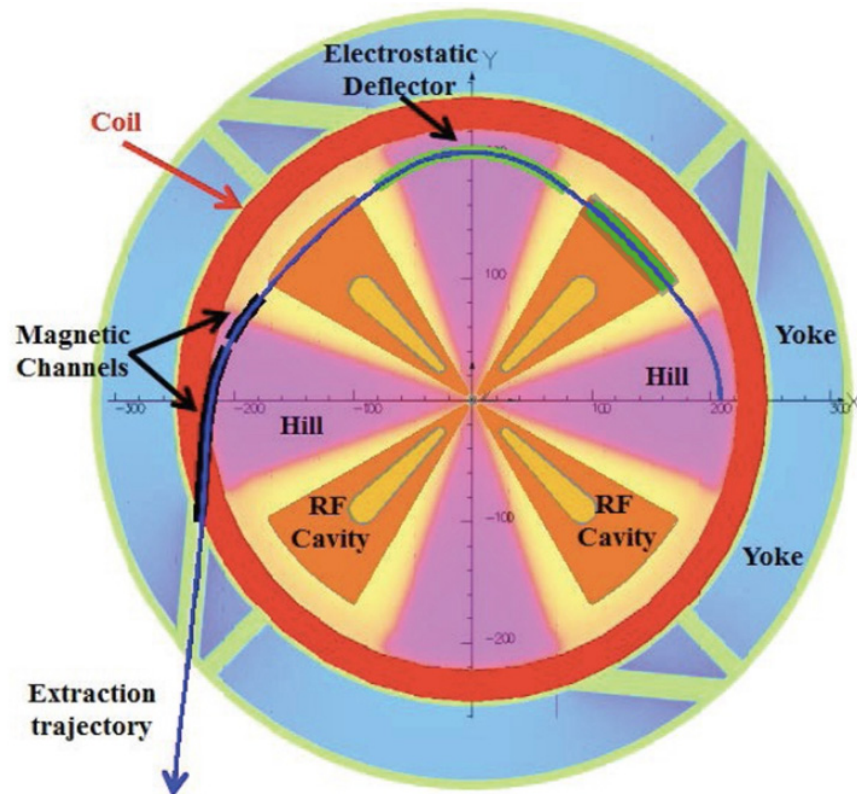
Using commercial ECR ion source (PK-ISIS of Pantechnik),

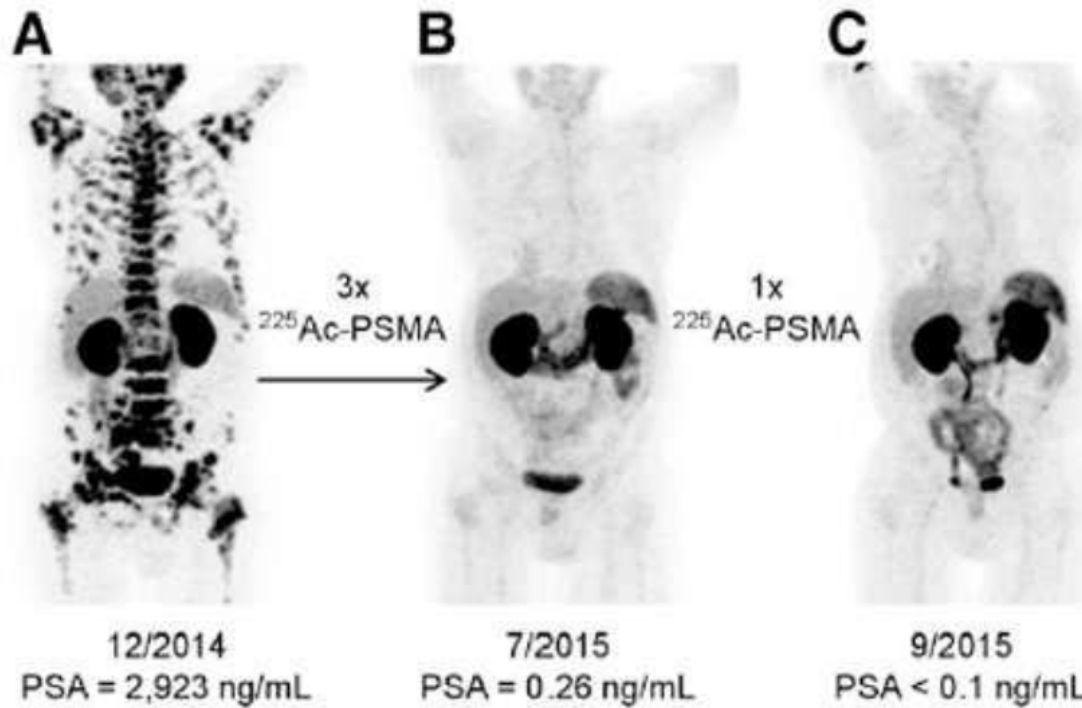
beam current up to 1 mA of

He⁺⁺ beam @ 240 MeV → 120 kW could

be extracted by E.D. and used to produce

new radioisotopes like 225Ac 4 alpha emitter





- ^{225}Ac is a therapeutic alpha emitter (9.9 day half-life)
- Parent of chain to emit 4 α ending with stable ^{209}Bi
- 50 μm radius of effect
- Currently produced from ^{226}Ra target purified from reactor waste
- Sufficient ^{225}Ac for studies
- BLIP and LANSCE at 100 μA would increase the world supply by 60 times
- Design of a Thorium target is in progress at TRIUMF
- IsoDAR production rate at 200 mCi/hr

[Eur J Nucl Med Mol Imaging](#). 2019 Jan;46(1):129-138.

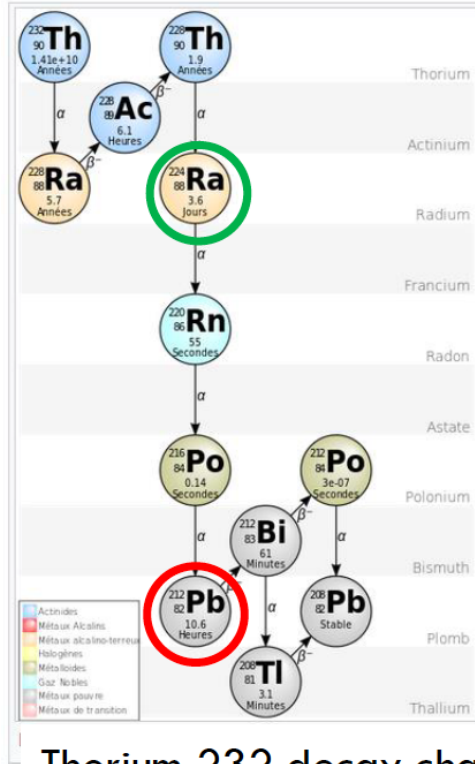
doi: 10.1007/s00259-018-4167-0. Epub 2018 Sep 19

$^{225}\text{Ac-PSMA-617}$ in chemotherapy-naive patients with advanced prostate cancer: a pilot study.

[Sathekge M](#)¹, [Bruchertseifer F](#)², [Knoesen O](#)³, [Reyneke F](#)⁴, [Lawal I](#)⁴, [Lengana T](#)⁴, [Davis C](#)⁴, [Mahapane J](#)⁴, [Corbett C](#)⁴, [Vorster M](#)⁴, [Morgenstern A](#)^{4,2}. **Conclusion** $^{225}\text{Ac-PSMA-617}$ RLT of chemotherapy-naïve patients with advanced metastatic prostate carcinoma led to a $\geq 90\%$ decline in serum PSA in 82% of patients

Generators from the $\alpha + {}^{232}\text{Th}$ reaction

${}^{212}\text{Pb}$ from ${}^{224}\text{Ra}$



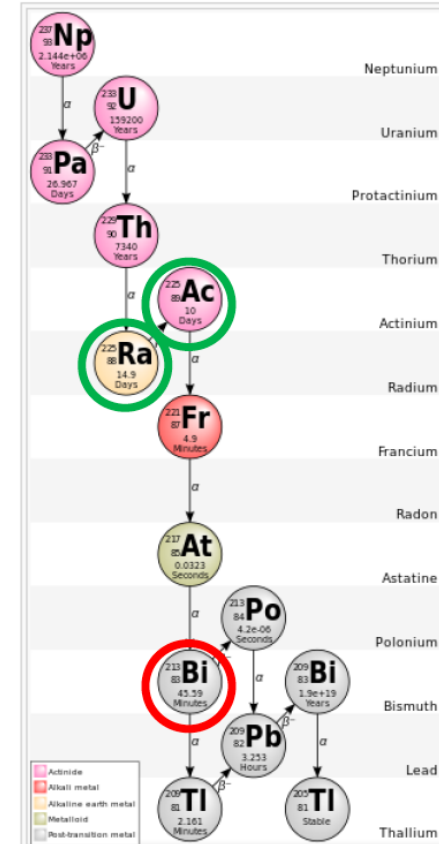
Thorium 232 decay chain

Courtesy of A. M. Frelin-Labalme, GANIL

Generators

Radio-isotopes
of interest

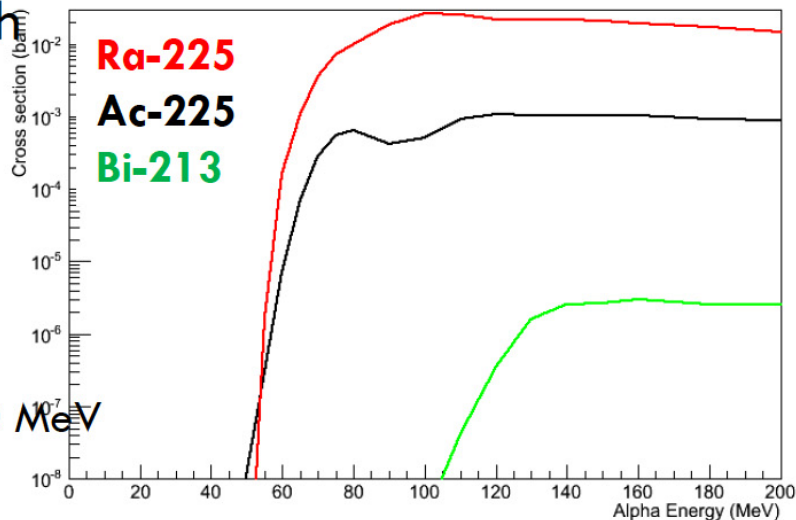
${}^{213}\text{Bi}$ from ${}^{225}\text{Ra}$ or ${}^{225}\text{Ac}$



Neptunium 237 decay chain

²²⁵Ac generator

- Database TENDL-2014: Reaction $\alpha + {}^{232}\text{Th}$
- Reaction threshold
 - ▣ ≈ 50 MeV for ²²⁵Ac and ²²⁵Ra
 - ▣ ≈ 100 MeV for ²¹³Bi
- FISPACT-II calculations:
 - ▣ Natural thorium target 0.05 cm so that $E_{\text{out}} \approx 50$ MeV
 - ▣ 80 MeV, $I=200$ μA (6.2×10^{14} α/s)
 - ▣ $T_{\text{irr}}=1$ and 10 d



	80 MeV	
	A(Bq/g)	% Atot
Irradiation 1 j	1.24E+08	0.39%
Irradiation 10 j	9.30E+08	0.495%

⇒ First cross-section measurements to constrain models

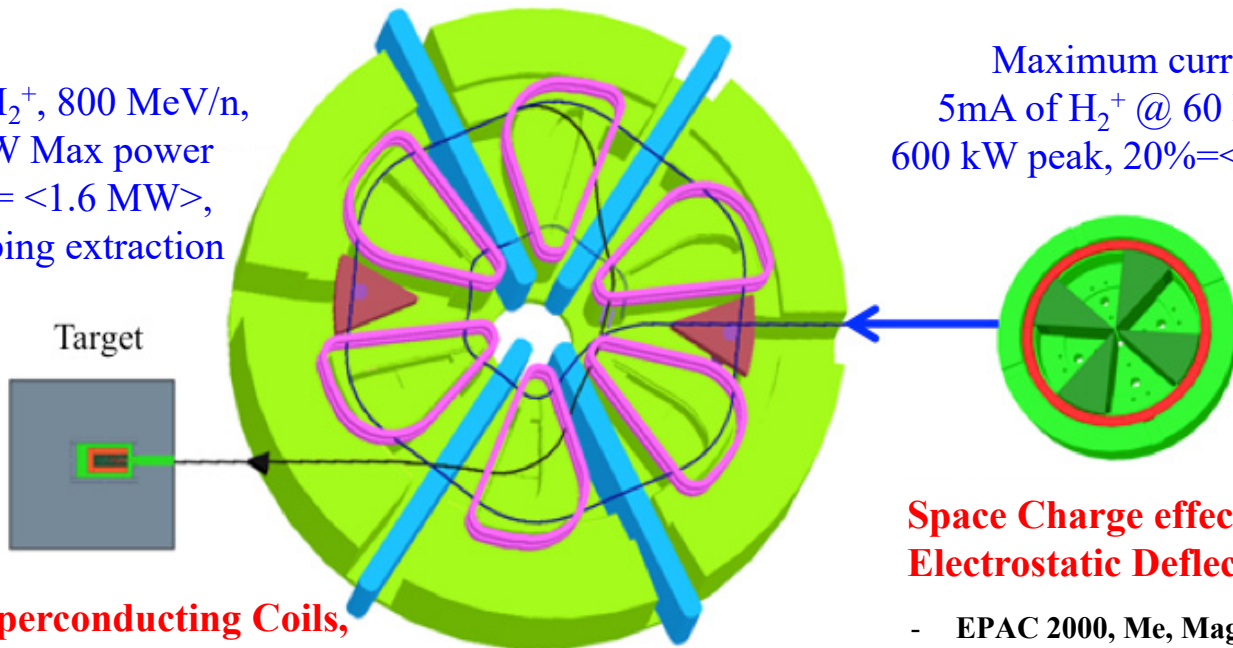
The base cyclotron module for DAEDALUS is designed to deliver proton beam 10 mA @ 800 MeV duty cycle 20%, average power <1.6 MW>

Superconducting Cyclotron, separated sectors, 800 MeV/amu

Injector Cyclotron, Compact, 60 MeV/amu

5 mA H_2^+ , 800 MeV/n,
8 MW Max power
20% = <1.6 MW>,
Stripping extraction

Maximum current,
5mA of H_2^+ @ 60 MeV/n
600 kW peak, 20% = <120 kW>



**Superconducting Coils,
Losses due to
residual gas and
Electromagnetic stripping**

**Space Charge effects,
Electrostatic Deflectors**

- EPAC 2000, Me, Maggiore, Rifuggiato, Shchepounov,
- Cyclotrons 2010, Me, Calanna, Maggiore, Piazza, Rifuggiato

DAEδALUS: A Path to Measuring δ_{CP} Using Decay-at-Rest Neutrino Sources, by J. Conrad & M. Shaevitz

Decay

At rest

Experiment for

δ_{CP} studies

At the

Laboratory for

Underground

Science

Primary physics goal: searching for

CP-violation in the neutrino sector

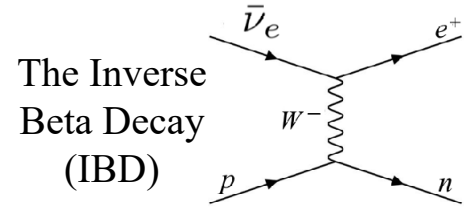


Short baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ experiment with
no matter effect

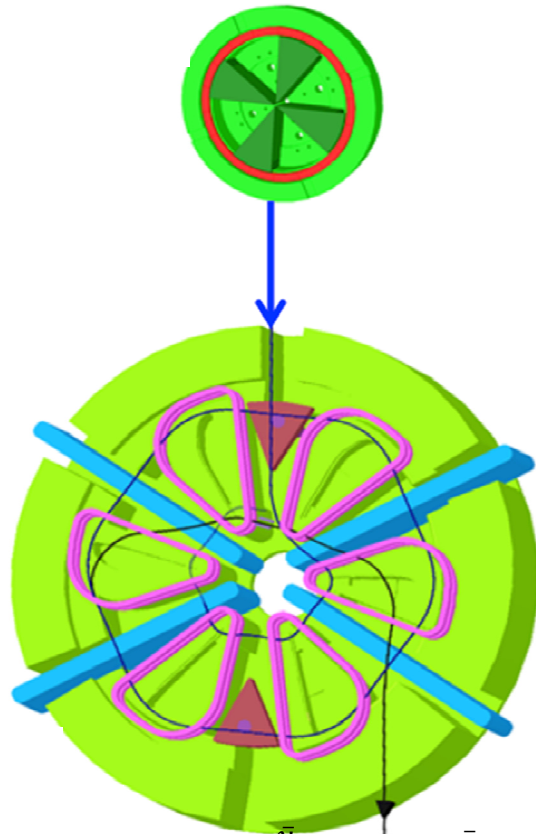


novel design which provides high-
statistics and low backgrounds

DAEDALUS project



Injector Cyclotron for H_2^+ , 60 MeV/amu
Extraction by Electrostatic Deflector



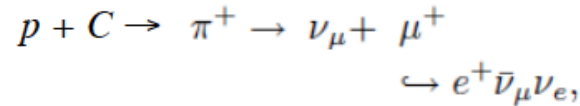
Superconducting Ring Cyclotron for H_2^+ , 800 MeV/amu, with stripping extraction

Production Target

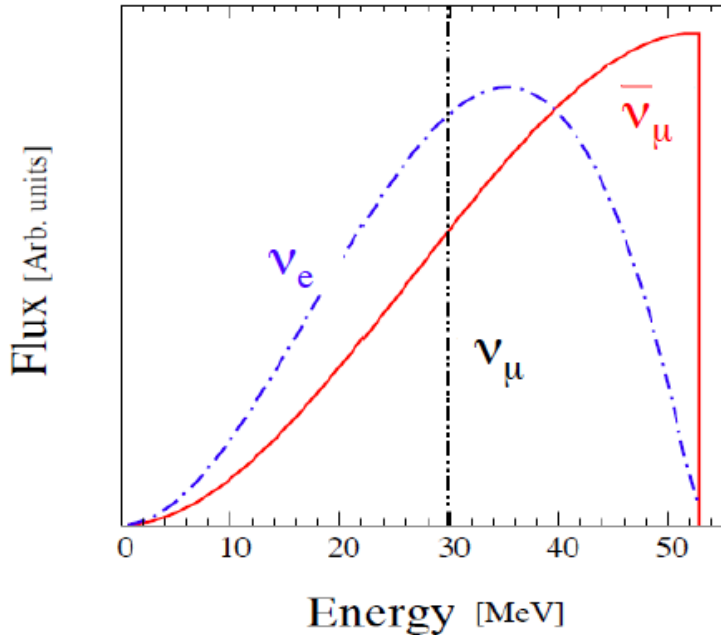
300 kiloton water detector to count the Inverse beta decay

The DAEδALUS Neutrino Source

π^+ decay-at-rest (DAR) beam:



A great place to search for
 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

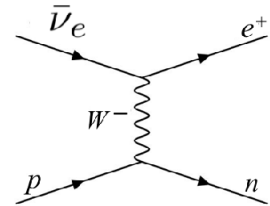


Shape driven by nature!

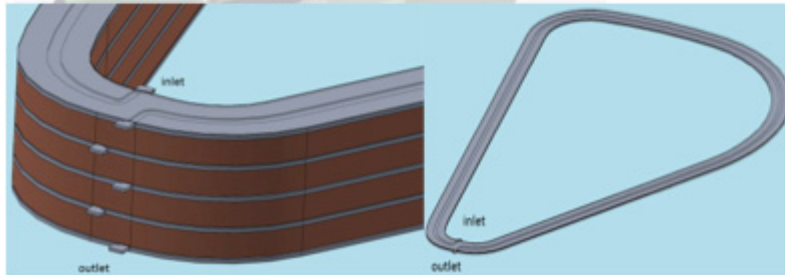
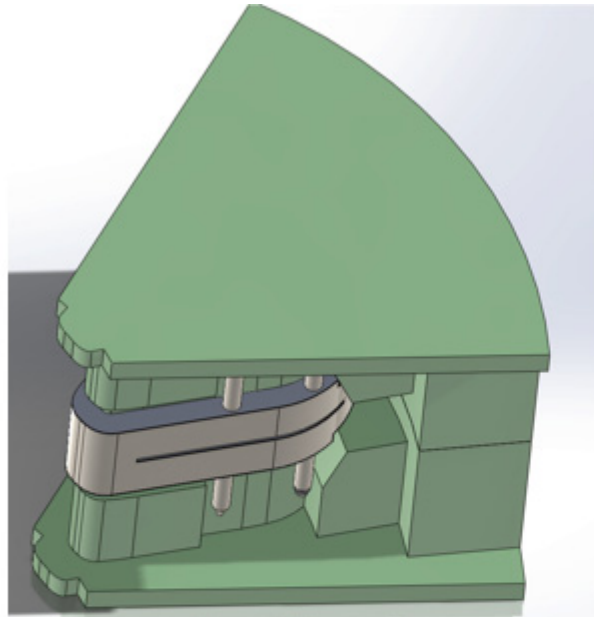
Only the normalization varies
from beam to beam

$\bar{\nu}_e$ is absent in the flux:
look for its appearance!

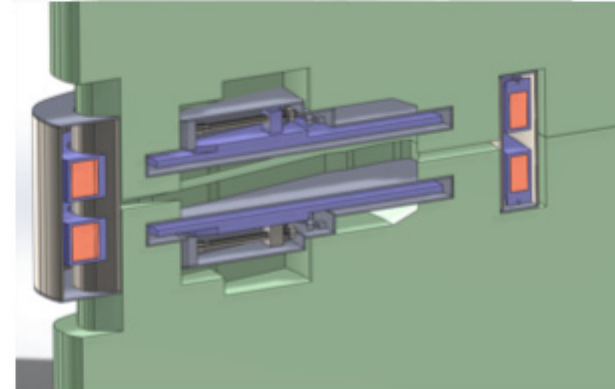
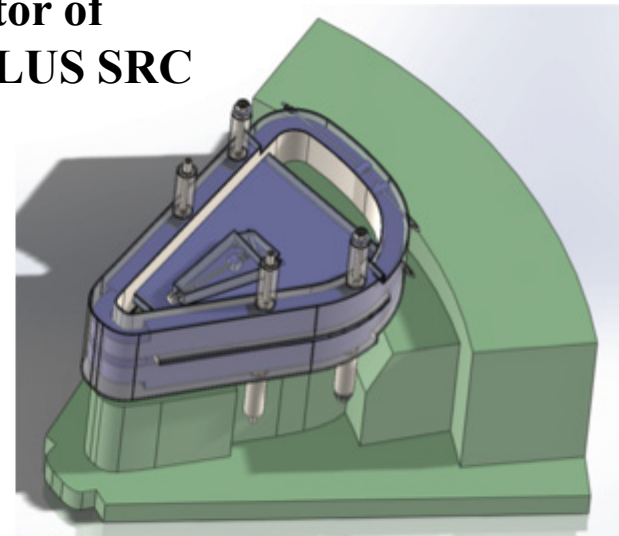
The Inverse
Beta Decay
(IBD)

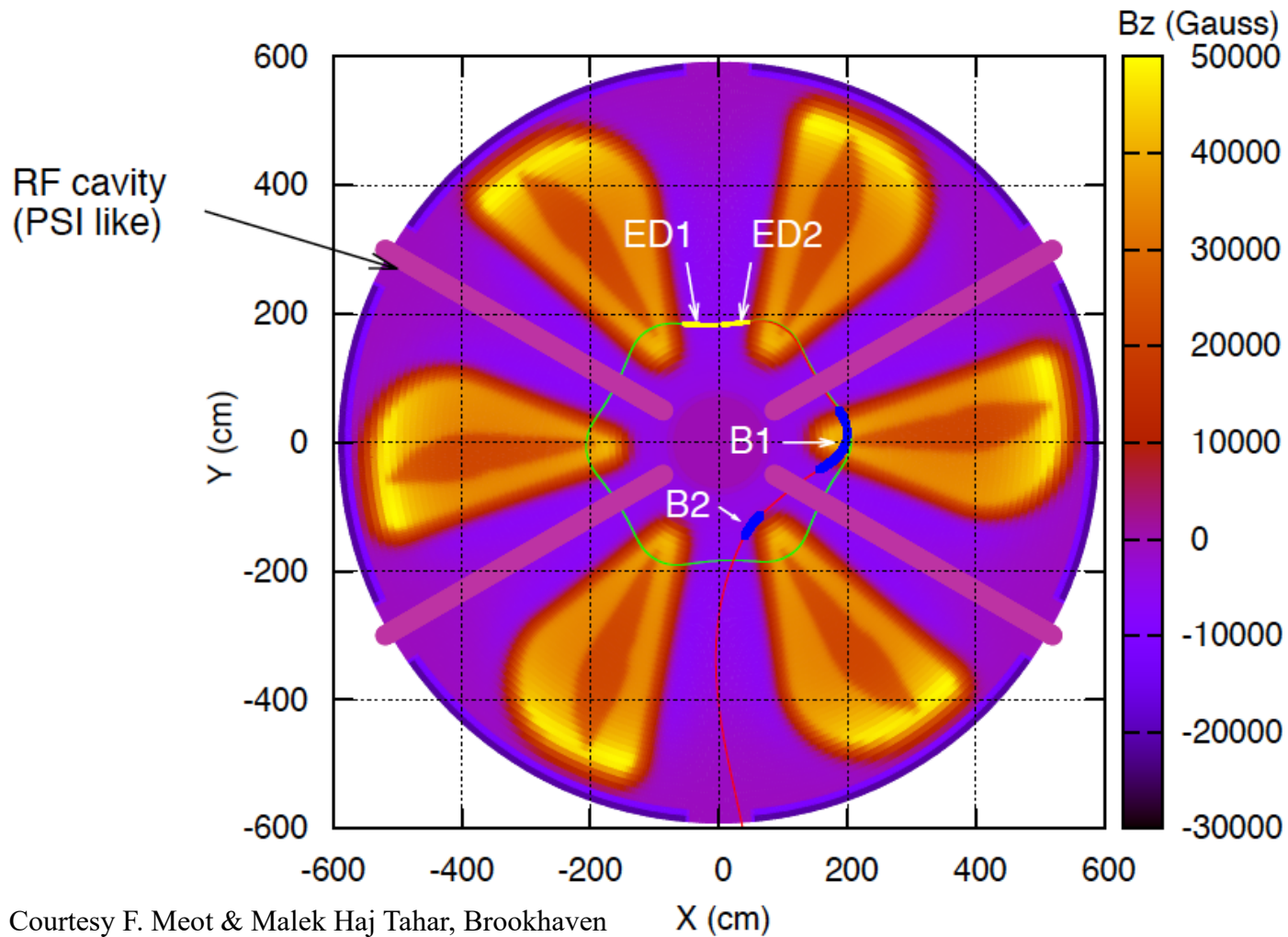


Preliminary study of
superconducting
magnet and cryostat
made by J. Minervini
Group, @ MIT-PSFC
arXiv.org > physics >
arXiv:1209.4886

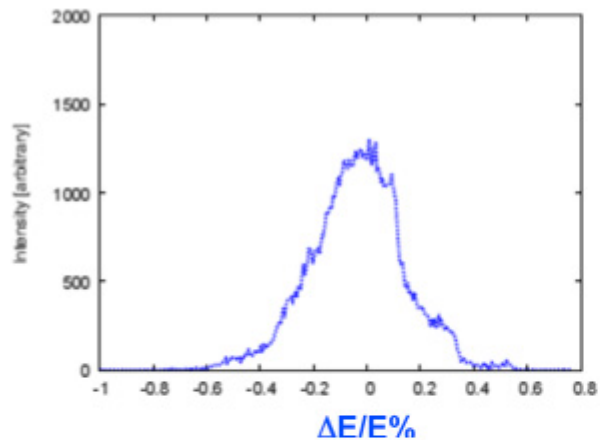


Sector of DAE δ ALUS SRC

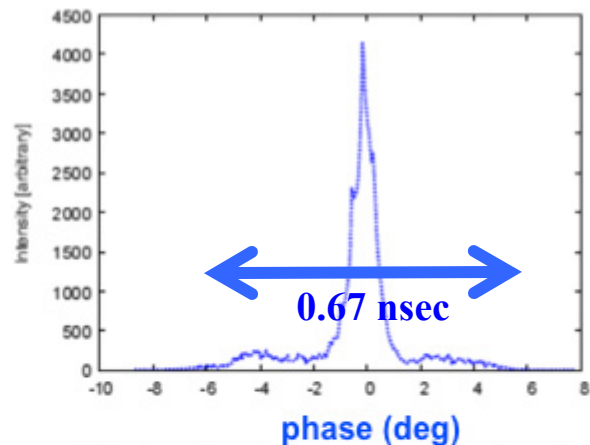




Courtesy F. Meot & Malek Haj Tahar, Brookhaven

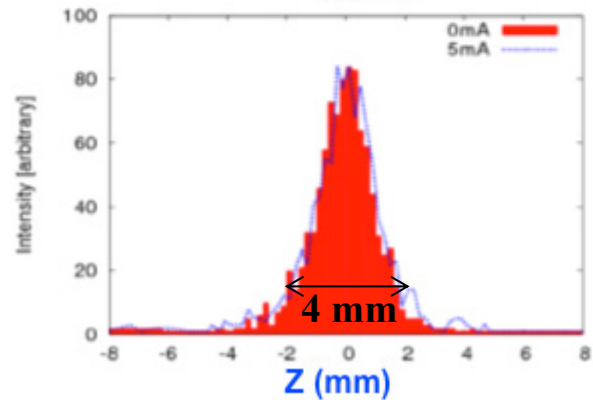


$\Delta E/E\%$



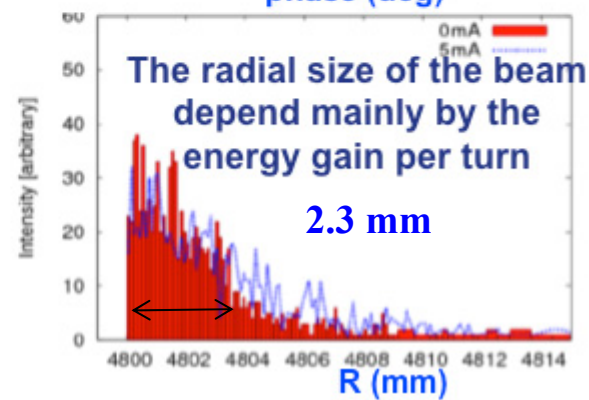
0.67 nsec

phase (deg)



4 mm

Z (mm)



The radial size of the beam
depend mainly by the
energy gain per turn

2.3 mm

R (mm)

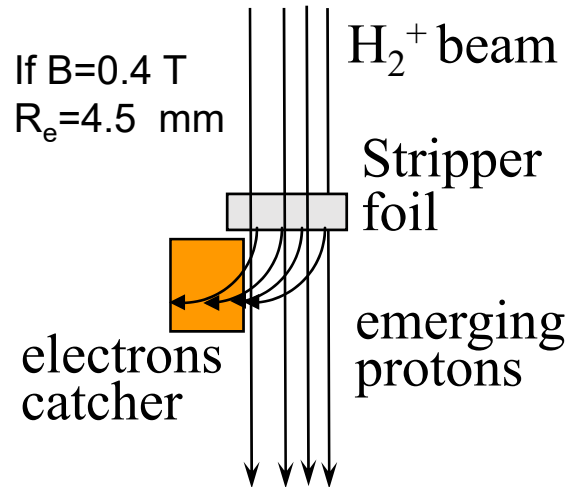
**Histogram of 5 mA H_2^+ beam at the stripper foil position,
simulation include space charge effects (OPAL code)**

**Stripper foil: 5 MW beam @ 800 MeV Xing a stripper foil 1 mg/cm² thick
release ~ 45 W due to nuclear interaction!**

**The electrons removed by the strippers have a full power of about
 $5 \text{ MW} * M_e / M_{H_2} = 5 / (2 * 1826) = \underline{1370 \text{ W}}$!**

Electrons are the main source of stripper damage

But, electrons can be stopped before them strike the stripper!



Stripper Thickness can be thin, because:

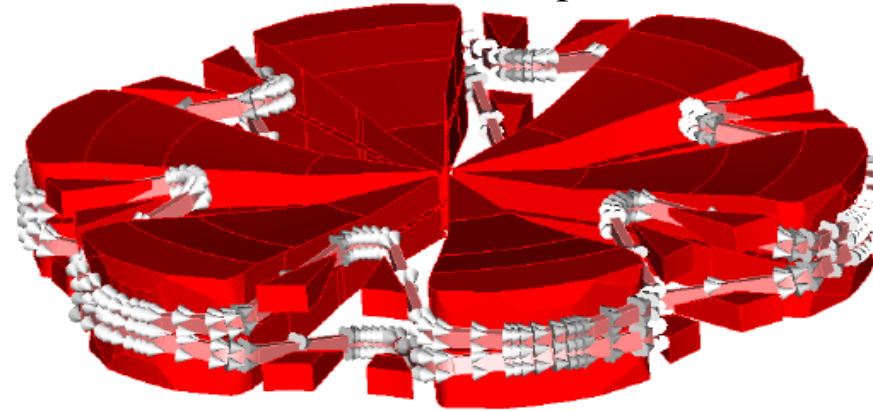
**H⁻ = (p+e+e) → p, e, e is a two steps process
(p+e+e) → H + e → p, e, e**

**H₂⁺ = (p+p+e) → p, p, e is a single step process,
lower probability for H₂⁺ → H + p**

The neutral H can be stopped by a catcher

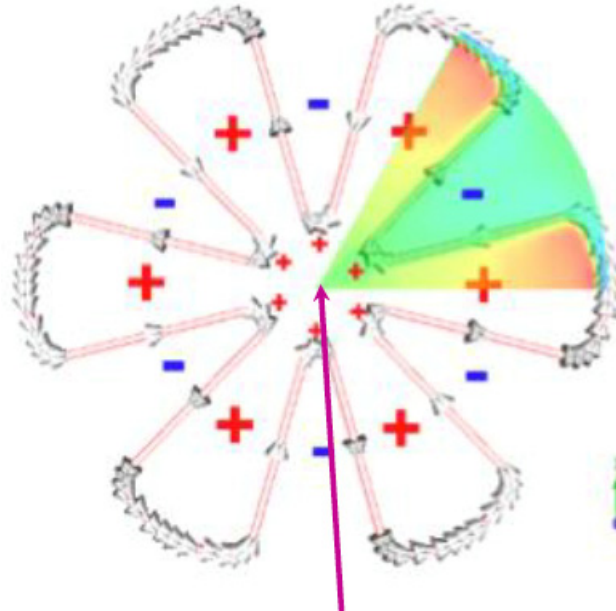
An Innovative Single Stage Cyclotron Driver (S2CD) Compact Cyclotron? Sector Cyclotron? Hybrid Cyclotron!

S2CD is an AIMA patent



Mandrillon, ThEC13, CERN, Geneva, 2013

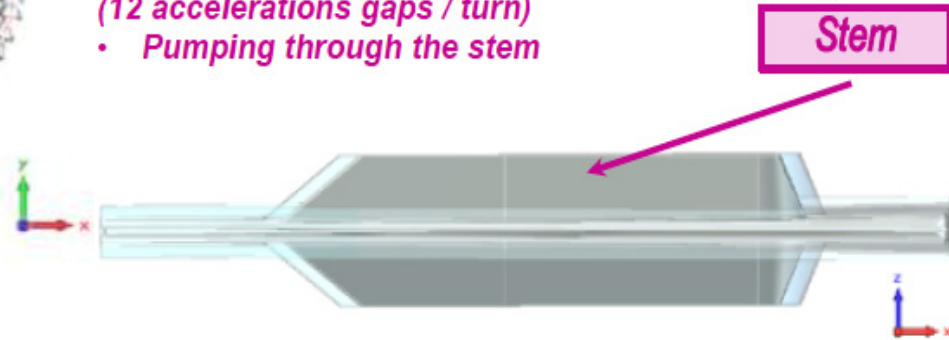
- 6 cavities inserted in the valleys (12 accelerations gaps / turn)
- Pumping through the stem



Two major advantages:

- 1) Low positive B-field in central region;
- 2) Negative field in the valleys;

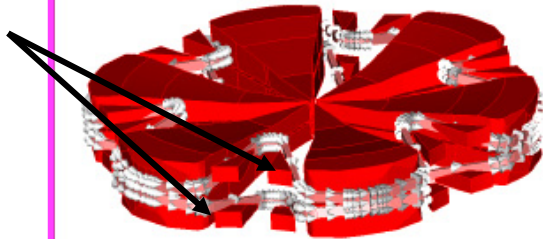
22nd ICCA, Cape Town, 26 September 2019



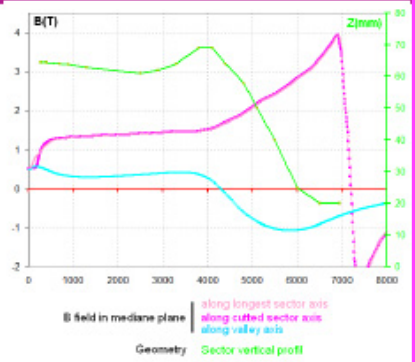
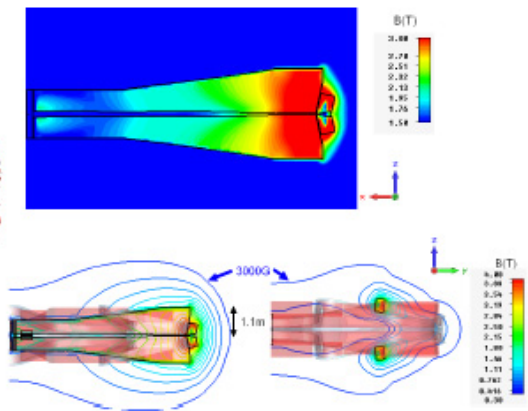
Vertical cross-section through the valley axis

Magnetic field layout of the 1600 MeV H²⁺ design

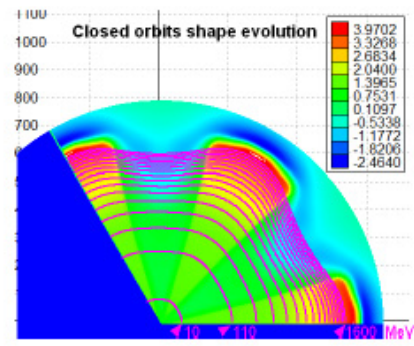
Insertion of iron in the region of reverse field to increase the flutter and avoid the spiral angle



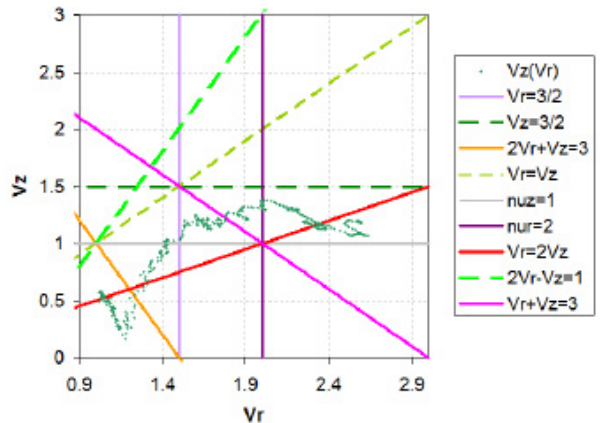
- > 6 straight hill sectors (14 tons)
- > 12 small valley sectors



- > **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!)

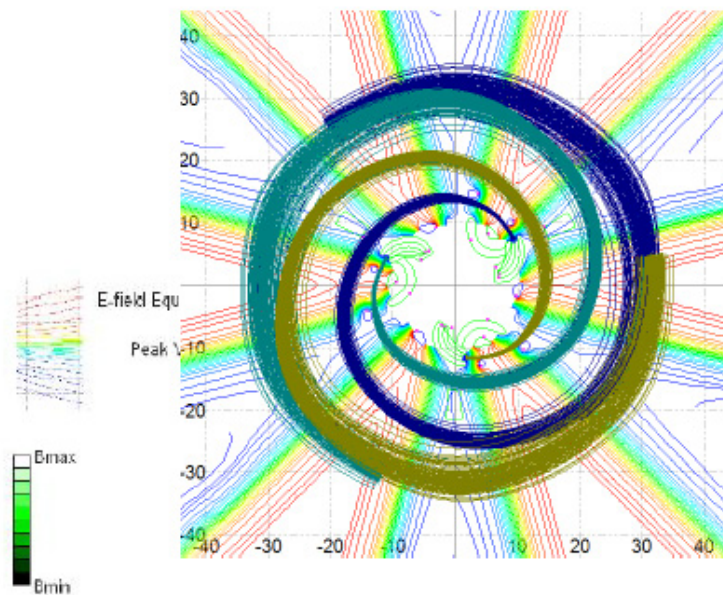
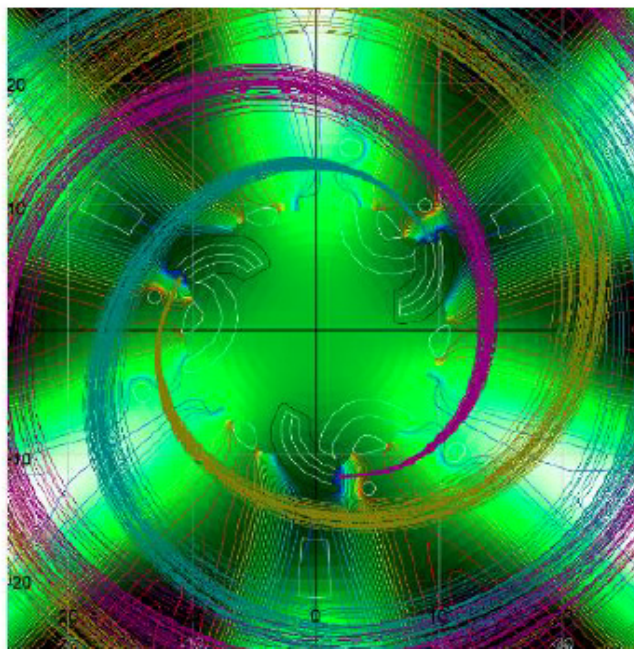


Probably could be convenient to introduce this solution also in Daedalus Cyclotron replacing iron with permendur vanadium to reduce the size and to increase the effect.

Triple injection central region

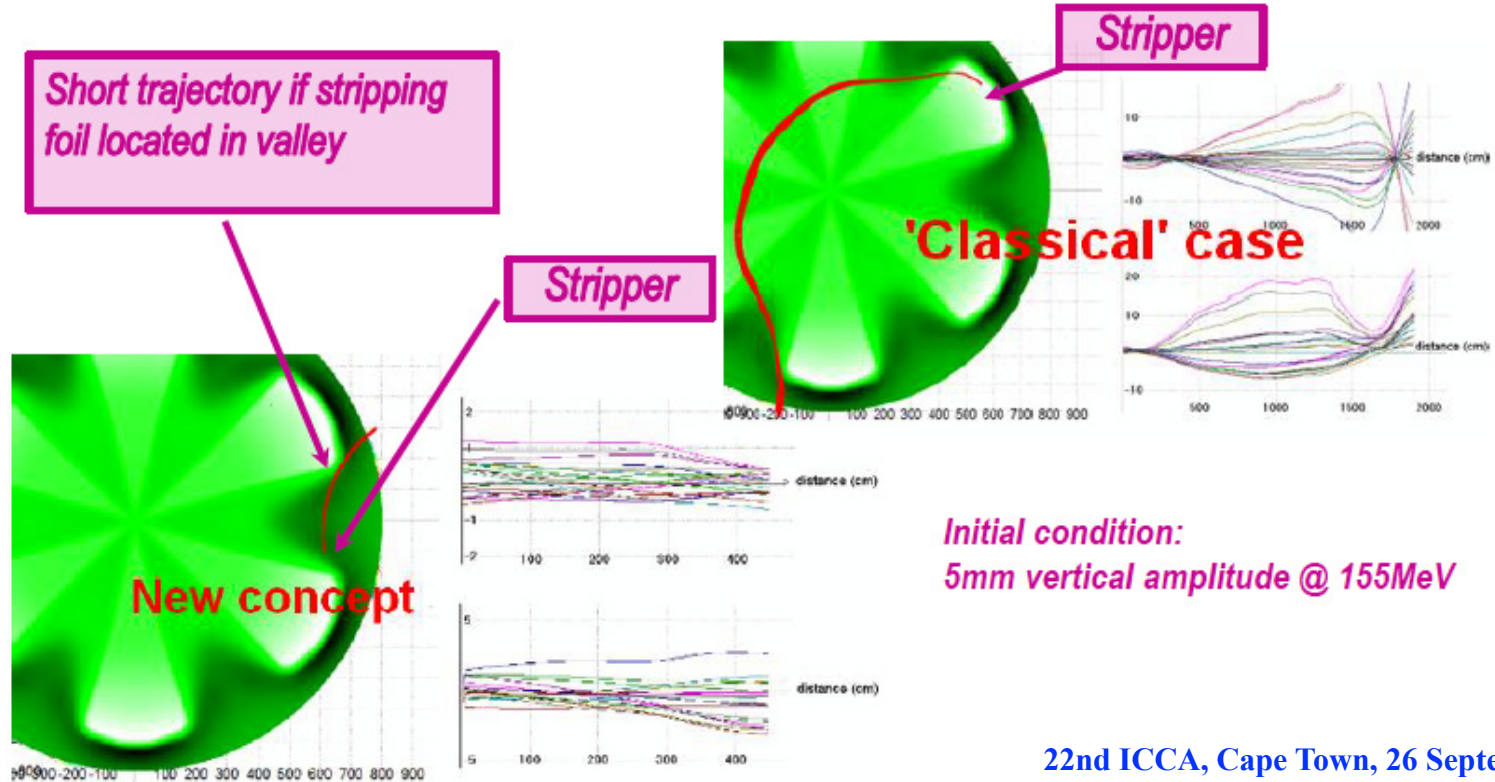
A major advantage: The B-field configuration in the central Region allows acceleration at low energies

→ An injector cyclotron is not needed anymore !



Extraction

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



The SRC match the request for future Meson Factories

(Cywinski et Al.,doi:10.1016/j.physb.2008.11.203PhysicaB(2009),doi:10.1016/j.physb.2008.11.203)

- (i) A pure pulsed mode (ideally at 25kHz \rightarrow T=40 microsec.), with power >500 kW
- (ii) A quasi-CW mode, with power > 2 MW
- (iii) An electrostatically tailored pulse mode (e.g. 5 ns, 25kHz), with power >50 kW

**(i) If macro pulse is 4 μ sec long and 36 μ sec off (25 kHz), duty cycle is 10%,
Peak current=10 mA \rightarrow average power 0.8 MW!**

**(ii) This request can be satisfied quite easily by the described SRC operated in cw
with average power up to 5 MW in a single beam line or 2.5 MW at two beam
lines**

(iii) The SRC, here presented, deliver a train of 1 nsec width pulses , with a period of 20.3 nsec (49.2 MHz), so selection of single bunch is feasible.

1 pulse in a 20 nsec period with repetition rate of 25 kHz \rightarrow duty cycle 0.0005,

$I_{\text{peak}}=10$ mA \rightarrow 4 kW, **power limit is due to current limit of H²⁺ sources.**

Can be achieved simultaneously at the previous mode on independent lines!

Dubna Neutron Source of the 4-th Generation

Neutron flux density: $\bar{\Phi}_{th} = 2 \cdot 10^{14}$; $\hat{\Phi}_{th} = 10^{17}$ n/cm²/s (20 times higher IBR-2)

Neutron pulse duration:

- A. Long pulse $\Delta t_{therm} = 150 \div 300 \mu s$ Reactor
- B. Short pulse $\Delta t_{therm} = 20 \div 30 \mu s$ Superbooster
- C. Very short $\Delta t_{therm} = 0.01 \div 1 \mu s$ Spallation

Proton accelerator for superbooster: deeply subcritical state of the superbooster
superbooster gives multiplication $M = 50 \div 500$
short neutron pulse duration

Open question: the optimum balance between resolution and intensity

Aksenov V.L., Ananiev V.D., Komyshev G.G., Rogov A.D., Shabalin E.P.

JINR P3-2016-90, Dubna, 2016; Phys. Part. Nucl., Lett., 2017, V.14, N 5, P.788

On Limit of Neutron Flux from Pulsed Neutron Source Based on Fission

Dubna Neutron Source of the 4-th Generation

Pulsed reactor plays the role of multiplying target station (superbuster)

deeply subcritical ($0.05 - 0.002 k_{eff}$)
reactor with periodic reactivity modulation
multiplication: $200 \div 500$

Proton Accelerator

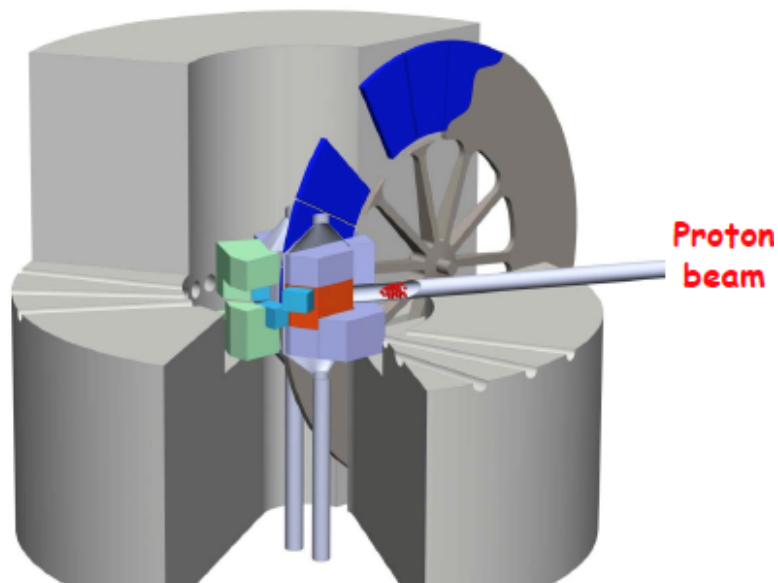
$$E_p = 1.2 \div 0.8 \text{ GeV}$$

$$W \leq 100 \text{ kW}$$

$$\bar{I}_p = 0.1 \text{ mA}, \hat{I}_p \leq 50 \text{ mA}$$

$$\Delta t_p = 20, 200 \mu\text{s}$$

$$\nu = 30, 10 \text{ Hz}$$



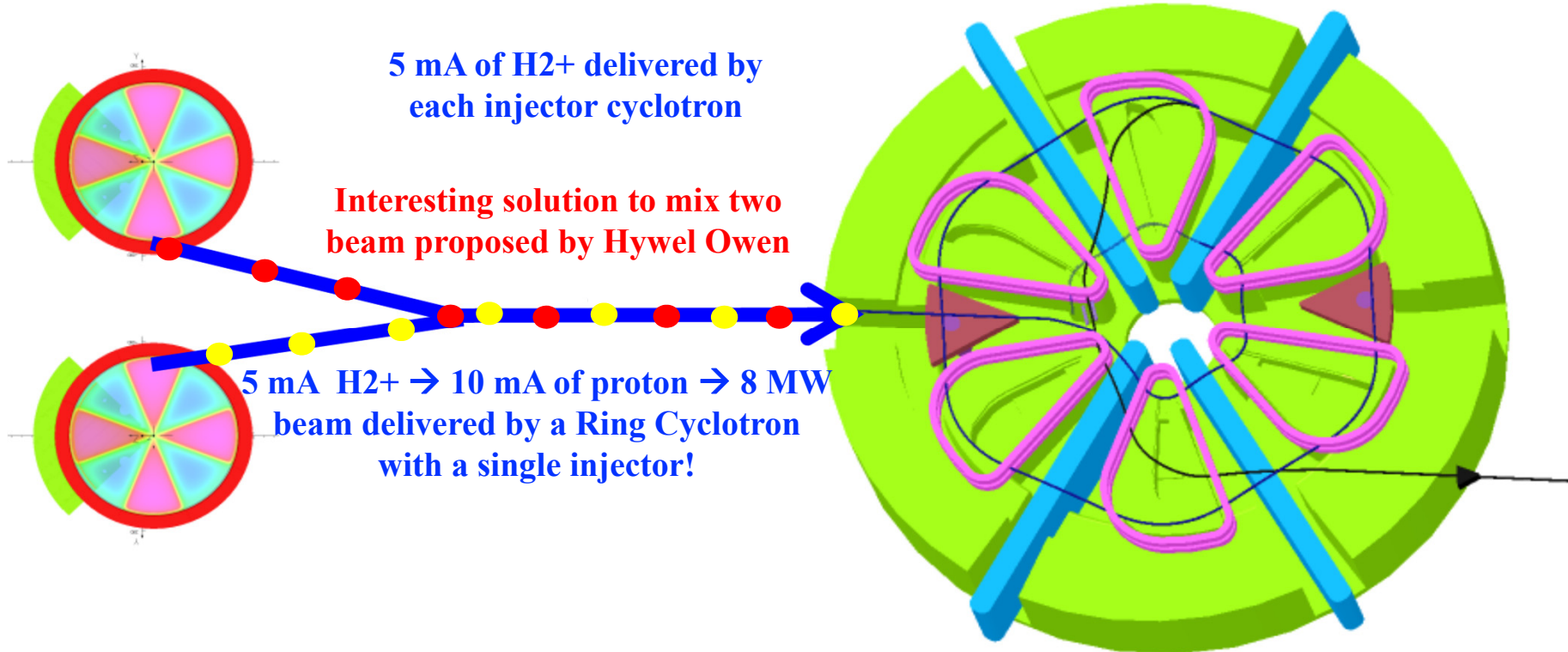
$$W = 10 - 15 \text{ MW}$$

$$\bar{\Phi}_{\text{therm}} = 10^{17}, \hat{\Phi}_{\text{therm}} = 2 \cdot 10^{14} \text{ n/cm}^2/\text{s}$$

$$\text{Long pulse} \leq 200\text{-}300 \mu\text{s}$$

$$\text{Short pulse } 20 - 30 \mu\text{s}$$

To use Daedalus Cyclotron as ADS Driver the beam current limit is posed by the source and by the compact injector cyclotron. We could use two injector cyclotrons and one Ring Cyclotron to increase the average beam power up to a Maximum of 16 MW!

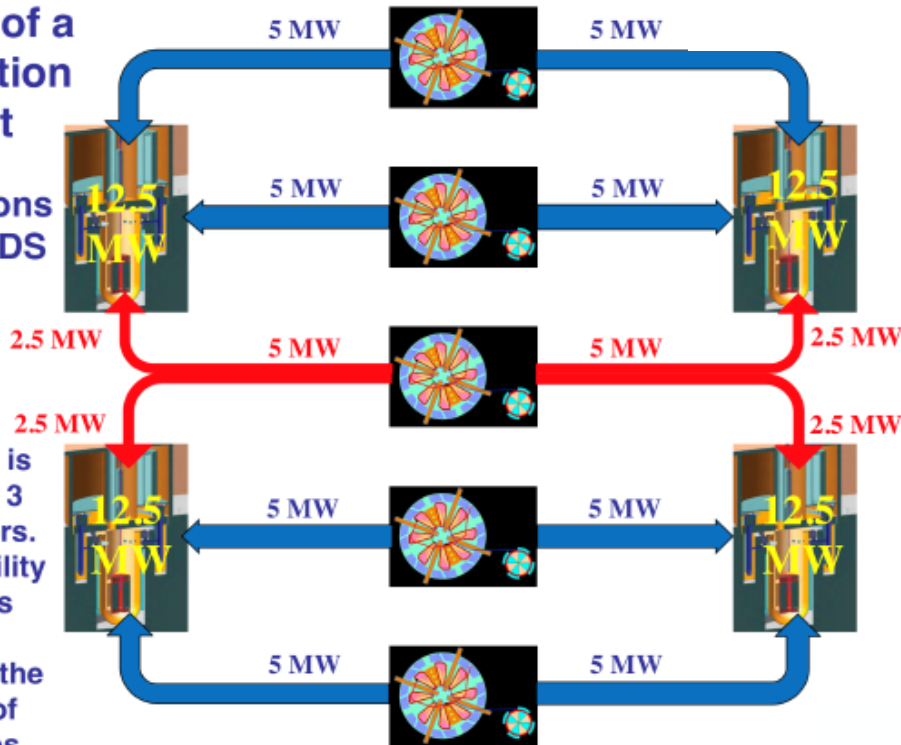


The Daeδalus accelerator for ADS

Layout of a production plant

5 cyclotrons drive 4 ADS

Each ADS is driven by 3 accelerators. Beam stability increases and decreases the number of beam trips



Design basis from S. Henderson, Thorium Energy Conference 2011

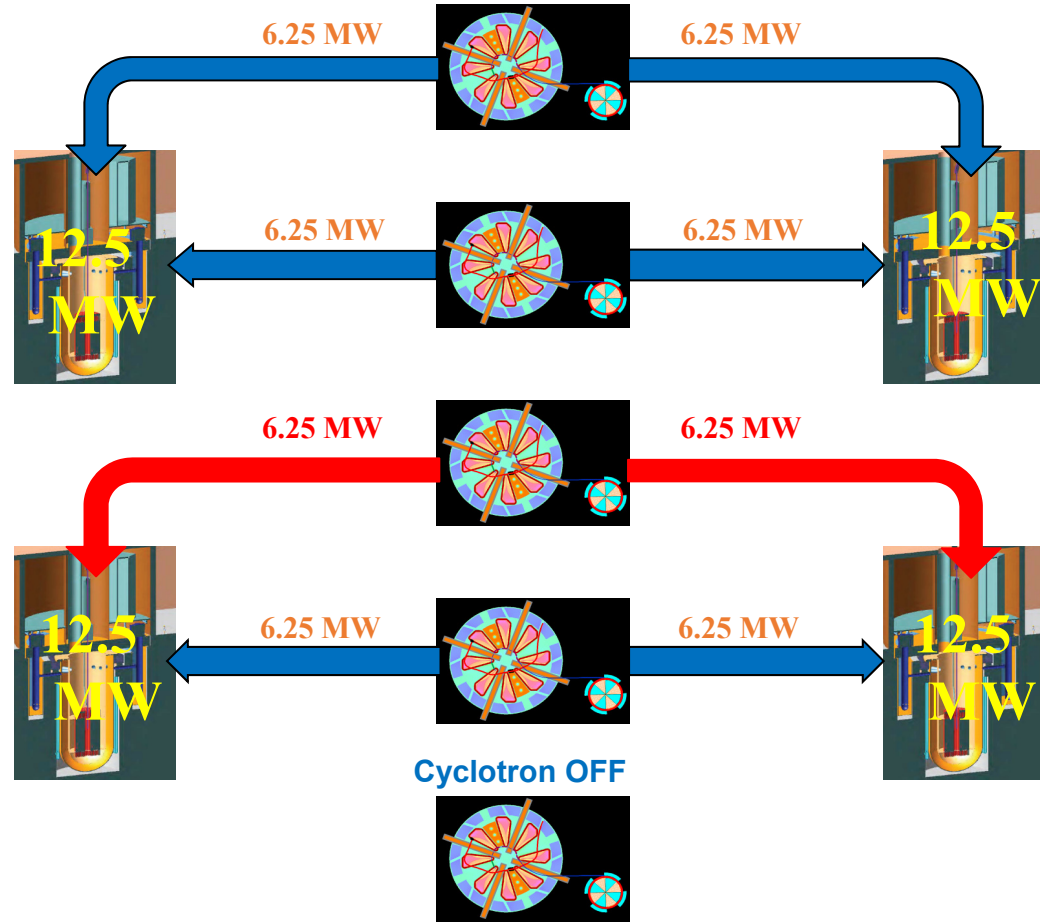
Each DAEDALUS cyclotron could deliver up to a maximum of 16 MW if feed by two injectors!

High power requirements for industrial scale applications (electricity generation)

Beam Trip Frequency: thermal stress and fatigue in reactor structural elements and fuel assembly sets stringent requirements on accelerator reliability.

In case of failure or beam trips in a cyclotron, it is possible to increase the beam current delivered by each Daeδalus cyclotron to maintain the beam power at 12.5 MW!

Alternative layout has been proposed also for the AIMA cyclotron to achieve redundancy!



How remove the Vibrational States from H_2^+ beam?

Layout of high field transfer line to remove vibrational state from H_2^+ beam at energy of 60 MeV/amu

Hiskies formula for Electrical field due to the ion speed and to the magnetic field

$$E_f = 3\beta\gamma B \text{ MV/cm}$$

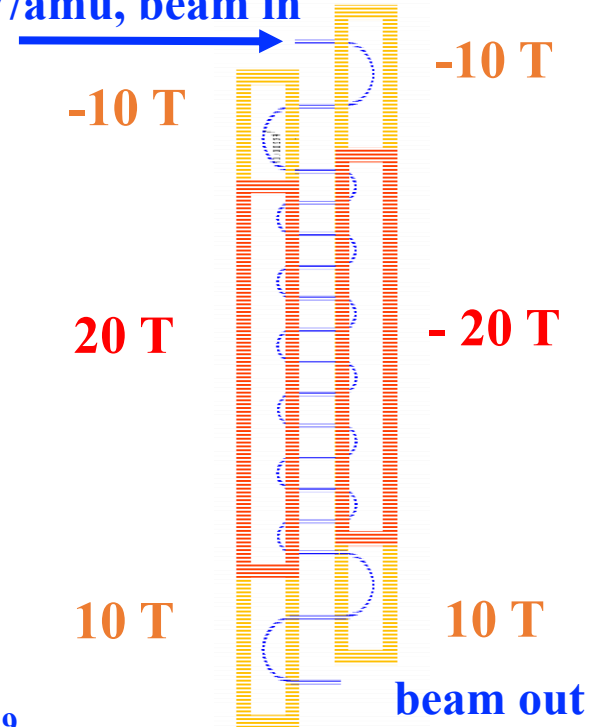
$$800 \text{ MeV/amu} \rightarrow \beta\gamma=1.57 \quad B_{\text{max}}=4.54 \text{ T} \rightarrow \beta\gamma B=7.12$$

$$60 \text{ MeV/amu} \rightarrow \beta\gamma=0.363 \quad B_{\text{max}}=19.6 \text{ T} \rightarrow \beta\gamma B=7.12$$

$$400 \text{ MeV/amu} \rightarrow \beta\gamma=1.015 \quad B_{\text{max}}=3.65 \text{ T} \rightarrow \beta\gamma B=3.70$$

$$60 \text{ MeV/amu} \rightarrow \beta\gamma=0.363 \quad B_{\text{max}}=10.0 \text{ T} \rightarrow \beta\gamma B=3.63$$

H_2^+ 60 MeV/amu, beam in



Production of low-vibrational-state H_2^+ ions

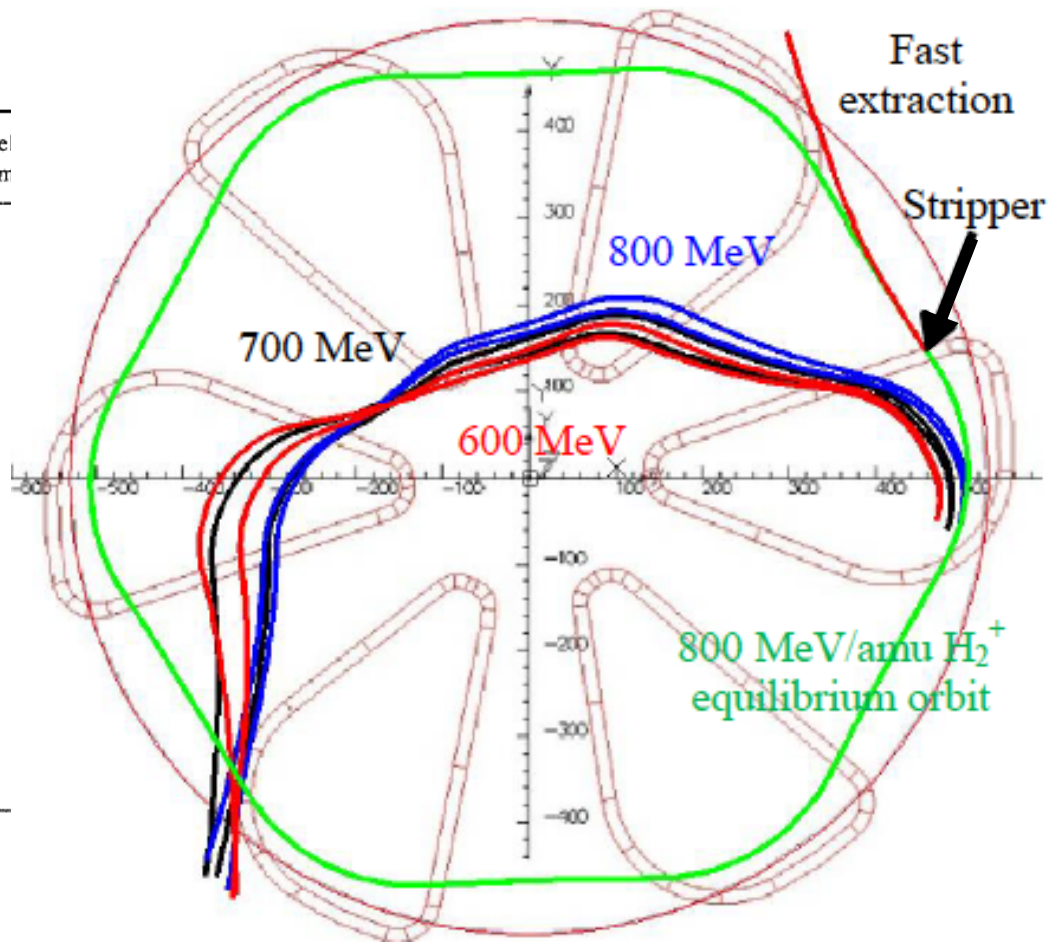
Table 1. H_2^+ vibrational populations. Taken from Cohen *et al* (1960).

v	Von Busch and Dunn	Franck-Condon	Energy (eV) below dissociation limit
0	0.119	0.092	2.645
1	0.190	0.162	2.374
2	0.188	0.176	2.118
3	0.152	0.155	1.877
4	0.125	0.121	1.651
5	0.075	0.089	1.44
6	0.052	0.063	1.243
7	0.037	0.044	1.059
8	0.024	0.030	0.890
9	0.016	0.021	0.734
10	0.0117	0.0147	0.593
11	0.0082	0.0103	0.465
12	0.0057	0.0072	0.351
13	0.00374	0.0051	0.252
14	0.00258	0.0036	0.168
15	0.00175	0.0024	0.100
16	0.00109	0.0016	0.0491
17	0.00056	0.0008	0.027
18	0.00012	0.0002	0.002

800 MeV

700 MeV

600 MeV



Production of low-vibrational-state H_2^+ ions

Table 1. H_2^+ vibrational populations. Taken from Cohen *et al* (1960).

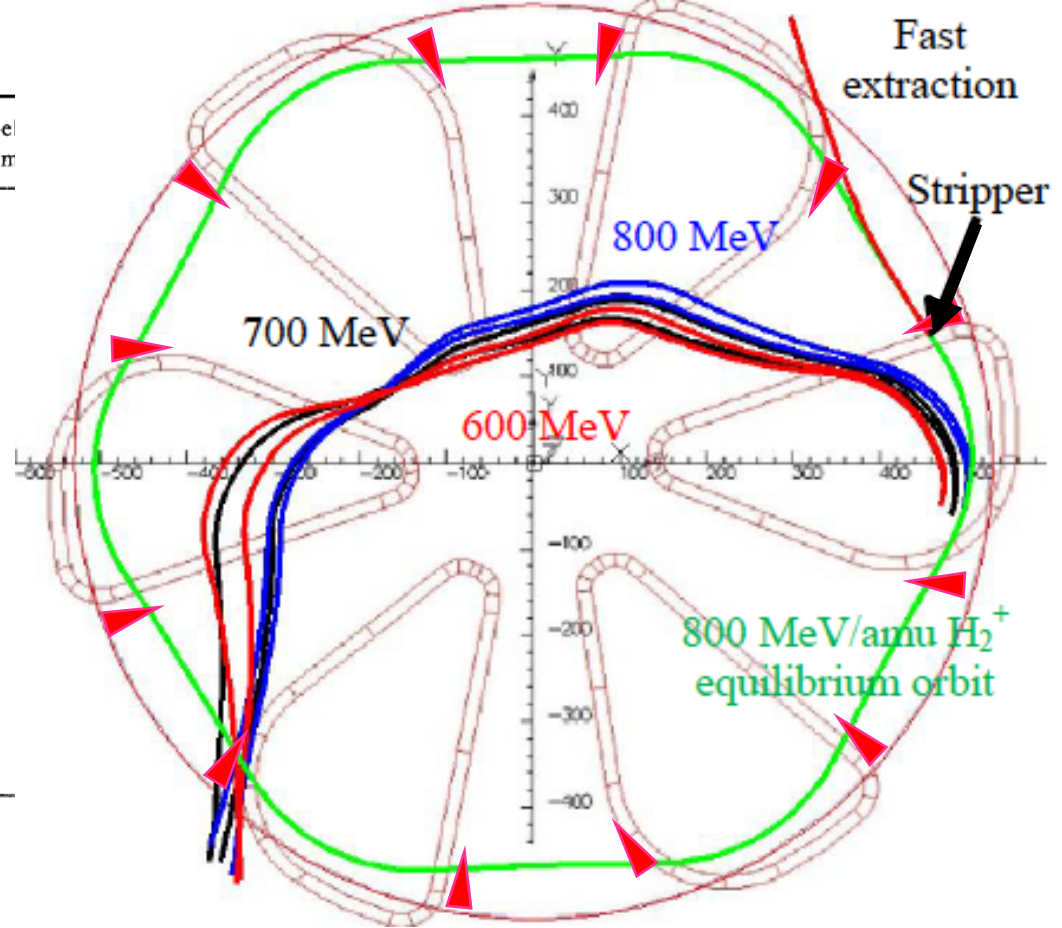
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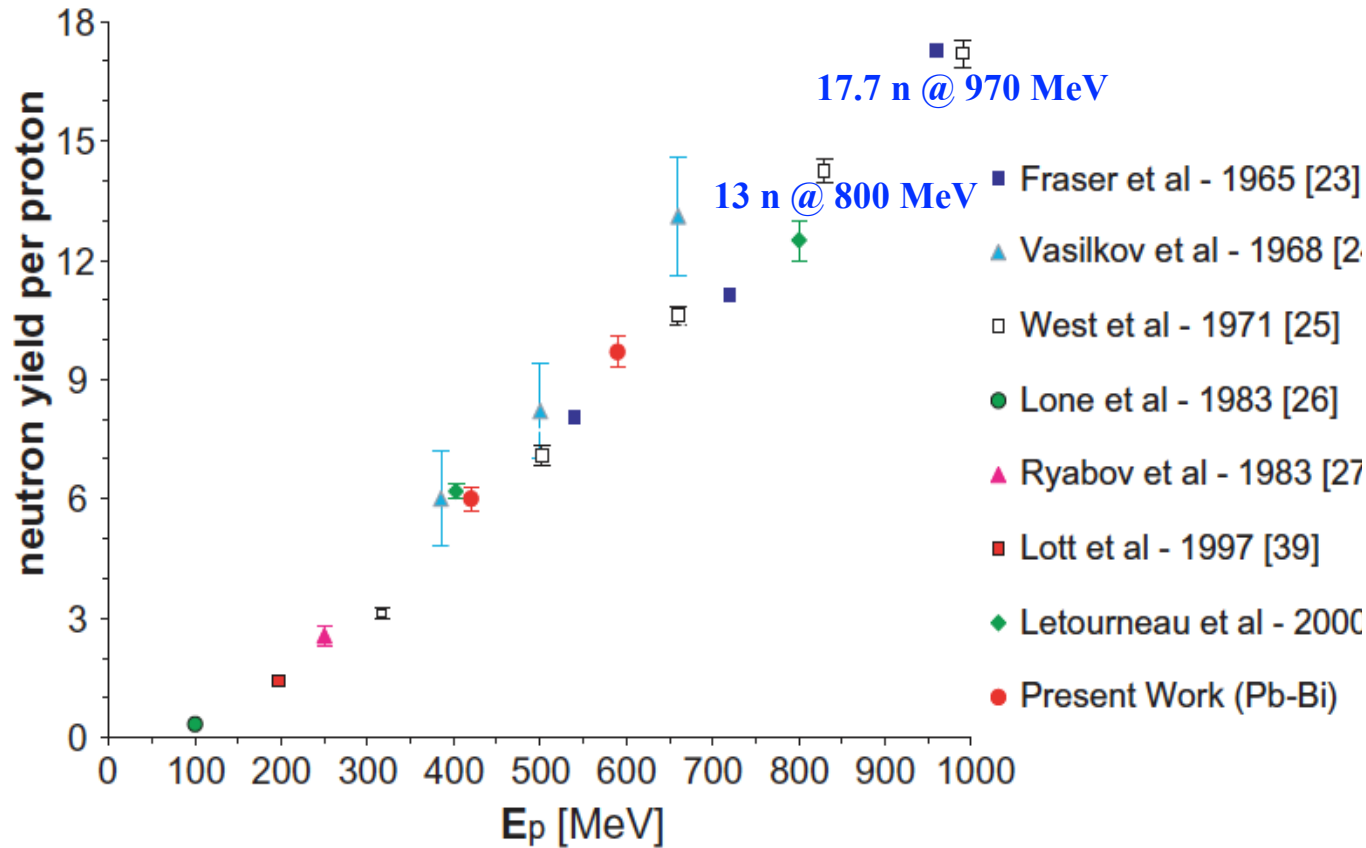
800 MeV

700 MeV

600 MeV

Permendur vanadium negative field?





Probably it is convenient to investigate solutions based on cyclotrons able to deliver protons at higher energy.

1 GeV proton produce +38 % of neutrons vs 800 MeV proton.
This means lower beam current of a factor 35% !

To produce the same neutrons total beam power 5-10% lower.

*Thanks for
your attention!*

Aldebaran

19/08/2019

Crediti e copyright: Dario Giannobile. Fonte: apod.nasa.gov