National Nuclear Physics Summer School

Cyclotrons for Nuclear Physics: Past, Present, Future

Daniel Winklehner, MIT

Preface

- Me: Daniel Winklehner, Postdoc at LNS in the Neutrino and Dark Matter Group. Email: *winklehn@mit.edu*
- *Goal of this lecture:*

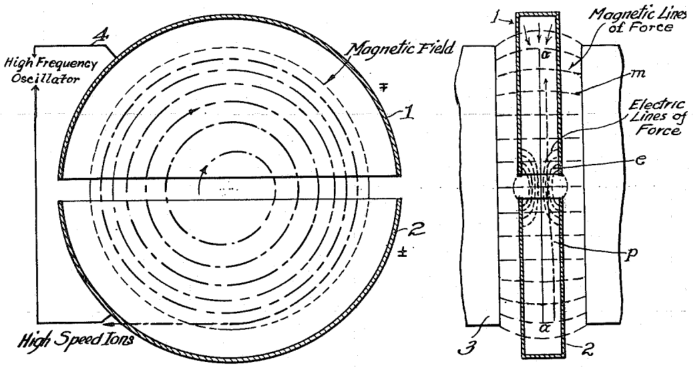
A relaxed hour-and-a-half about the history and future of an iconic particle accelerator.
No homework, no quiz. :)

- Additional Information:
  - John Livingood: *Principles of Cyclic Particle Accelerators*
  - Joint Accelerator Conferences Website: *http://www.jacow.org/*
  - United States Particle Accelerator School (USPAS): *http://uspas.fnal.gov*

These slides contain material from a variety of sources. I tried to put references on the slides as much as possible. Apologies for unquoted original material.

Outline

- **Prelude:** Basic particle accelerator principles and figures of merit
- **Act I:** The ghost of cyclotrons past, or:
  "Who is Ernest Orlando Lawrence?"
- **Intermezzo:** Cyclotron concepts,
  types of cyclotrons, uses, and limitations
- **Act II:** The ghost of cyclotrons present, or:
  "Why are cyclotrons still important?"

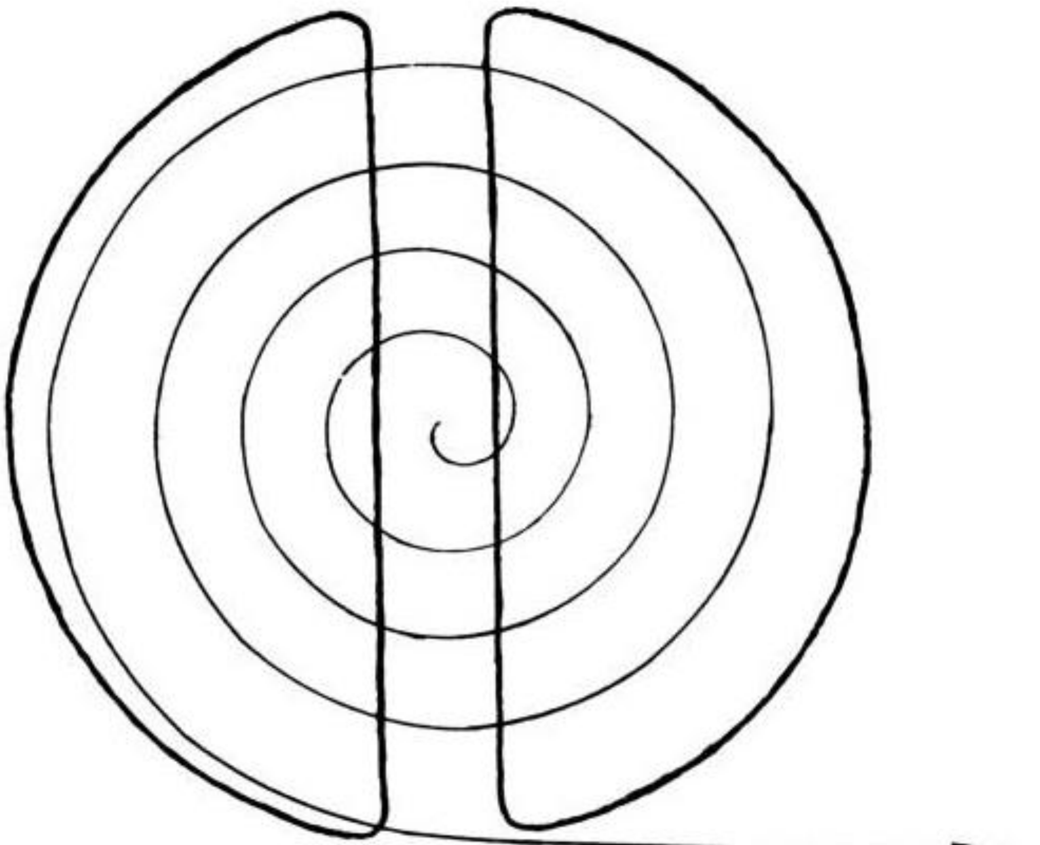


From Lawrence's 1934 patent
Source: wikipedia.org

  – Current state-of-the-art cyclotrons and their applications
- **Act III:** The ghost of cyclotrons yet-to-come, or:
  "It's nice, but does it cure cancer?" (spoiler: yes, sometimes.)
  – Ironless cyclotron, cyclotron gas stopper, cyclotrons for neutrino physics, Accelerator Driven Systems (ADS) …

The cyclotron as seen by…

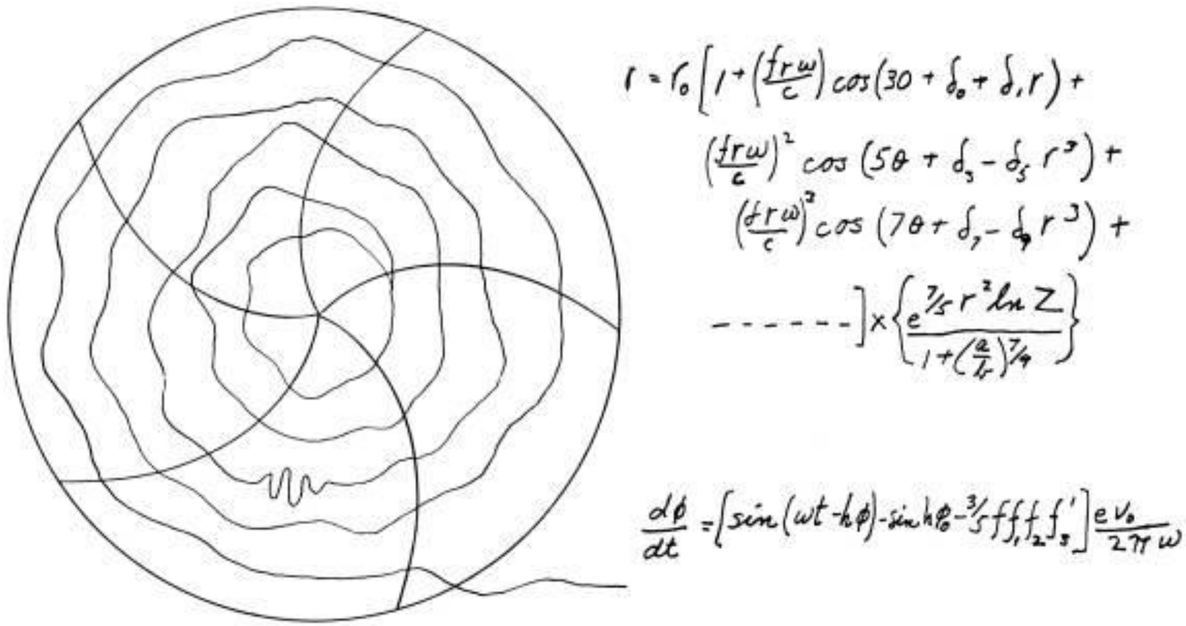
By David L. Judd and Ron MacKenzie



…the inventor

The cyclotron as seen by…

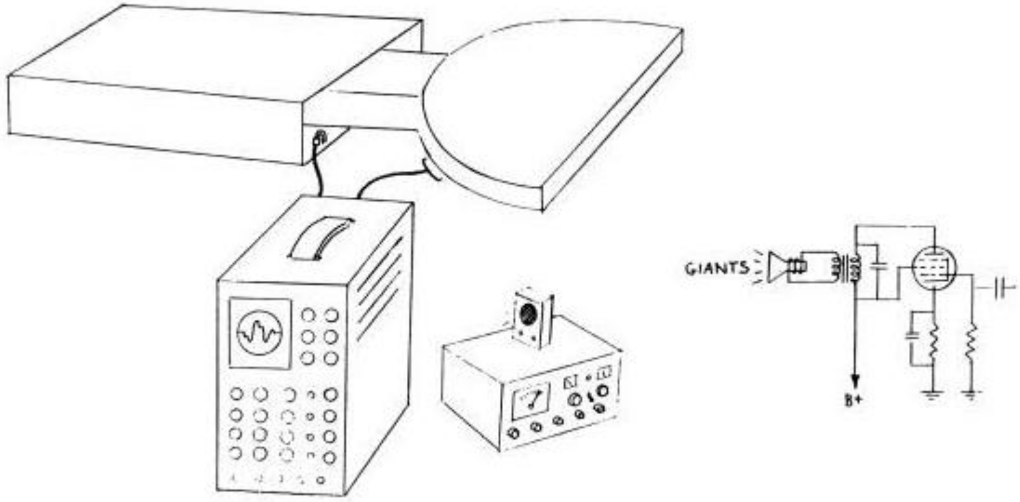
By David L. Judd and Ron MacKenzie



…the accelerator theorist

The cyclotron as seen by…

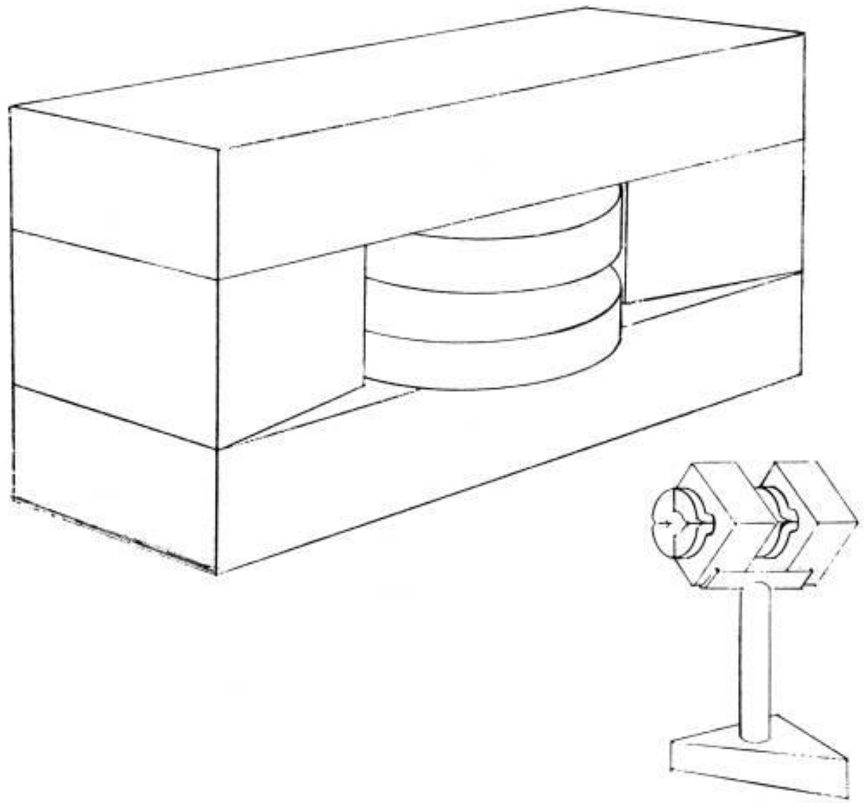
By David L. Judd and Ron MacKenzie



…the electrical engineer

The cyclotron as seen by…

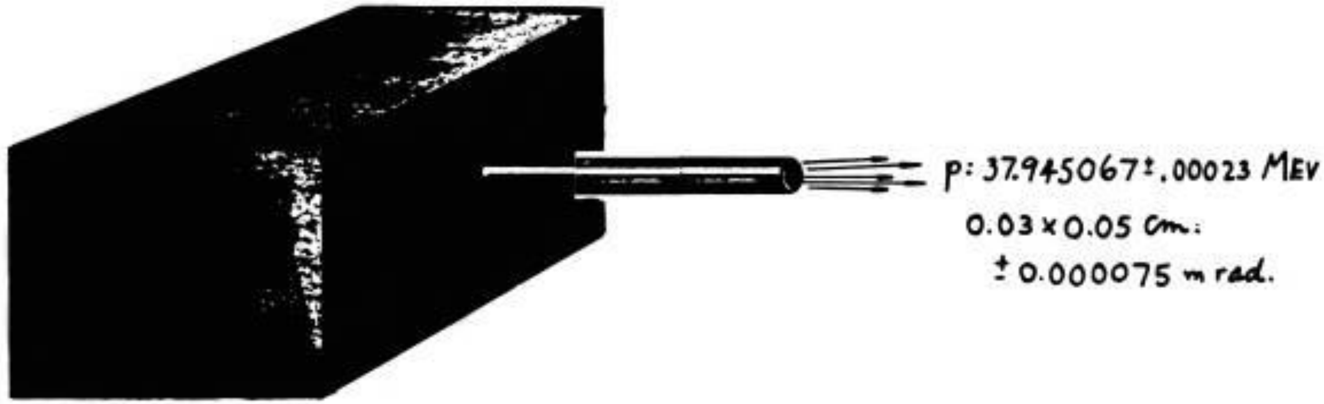
By David L. Judd and Ron MacKenzie



…the mechanical engineer

The cyclotron as seen by…

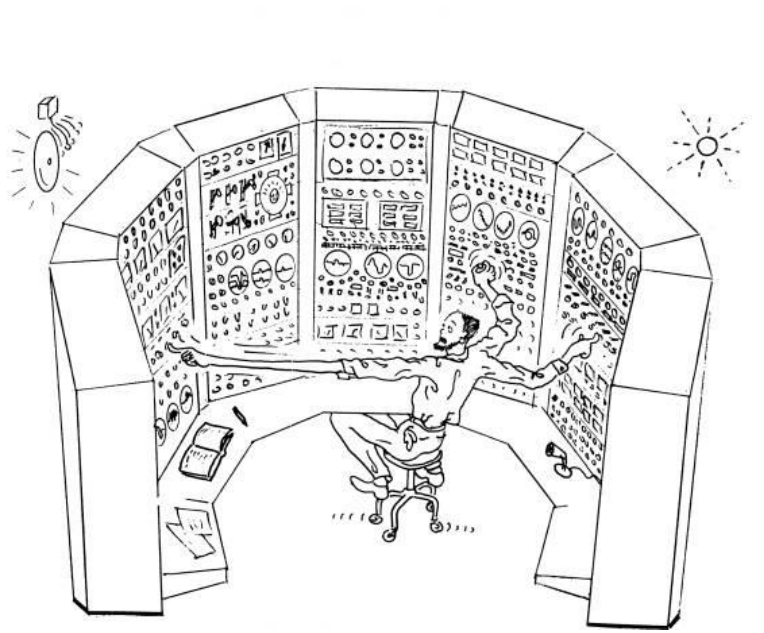
By David L. Judd and Ron MacKenzie



…the experimentalist

The cyclotron as seen by…

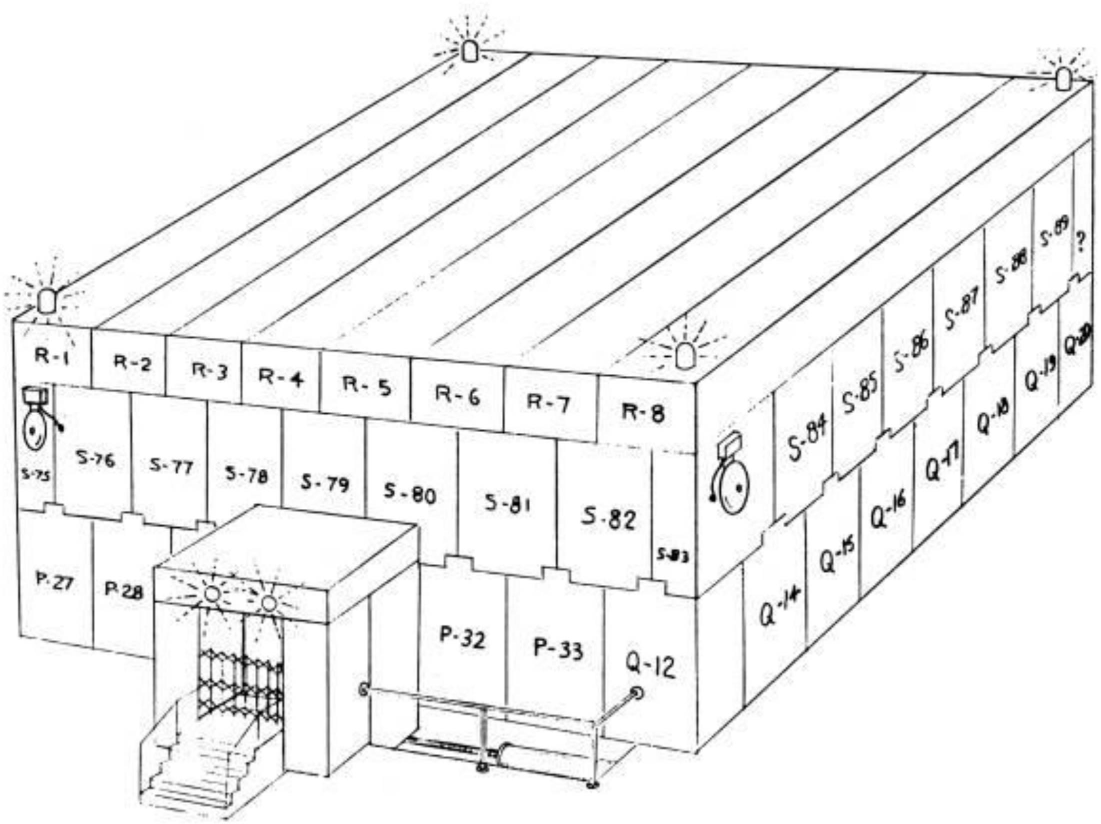
By David L. Judd and Ron MacKenzie



…the operator

The cyclotron as seen by…

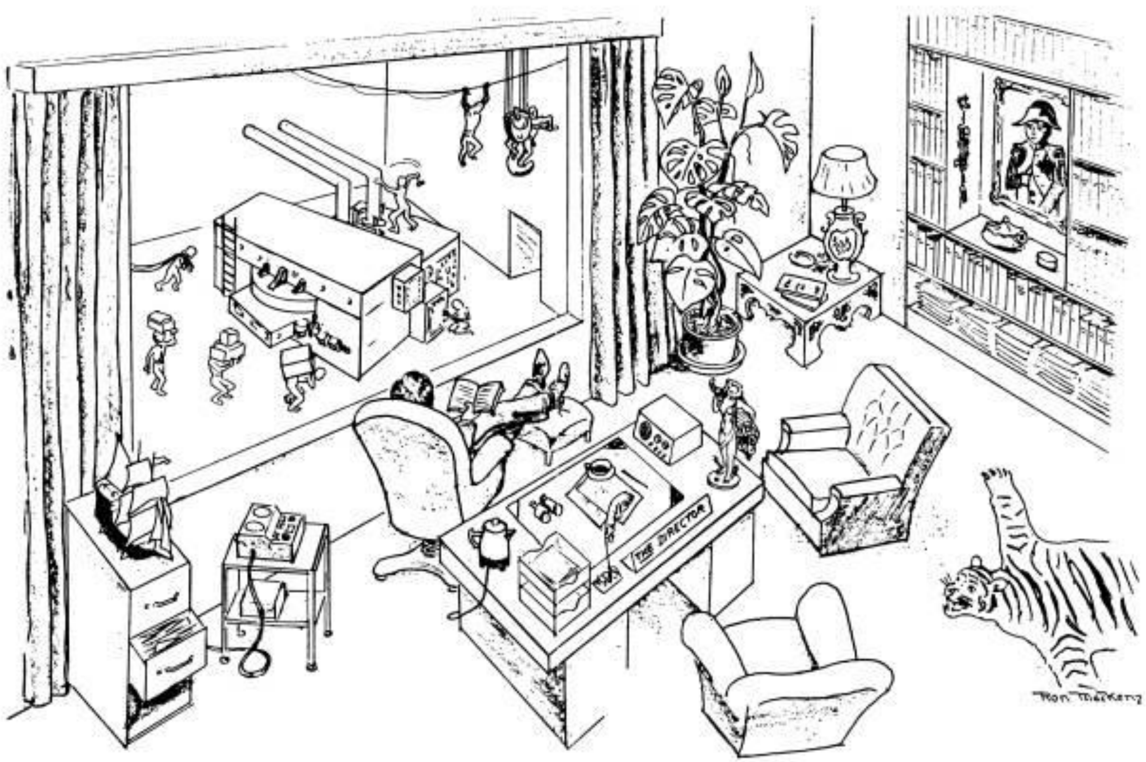
By David L. Judd and Ron MacKenzie



…the health physicist

The cyclotron as seen by…

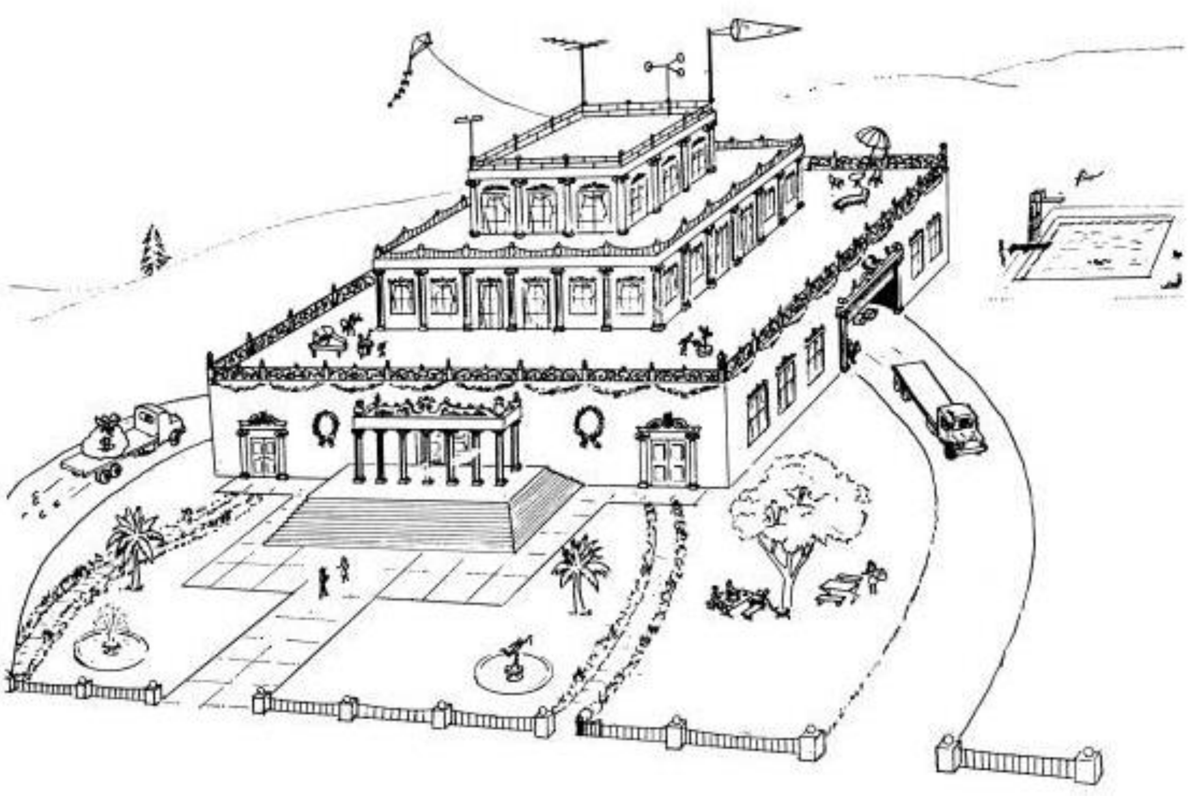
By David L. Judd and Ron MacKenzie



…the laboratory director

The cyclotron as seen by…

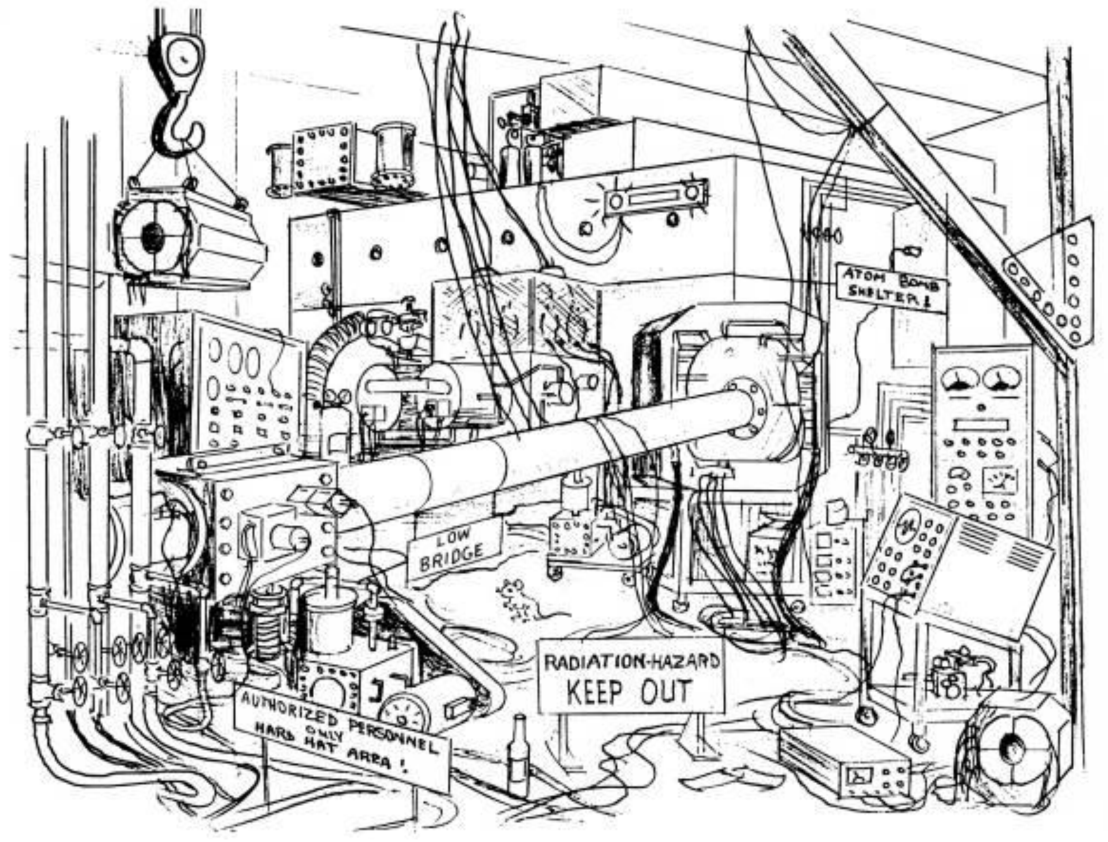
By David L. Judd and Ron MacKenzie



…the funding agency

The cyclotron as seen by…

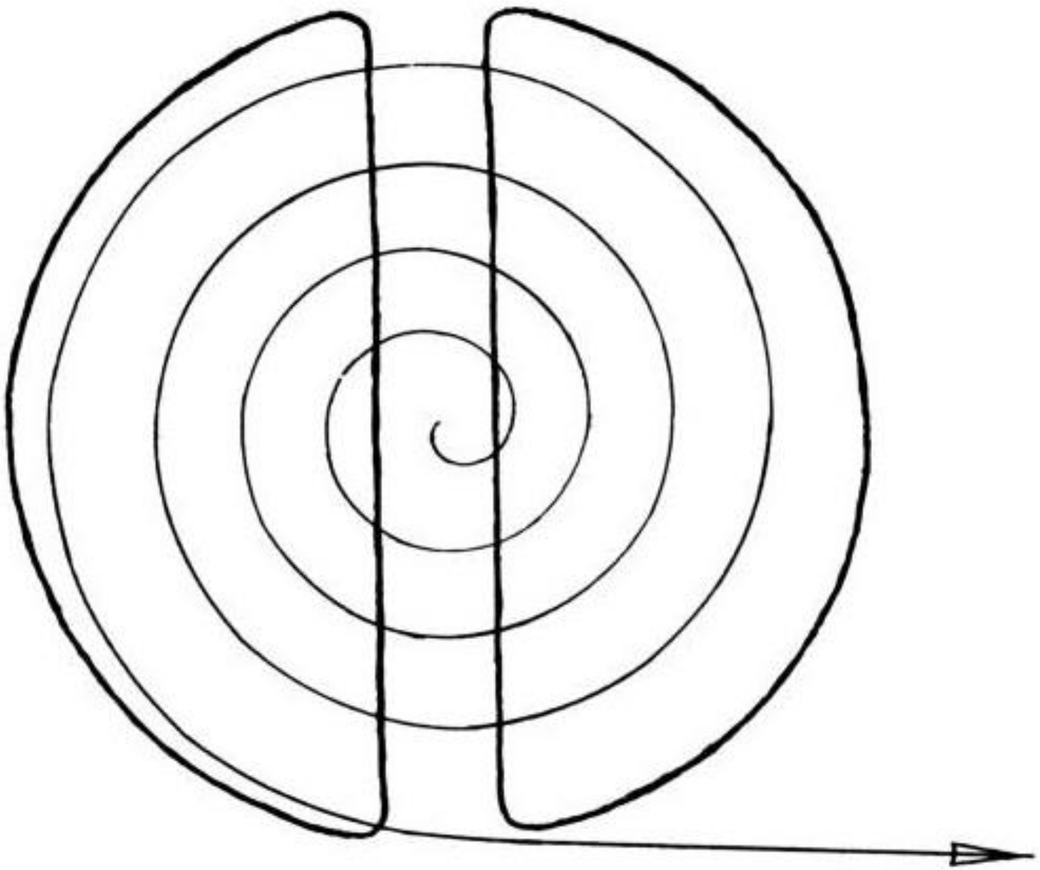
By David L. Judd and Ron MacKenzie



…the visitor

The cyclotron as seen by…

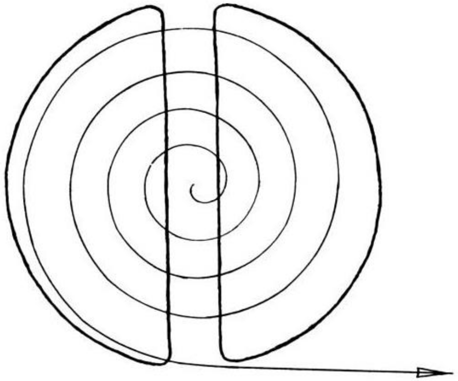
By David L. Judd and Ron MacKenzie

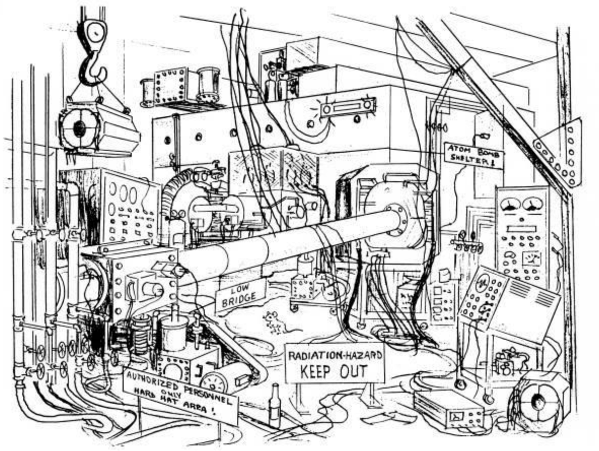


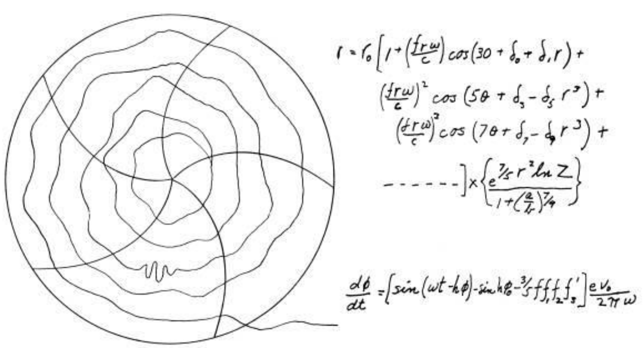
…the student

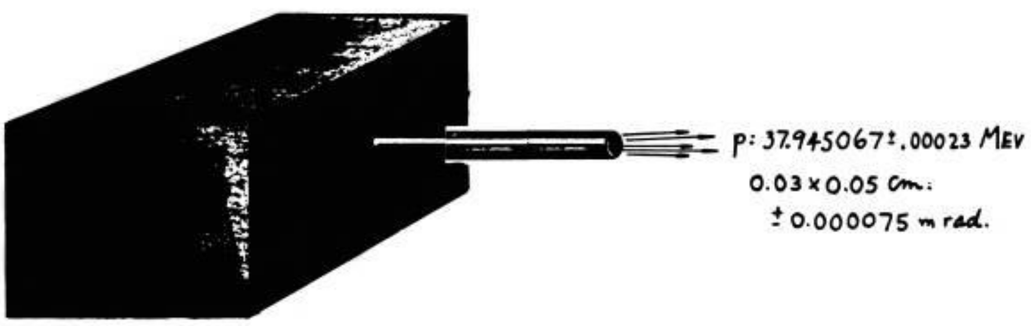
The cyclotron as seen by…

By David L. Judd and Ron MacKenzie









…you, after today

Quick Recap: Beam Parameters

A beam is…"an ensemble of particles that travel mostly in the same direction" (let's use z)

- Typically: $v_z \gg v_x, v_y$
- Can be comprised of multiple ion species:

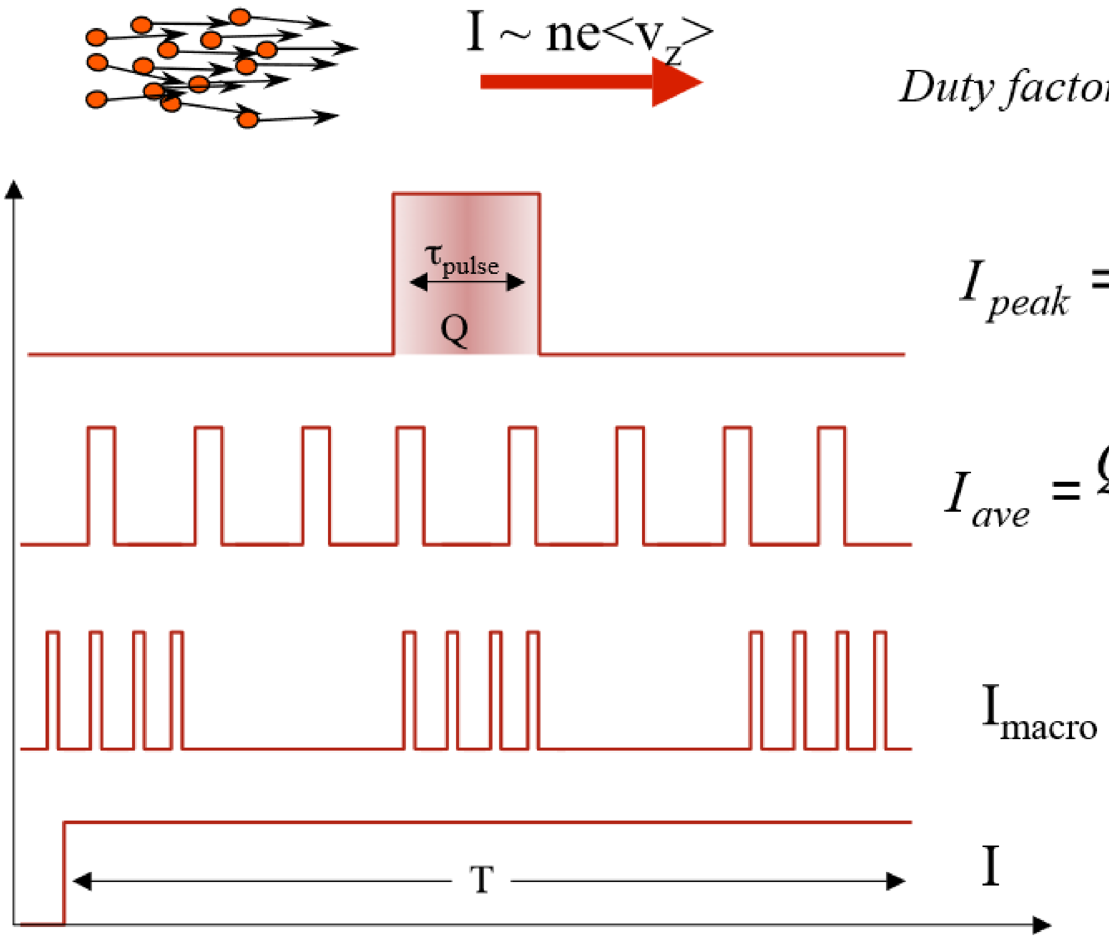
$$q_i = Q_i \cdot e,\ m_i = A_i \cdot amu\ (931.5\,\mathrm{MeV/c^2})$$

- Since we are dealing with moving charge, there is a current

$$J_i \cdots \text{species current density, } \mathrm{I}_i \cdots \text{ species total current (A)}$$

- Beam can be DC, cw, or pulsed/bunched

Longitudinal Beam Properties
Bunch Currents



$$Duty\ factor = \frac{\sum \tau_{pulse}}{T}$$

$$I_{peak} = Q / \tau_{pulse}$$

$$I_{ave} = Q_{tot} / T$$

From: W. Barletta

Distributions in 6D Phase Space (+t)

- Particle number density:

$$n(x, y, z, p_x, p_y, p_z, t)$$

or $$n(x, y, z, v_x, v_y, v_z, t)$$

- Charge density: $\rho = q \cdot n$
- Simplification: $n(x, x', y, y', z, \Delta p/p)$ ("Trace Space")

$$x' = \frac{dx}{dz} = \frac{v_x}{v_z}, \quad y' = \frac{dy}{dz} = \frac{v_y}{v_z}$$

4D/2D Projections / Slices

- If there is no coupling between longitudinal motion and transversal motion the transversal Trace Space density is

$$n(x, x', y, y')$$

- Maybe we are even only interested in 2D projections

$$n(x, x') = \iint dy dy' n(x, x', y, y')$$

- Or slices (interesting in diagnostics and simulations)

$$n(r, r') = n(x, x', y = 0, y' = 0)$$

- Because these can tell us something about our beam line transport…

Kapchinsky-Vladimirsky Distribution

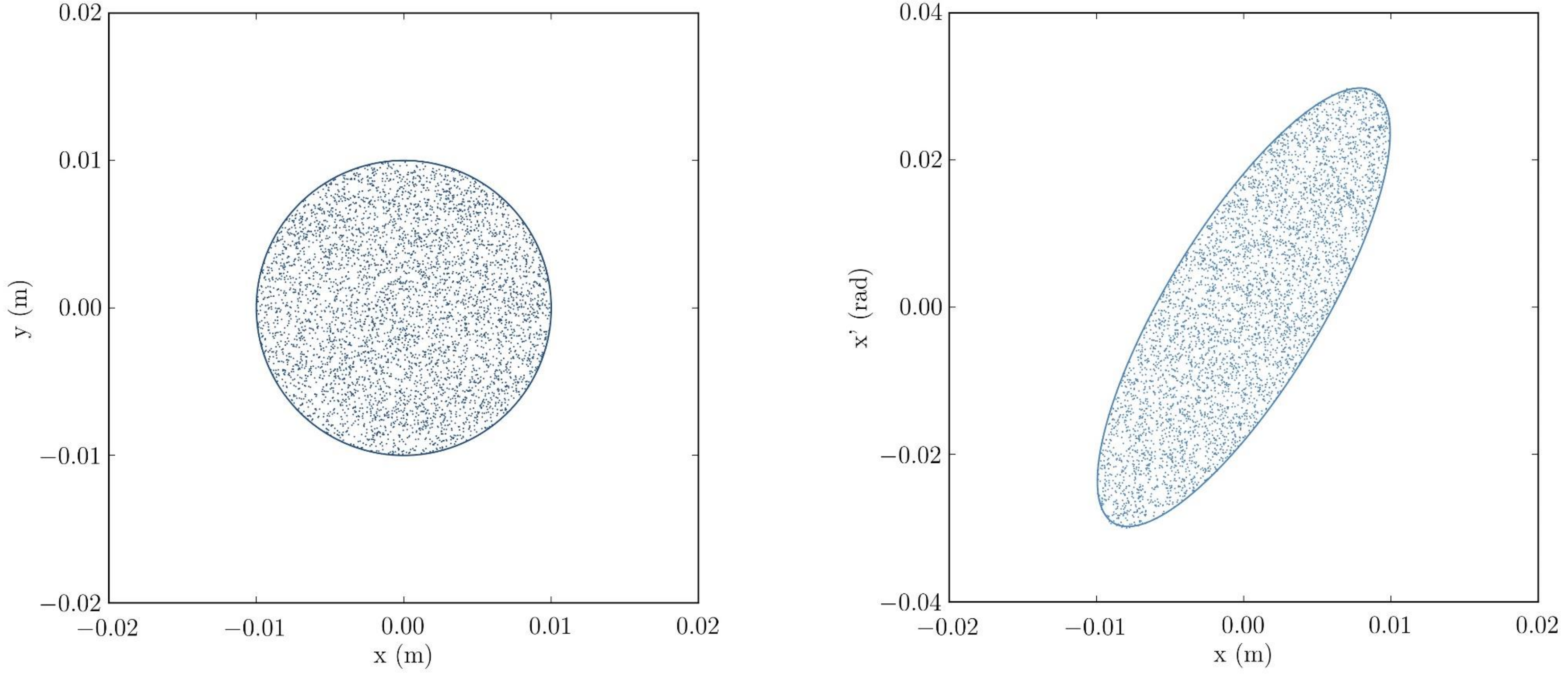
- The K-V distribution is a uniformly distributed hollow ellipsoid in Trace space:

$$f(x, y, x', y') = f_0 \cdot \delta \left(\frac{x_b^2 x'^2 + \sqrt{x'^2_b x_b^2 - \epsilon_x^2} x x' + x'^2_b x^2}{\epsilon_x^2} + \frac{y_b^2 y'^2 + \sqrt{y'^2_b y_b^2 - \epsilon_y^2} y y' + y'^2_b y^2}{\epsilon_y^2} - 1 \right)$$

with x_b, y_b the maximum beam extent (b for 'beam') in x and y directions, x'_b, y'_b the maximum angles, and ϵ_x, ϵ_y the (full) beam emittances.

- All projections in 2D subspaces are uniformly filled ellipses.

Trace Space Example



K-V Beam – Projections are uniform ellipses

Liouville’s Theorem

- States that for non-interacting particles in a system that can be described by a Hamiltonian, the phase space density is conserved.

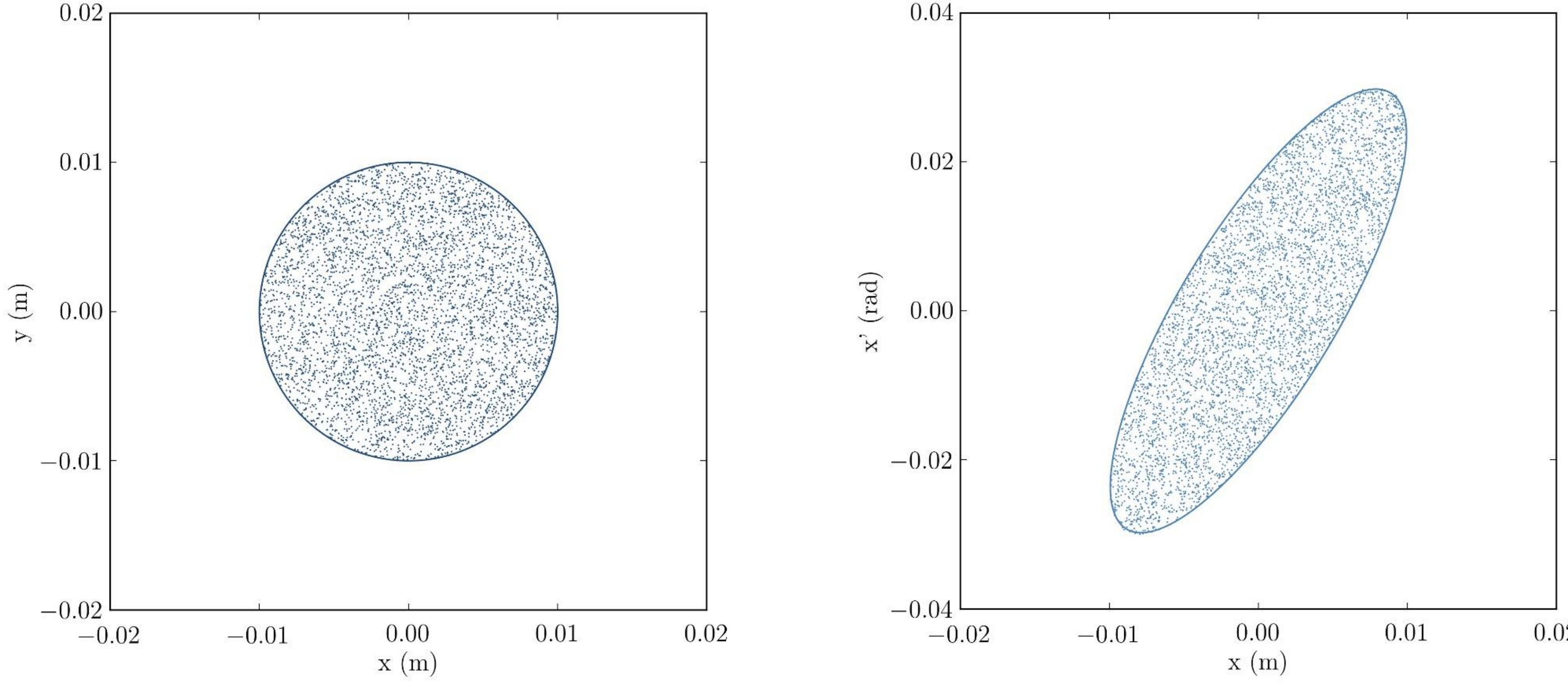
$$\frac{dn}{dt} = 0, \text{ or } n = n_0 = const.$$

- in terms of mechanical momentum:

$$\iint d^3q_i d^3P_i = const.$$

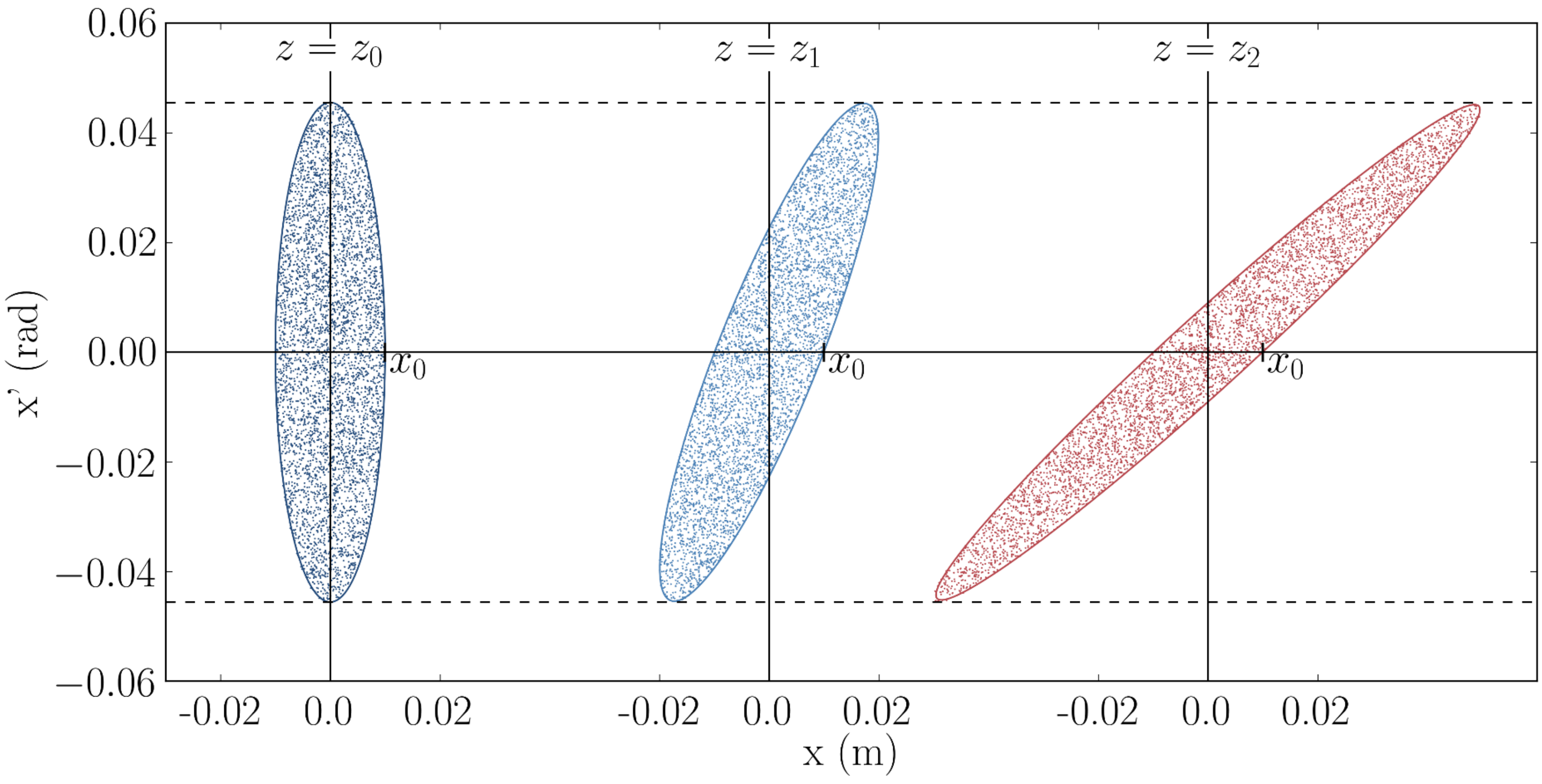
- (also true for linear space-charge)
- Trace space area: $A_x = \frac{1}{P}\iint dx dP_x = \frac{1}{\gamma\beta mc}\iint dx dP_x$

Trace Space Example



K-V Beam – Projections are uniform ellipses

Phase Space Evolution - Drift



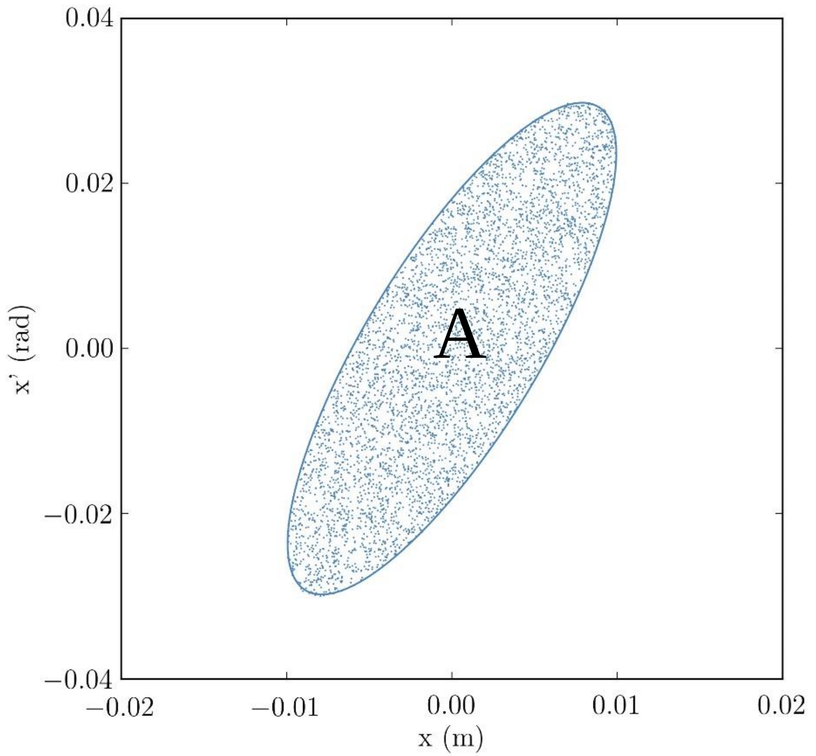
Geometric Emittance

- Definition from Area

$$\epsilon_x = \frac{A_x}{\pi} \quad [\pi\text{-}mm\text{-}mrad]$$

$$A_x = \frac{1}{P}\iint dx dP_x = \frac{1}{\gamma\beta mc}\iint dx dP_x$$

$$A_x = \frac{1}{\gamma\beta}\iint dx dx'$$



- Normalized Emittance:

$$\epsilon_{x,norm.} = \gamma\beta\epsilon_x$$

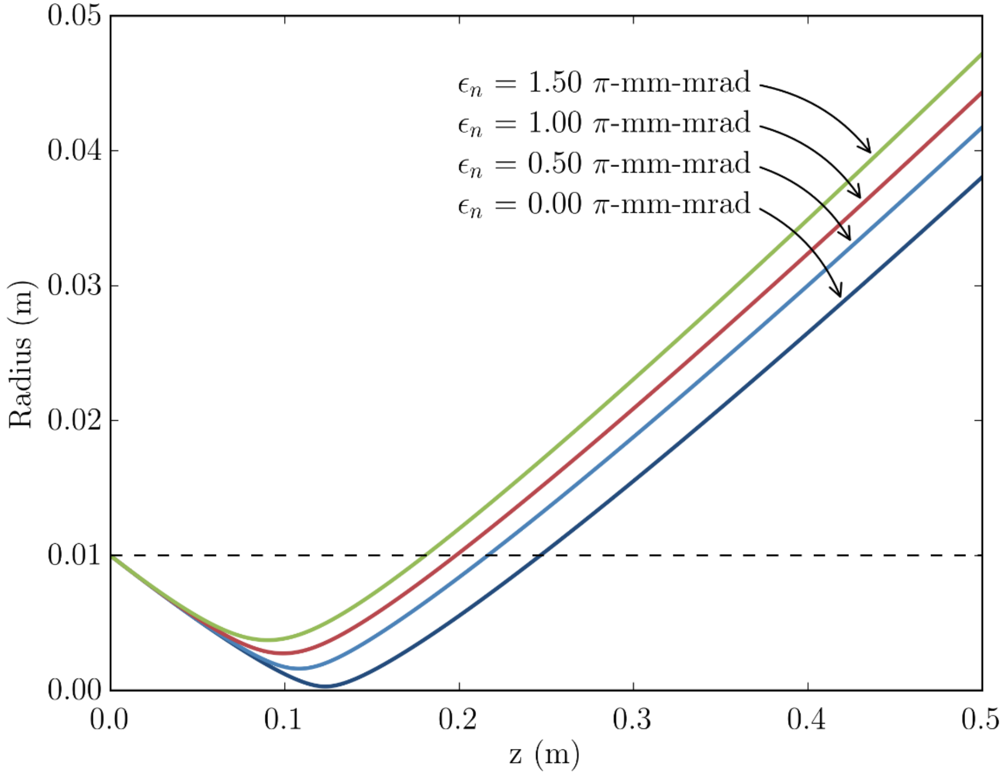
- Const. even under acceleration

Emittance vs. beam dynamics

- Courant-Snyder form of envelope equation:

$$x_m'' + \kappa x_m - \frac{\epsilon_x^2}{x_m^3} = 0$$

- Emittance works against focusing…

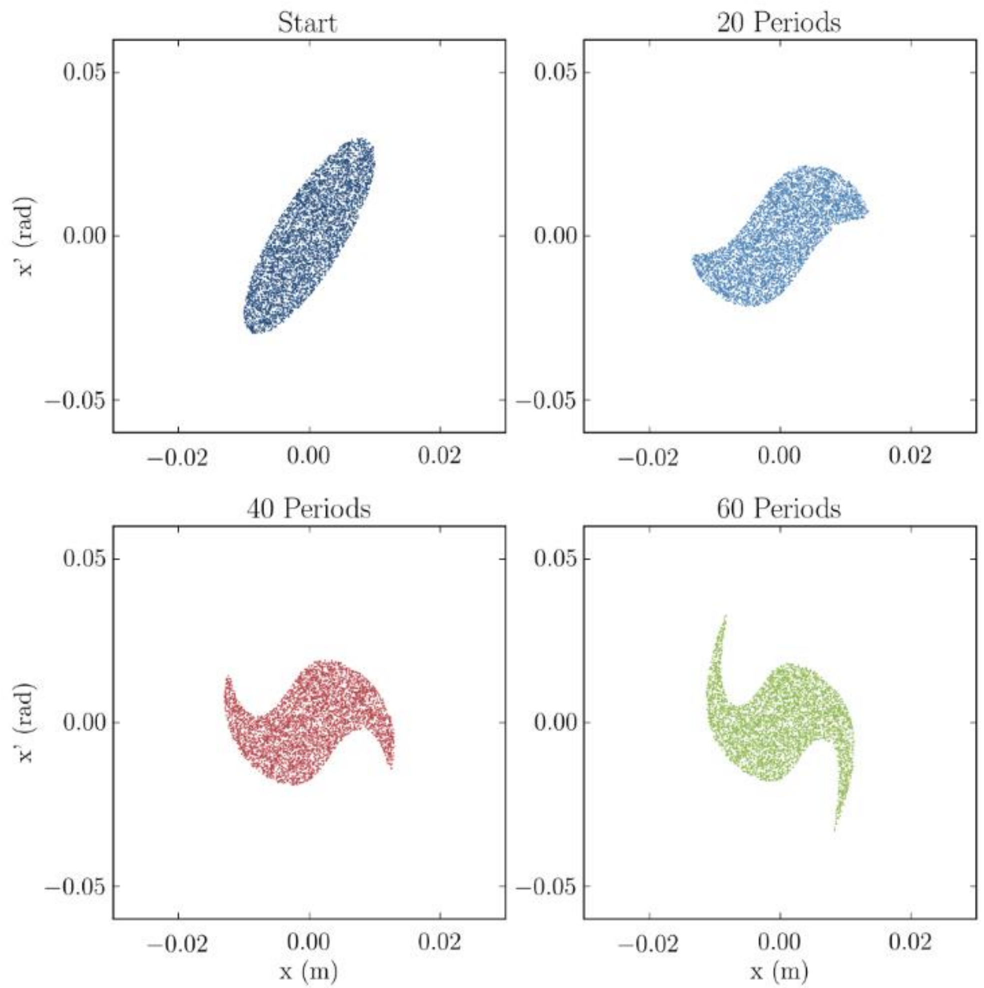


Why preserve (reduce?) emittance?

- Kind of a no-brainer ;)
- Emittance determines the size of the final focus at a certain focal length from the focusing device.
- Emittance determines the distance beam transport elements have to have.
- Emittance determines the distance beam transport elements have to have.
- Emittance…the smaller the better…
- And we have a good definition…right?

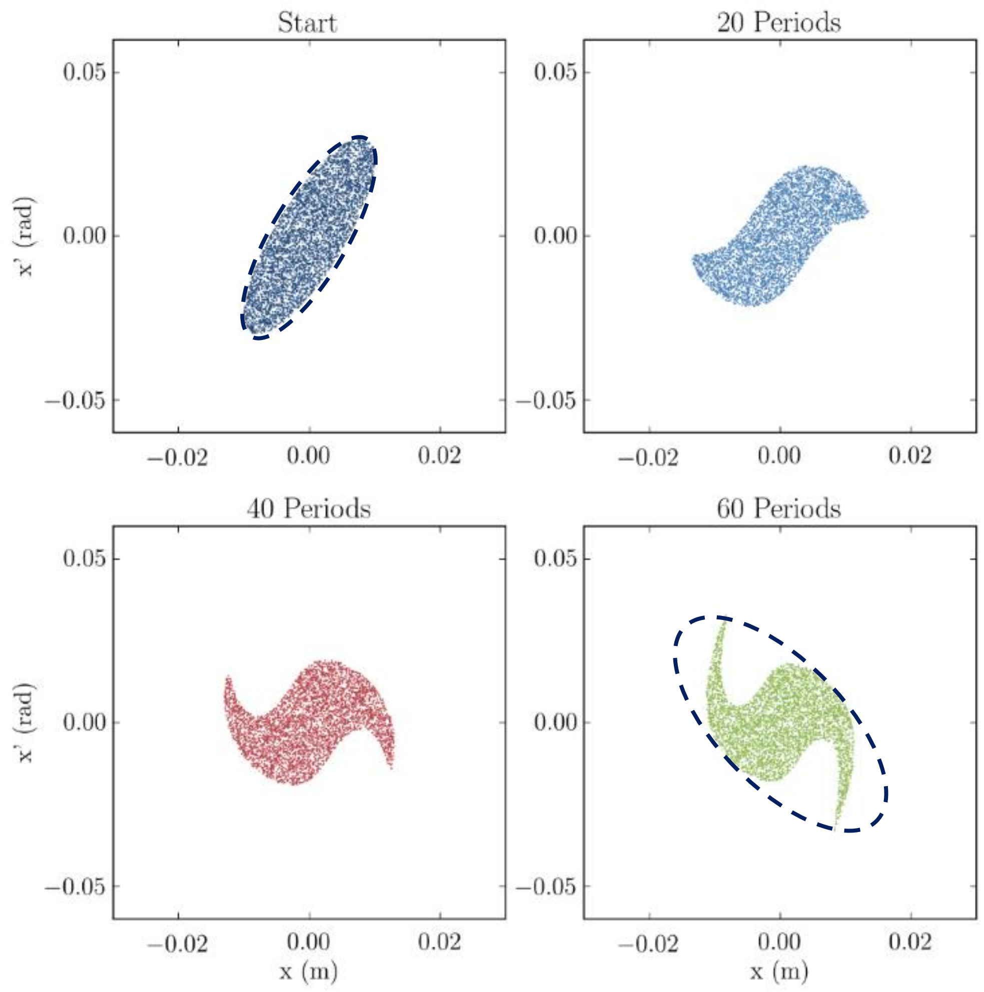
Phase Space Evolution - Aberration

- Simple envelope equation solver with spherical aberration…
- Filamentation of the trace space

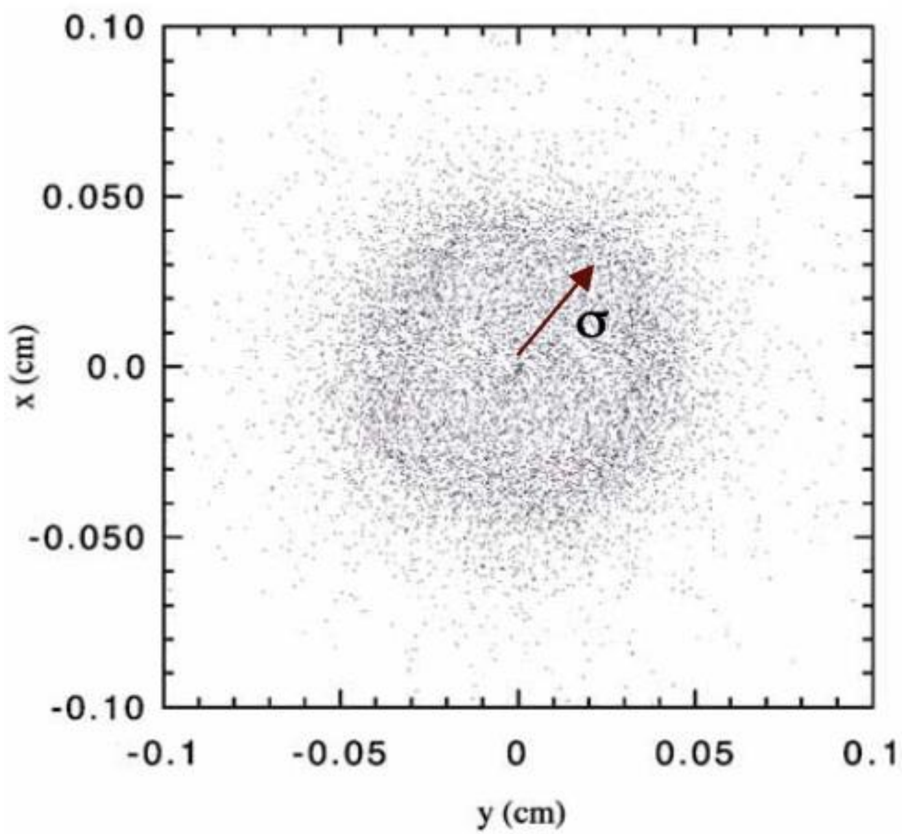


Phase Space Evolution - Aberration

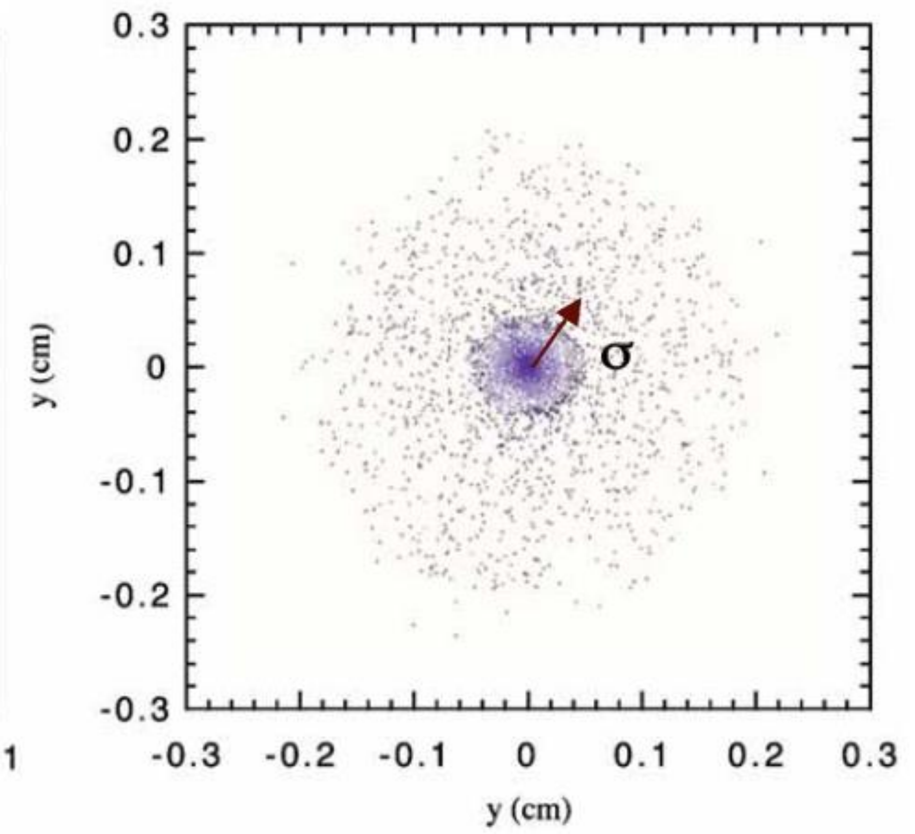
- Simple envelope equation solver with spherical aberration…
- Filamentation of the trace space
- Ellipse surrounding the beam is growing.
- Actual phase space volume is conserved (still Hamiltonian system)



Other beam Cross-Sections



Gaussian beam



Beam with halo

From: W. Barletta

Massachusetts Institute of Technology

RMS Emittance

- Second moments of a distribution f(x,y,x’,y’):

$$\langle x^2 \rangle = \frac{\iiiint x^2 f(x,y,x',y')dxdydx'dy'}{\iiiint f(x,y,x',y')dxdydx'dy'}$$

$$\langle x'^2 \rangle = \frac{\iiiint x'^2 f(x,y,x',y')dxdydx'dy'}{\iiiint f(x,y,x',y')dxdydx'dy'}$$

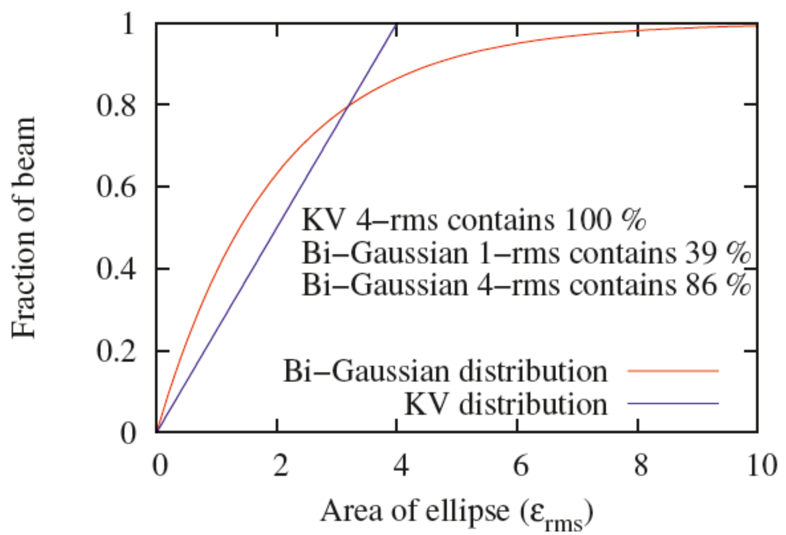
$$\langle xx' \rangle = \frac{\iiiint xx' f(x,y,x',y')dxdydx'dy'}{\iiiint f(x,y,x',y')dxdydx'dy'}$$

- Emittance:

$$\epsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2} \qquad [mm\text{-}mrad]$$

How does this compare to full emittance?

- Well, that depends…on the actual distribution.
- K-V Distribution: $\epsilon_x = 4\epsilon_{x,rms}$
- Waterbag Distribution: $\epsilon_x = 6\epsilon_{x,rms}$
- (Bi-)Gaussian Distribution: $\epsilon_x = n^2\epsilon_{x,rms}$ if truncated at $n \cdot \sigma$



Graph by T. Kalvas

Brightness

- The brightness is commonly defined as current density per unit solid angle:

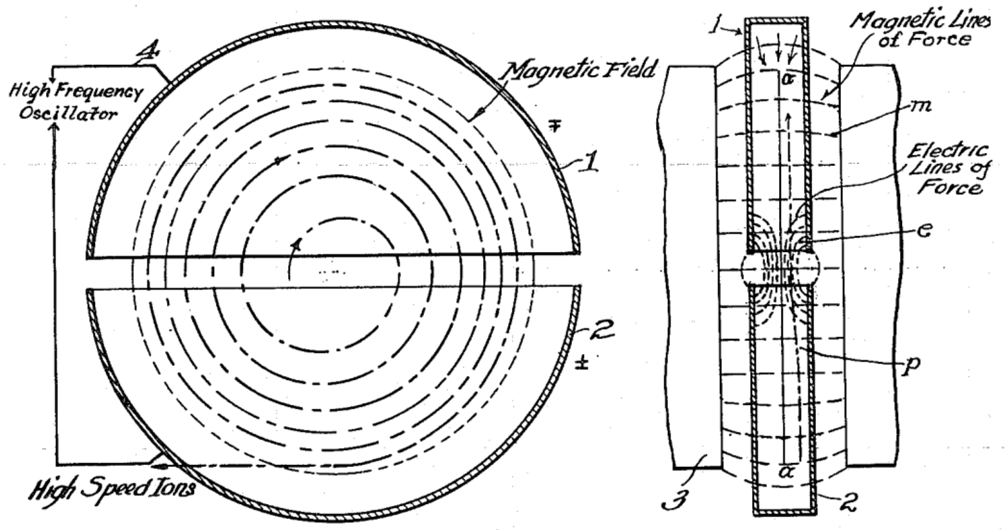
$$B = \frac{J}{d\Omega} = \frac{dI}{dS d\Omega}$$

- Or in terms of the transversal projections:

$$\bar{B} = \frac{2I}{\pi^2 \epsilon_x \epsilon_y} \qquad \left[\frac{A}{m^2\text{-}rad^2}\right]$$

- Normalized:

$$B_n = \frac{B}{\beta^2 \gamma^2}$$



From Lawrence's 1934 patent, Source: wikipedia.org

Act I

A BRIEF HISTORY OF CYCLOTRONS

The Invention

- 1929: Ernest Orlando Lawrence has the idea for the cyclotron after reading about Widerøe's linear accelerator.
- The first cyclotron: Brass, wire, and sealing wax. Cost ~25$, 4" diameter.
- 1931: 11" cyclotron was built by M. Stanley Livingston (Lawrence's grad student) – acceleration of protons to >1 MeV
- 1933: 27" cyclotron… trend to go bigger and bigger (largest: 184")
- 1934: Lawrence patents the cyclotron

Ernest Orlando Lawrence, Source: wikipedia.org

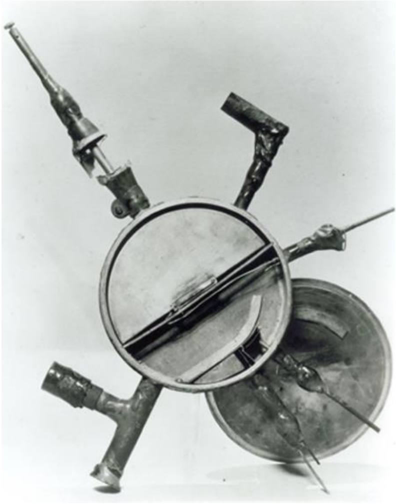
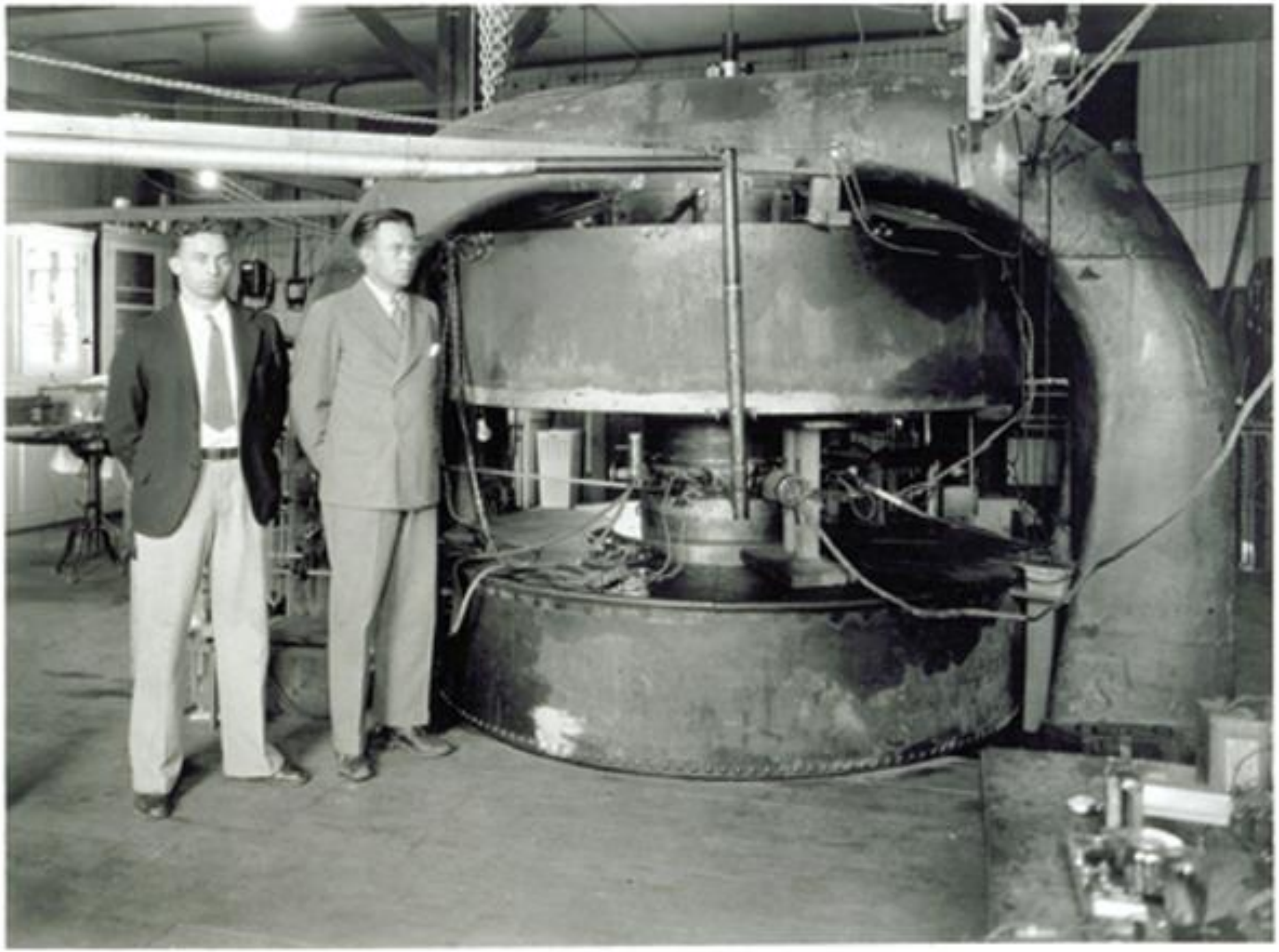


Image Source: https://www.physics.rutgers.edu/cyclotron/cyc_history.shtml

Livingston, Lawrence, and 27" cyclotron



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The Basic Principle

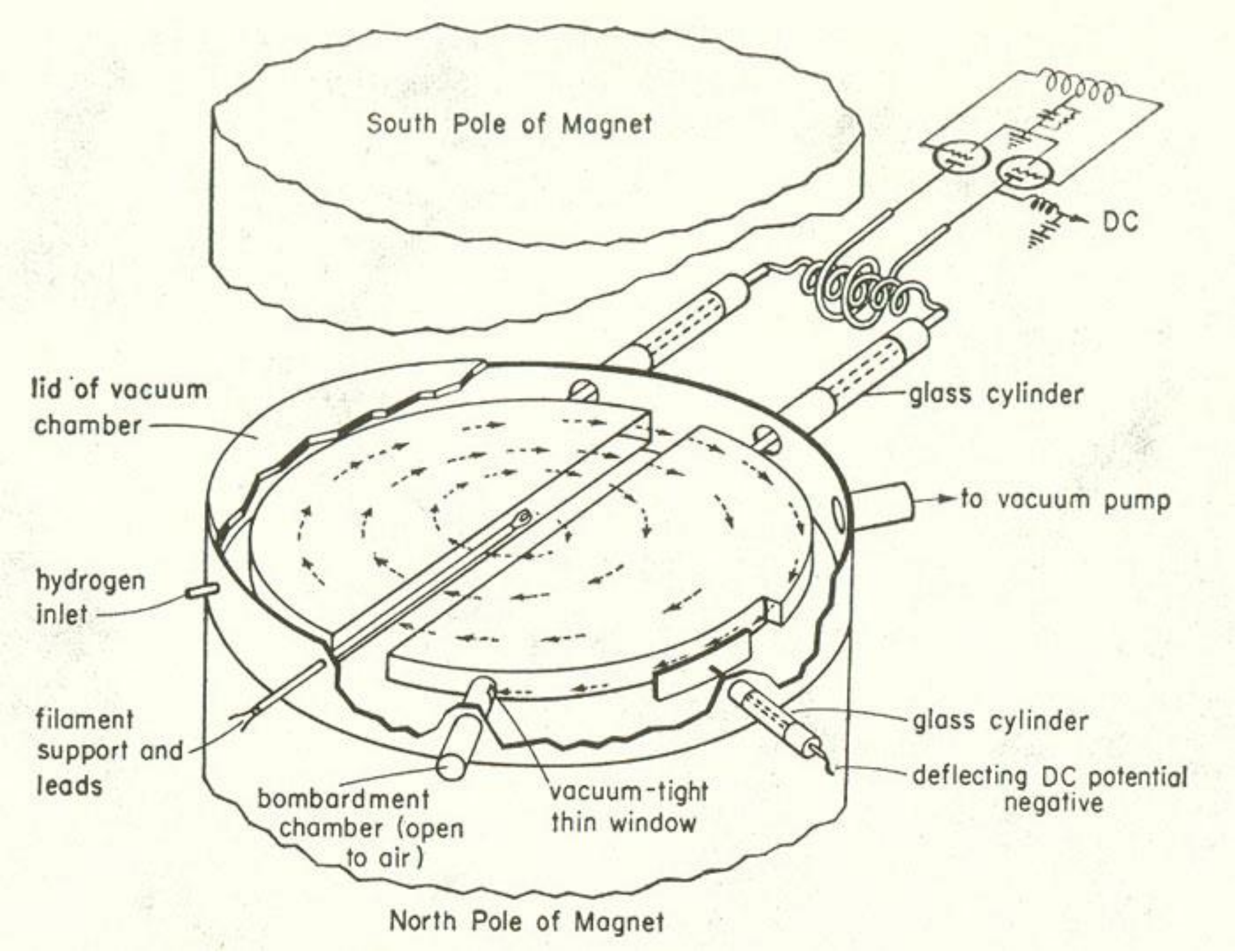


Image Source: https://www.physics.rutgers.edu/cyclotron/theory_of_oper.shtml

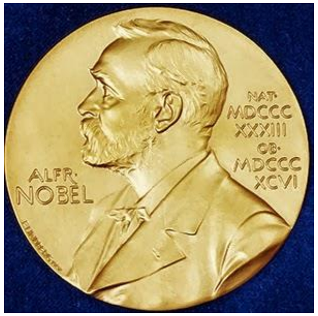
Massachusetts Institute of Technology

The Heyday

- Until the 1950's, cyclotrons were the accelerator of choice to do nuclear physics experiments.
- Many were built at major universities in the US (Berkeley, Princeton, MIT, Cornell, Yale, Harvard,…), and around the world.
- Many discoveries were made (new elements, isotopes, …)
- Increase in size to reach higher energies worked for a while, then relativistic effects prohibited larger cyclotrons.
- Remedies were synchrocyclotrons and isochronous machines (see later section of this lecture),
- After 1960, cyclotrons were soon surpassed by synchrotrons to reach higher energies.

Achievements

- 1939: Lawrence wins Nobel Prize for the invention of the cyclotron.
- 1951: Edwin McMillan, Glenn Seaborg win Nobel Prize in chemistry *for their discoveries in the chemistry of the transuranium elements*.
- Commissioned in 1989, the NSCL K1200 cyclotron is the highest-energy continuous beam (cw) accelerator in the world! (Info valid until 2006)
- PSI Ring Cyclotron can accelerate 2.2 mA cw beams



Intermezzo

CYCLOTRON CONCEPTS

The "Classic" Cyclotron

- Weak focusing dipole magnet (cf. Lecture on accelerators by Elke Aschenauer)
- Governing equations:

$$F_C = \frac{mv^2}{r} \quad F_B = qvB \rightarrow \frac{mv}{q} = \frac{p}{q} = rB \qquad \omega = 2\pi f = \frac{qB}{m}$$

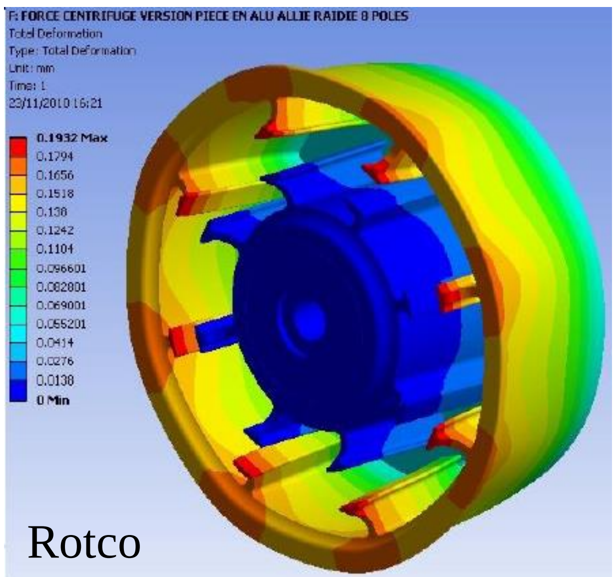
- Problem: relativistic mass increase with higher velocity leads to desynchronization.

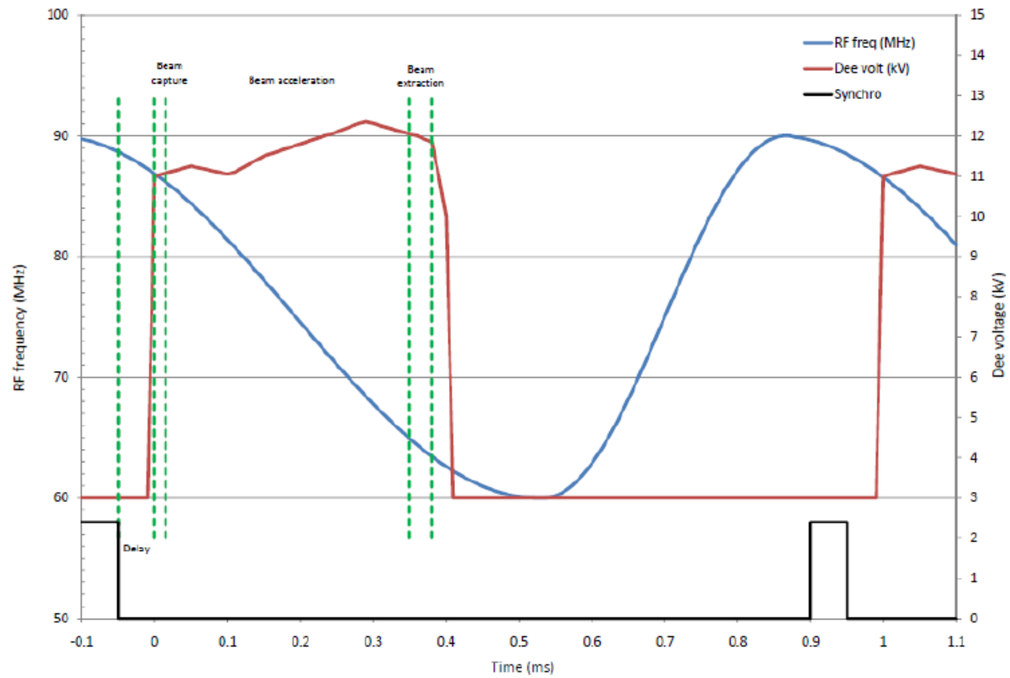
$$r = \frac{\gamma\beta m_0 c}{qB} \qquad \omega = 2\pi f = \frac{qB}{\gamma m_0}$$

- Mitigate by:
  - Changing frequency during acceleration → Synchrocyclotron
  - Changing B-field with radius (increase with radius, opposite of weak focusing) → Isochronous (or AVF) machine

Synchrocyclotrons

- 184” Berkeley cyclotron by Lawrence was first synchrocyclotron
- Weak focusing, but no longer cw operated!
- Change frequency during acceleration of essentially one bunch at a time



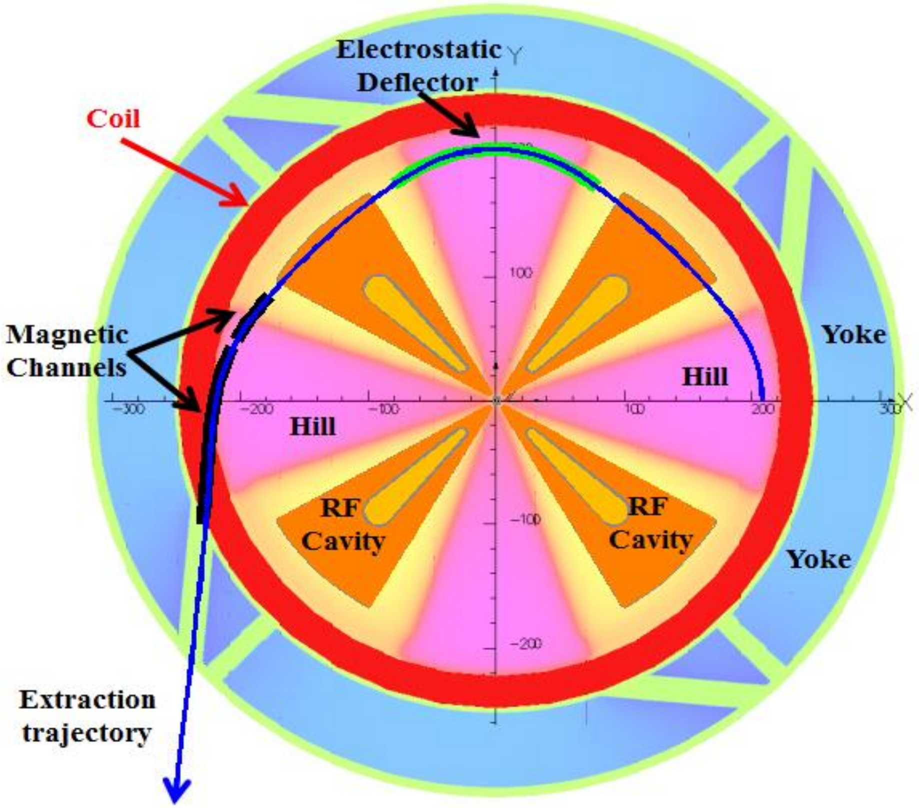


Figures from: IBA S2C2 Synchrocyclotron Report

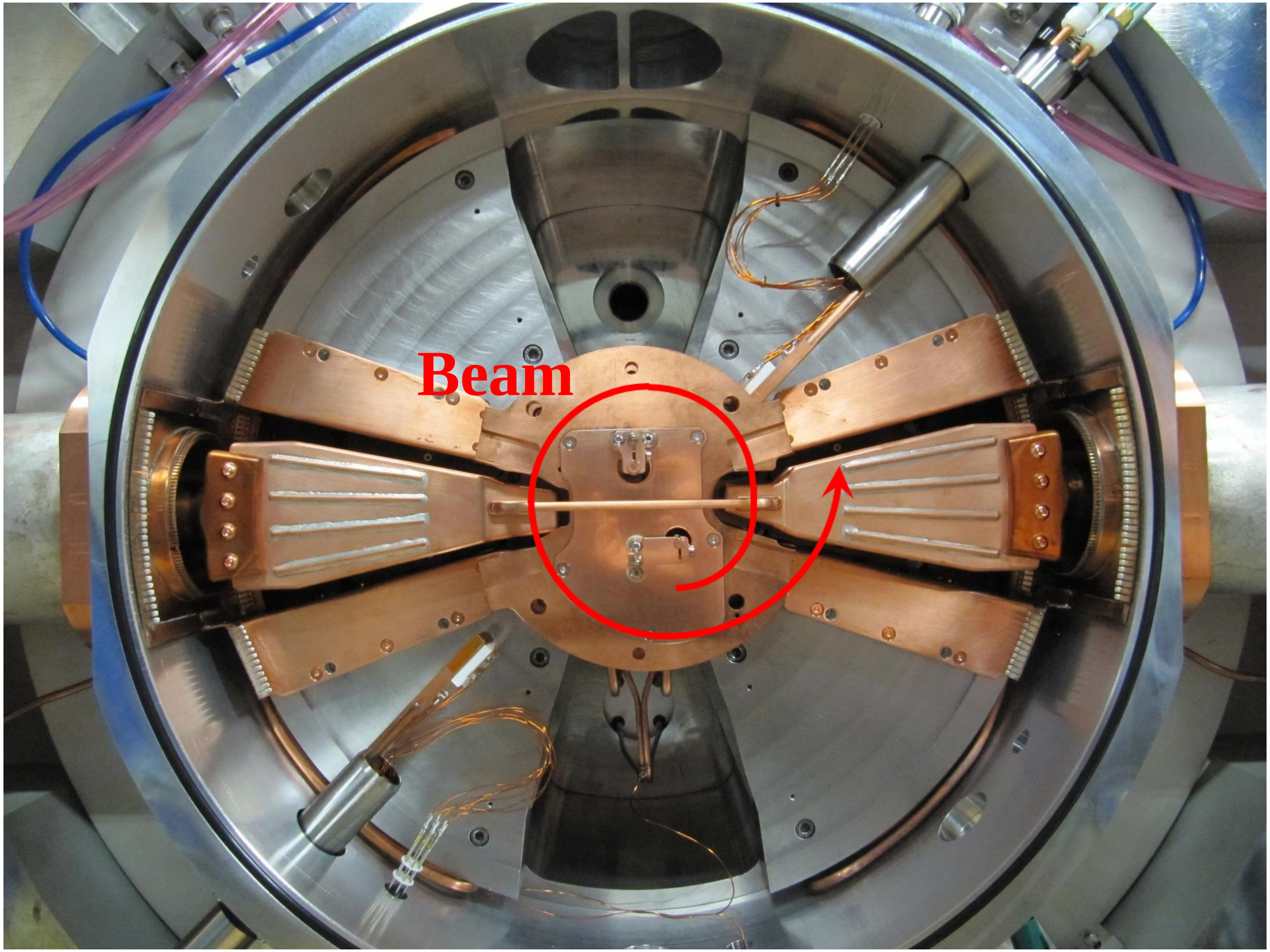
Massachusetts Institute of Technology

Isochronous Cyclotrons

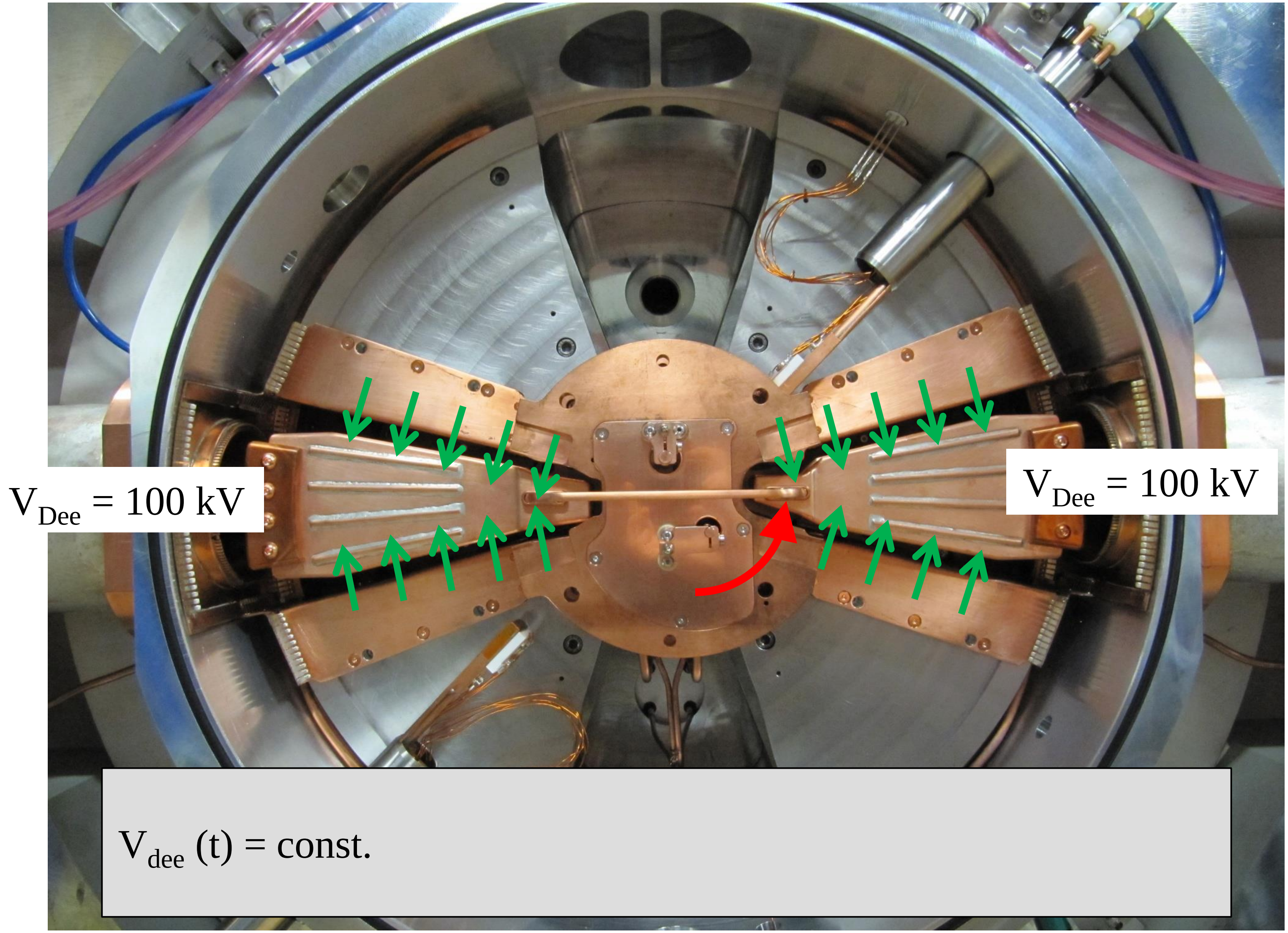
- AVF (Azimuthally Varying Field) → Hills/Valleys
- Edge focusing
- Either compact (single coil) or ring type
- Double gap cavities
- Higher harmonic modes



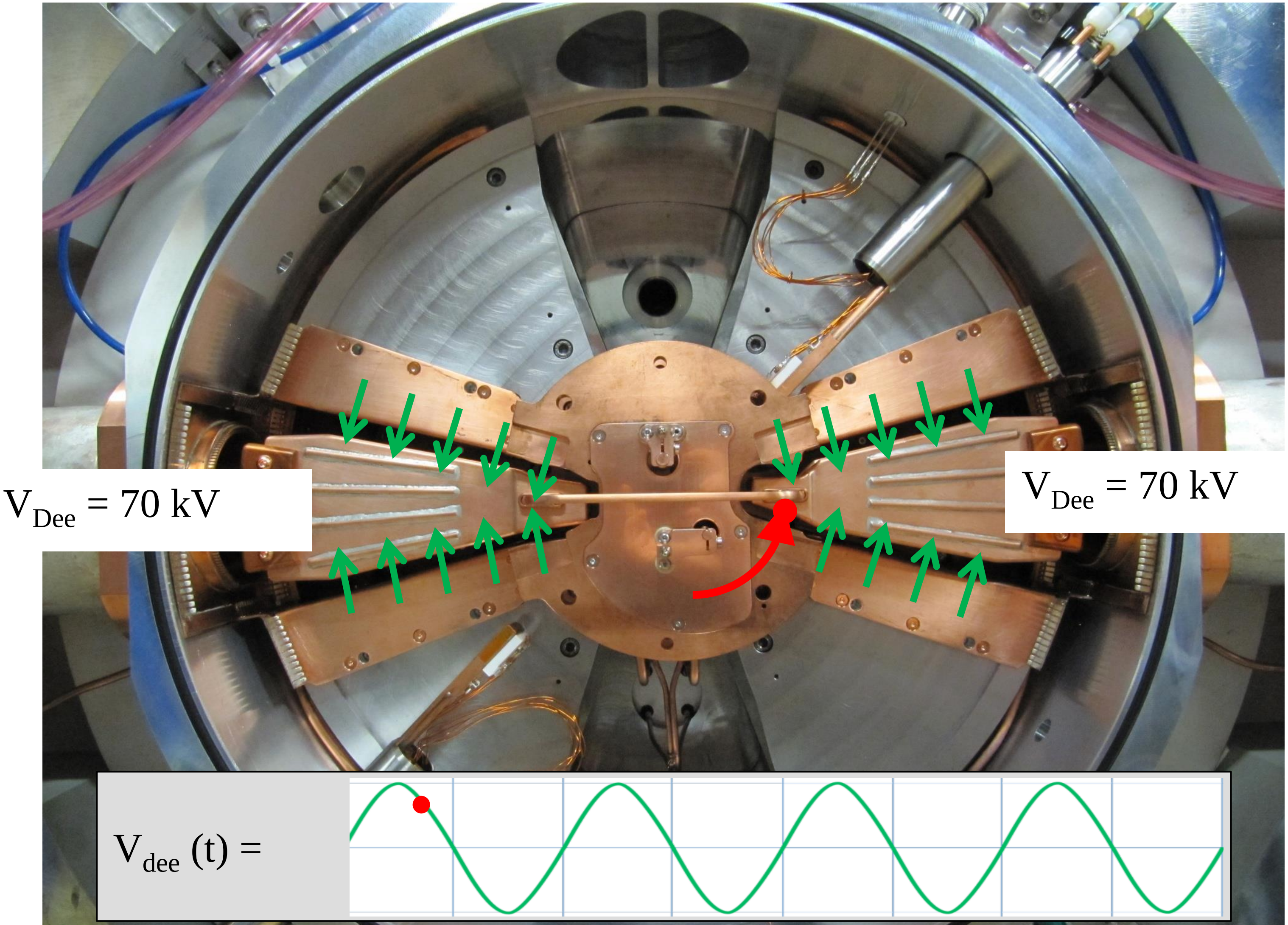
Cyclotrons 101



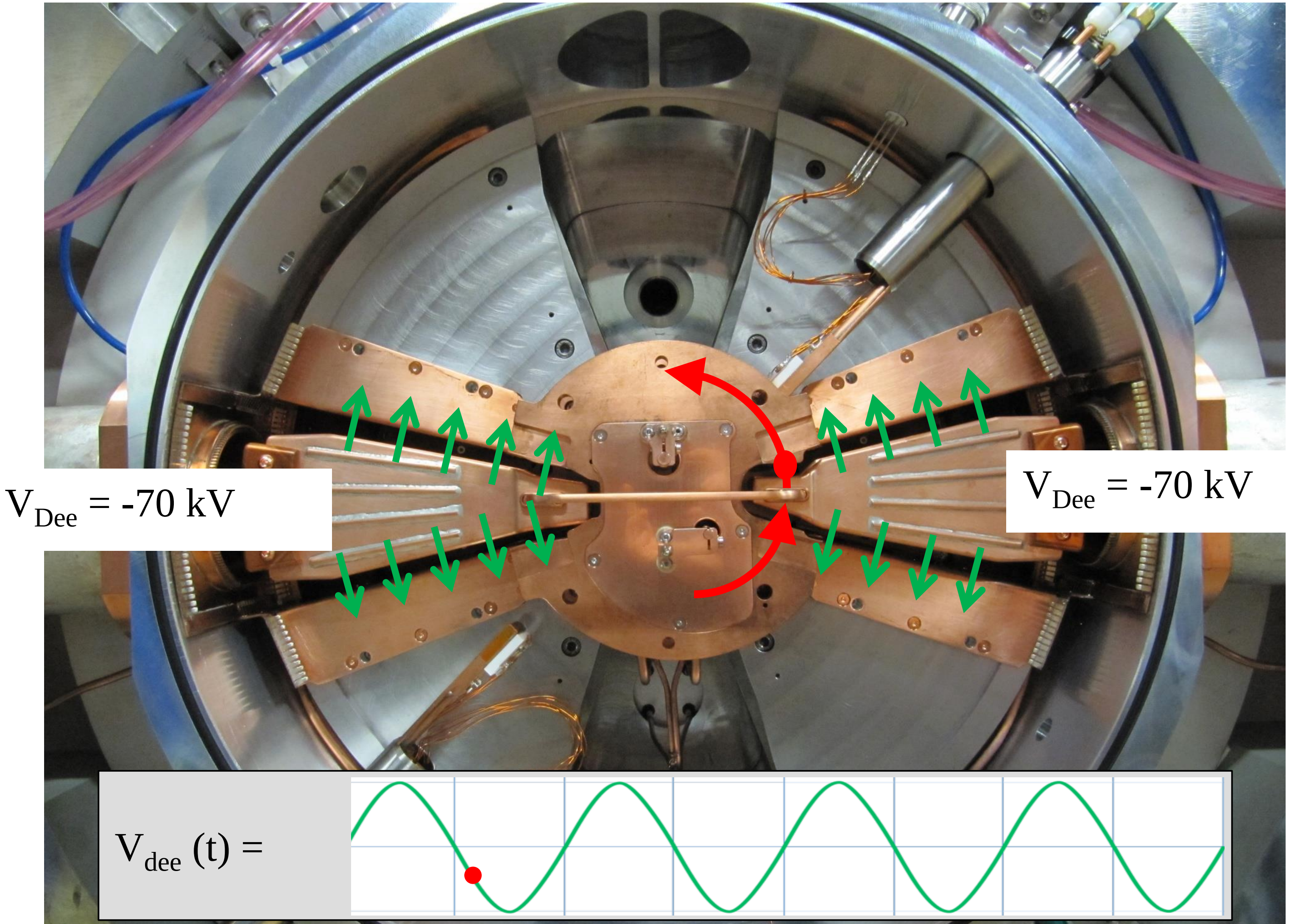
Cyclotrons 101



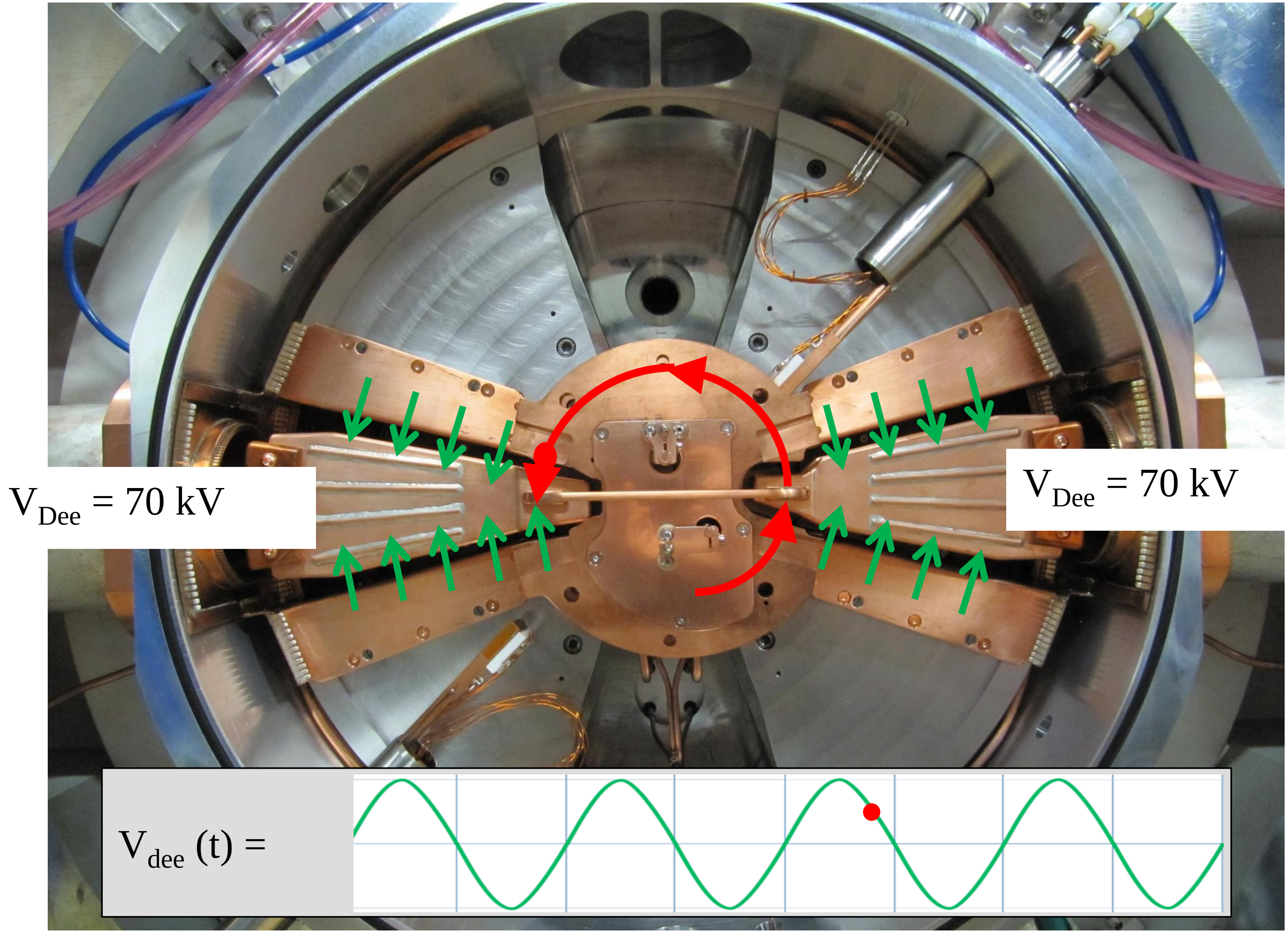
Cyclotrons 101



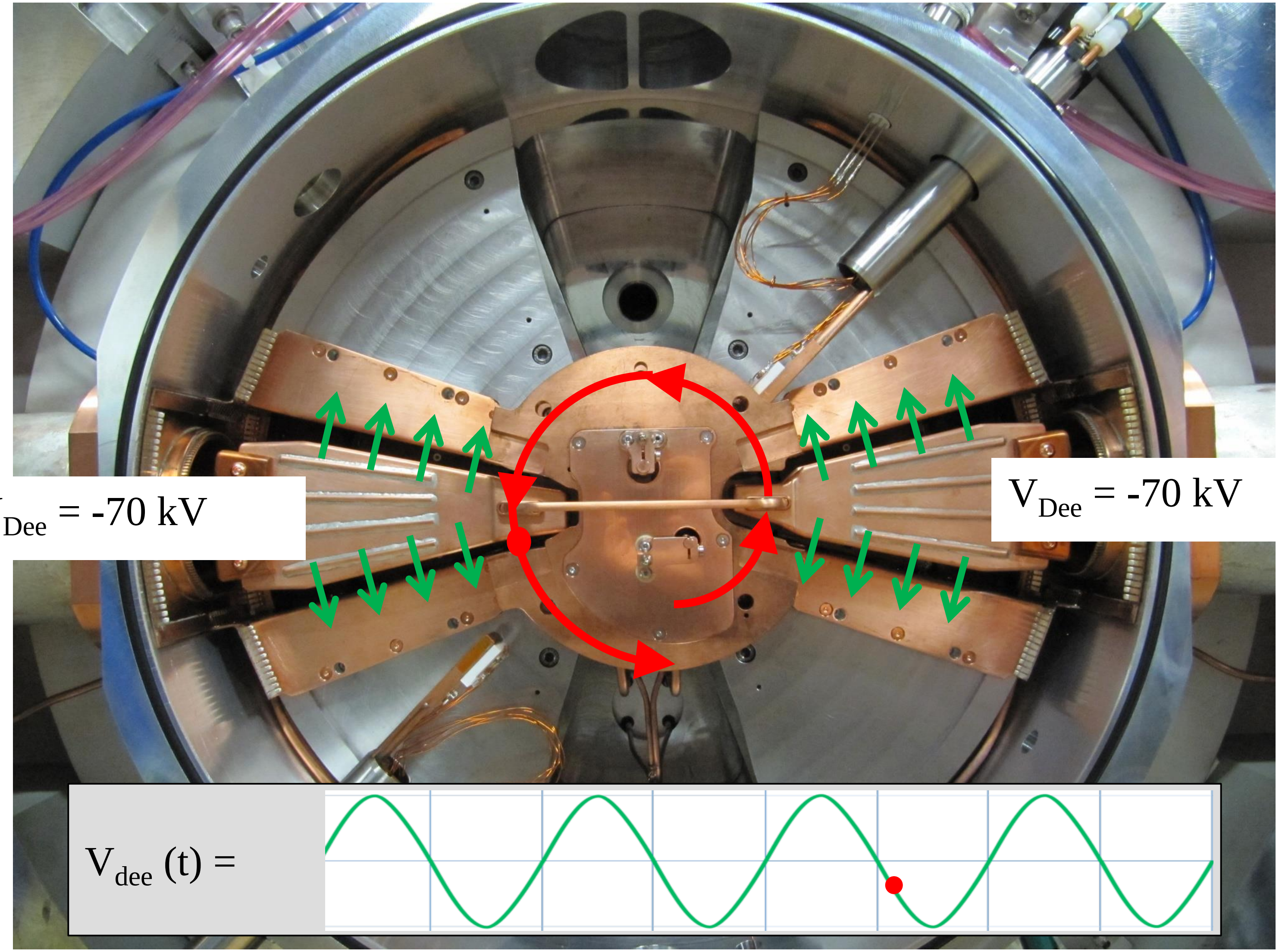
Cyclotrons 101



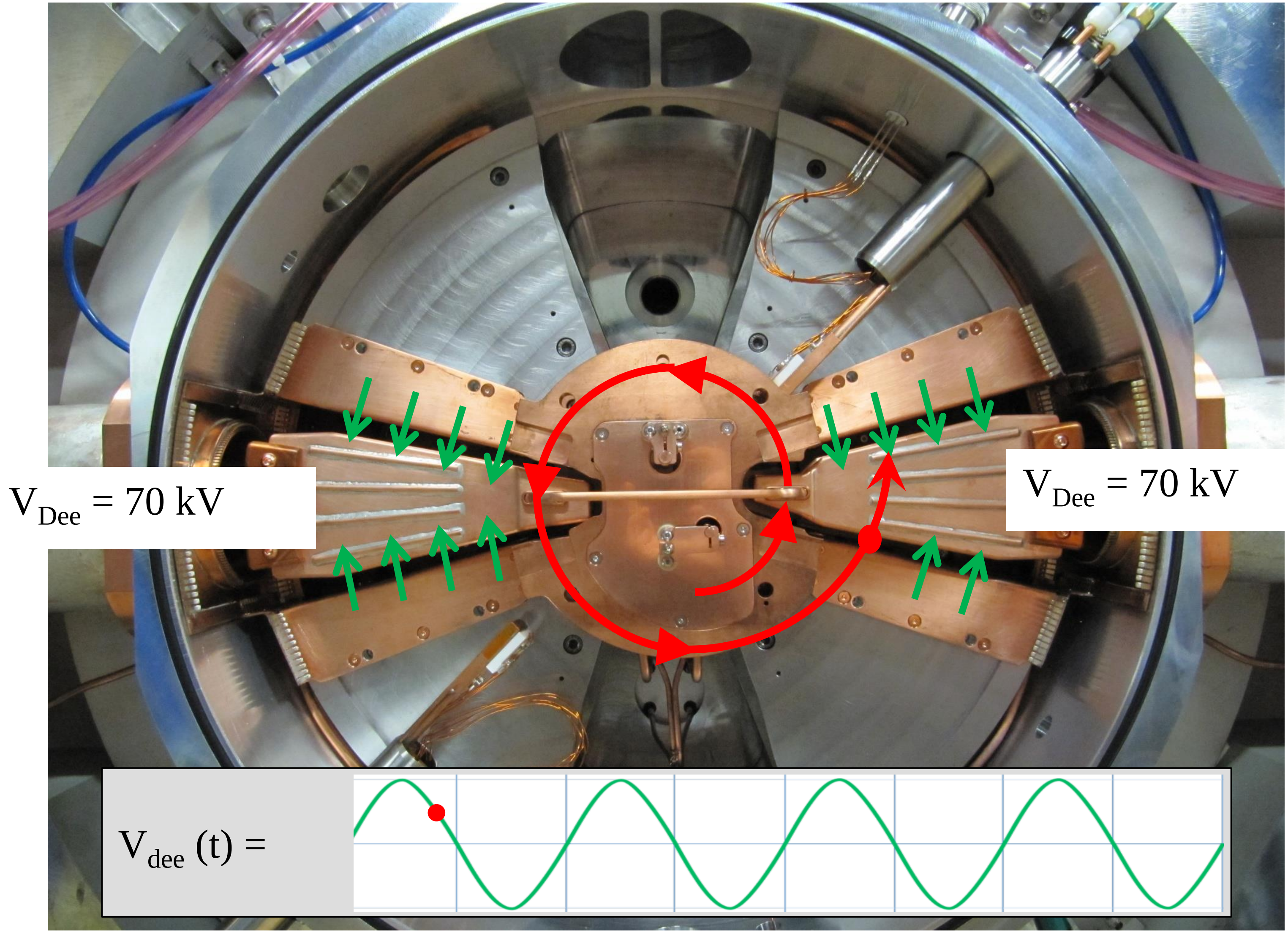
Cyclotrons 101



Cyclotrons 101



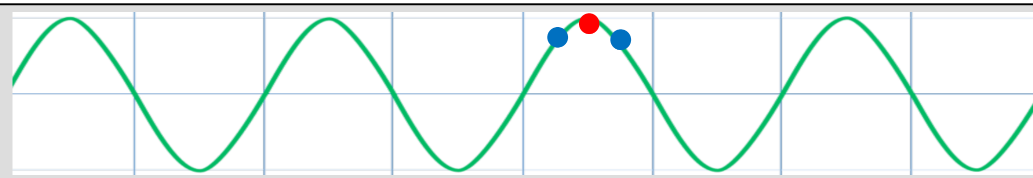
Cyclotrons 101



Phase Stability

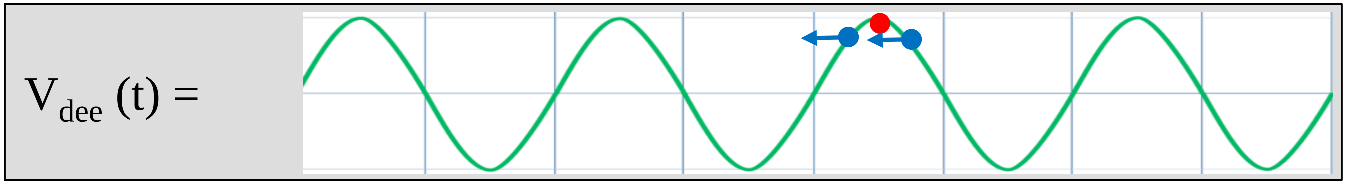
- What if particle comes in slightly off-phase (B-field errors, relativistic kinematics, bunch length, energy spread)?

V_{dee} (t) =



Phase Stability

- What if particle comes in slightly off-phase (B-field errors, relativistic kinematics, bunch length, energy spread)?



Phase Stability

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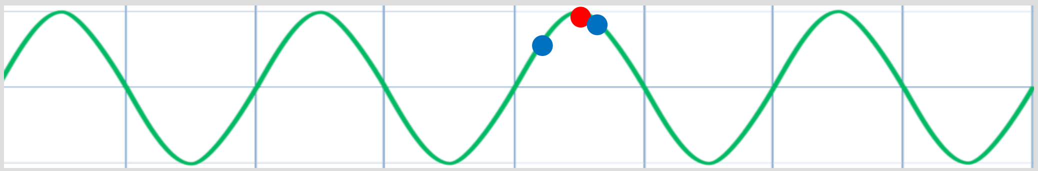
$V_{dee}(t) =$



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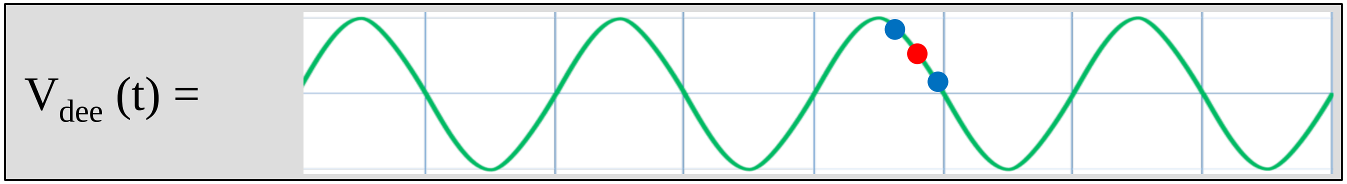
Phase Stability

- What if particle comes in slightly off-phase (B-field errors, relativistic kinematics, bunch length)?

- Run at shifted phase $\Phi_S \sim 60°$ (*synchronous phase*)



Phase Stability

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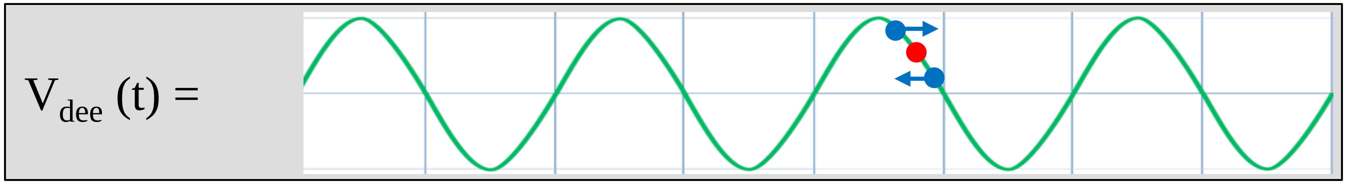
- Run at shifted phase Φ_S ~ 60° (*synchronous phase*)



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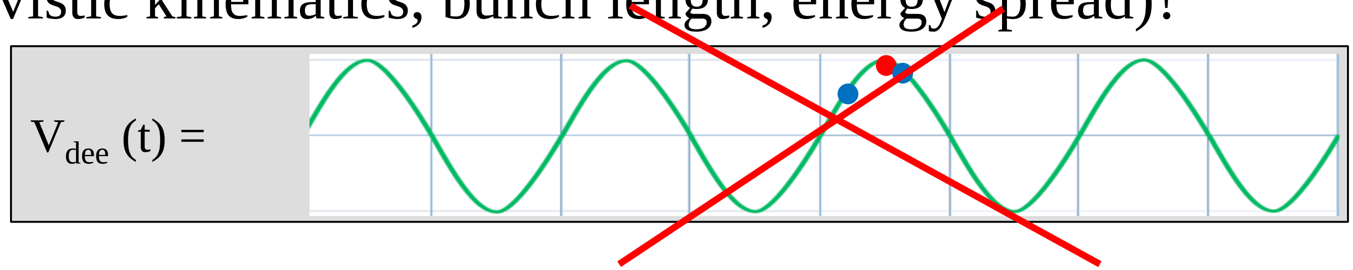

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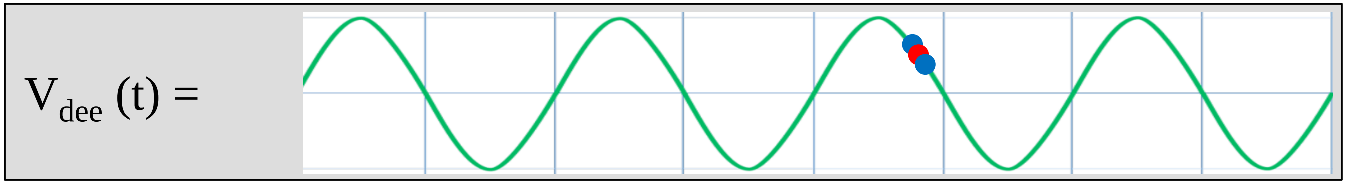
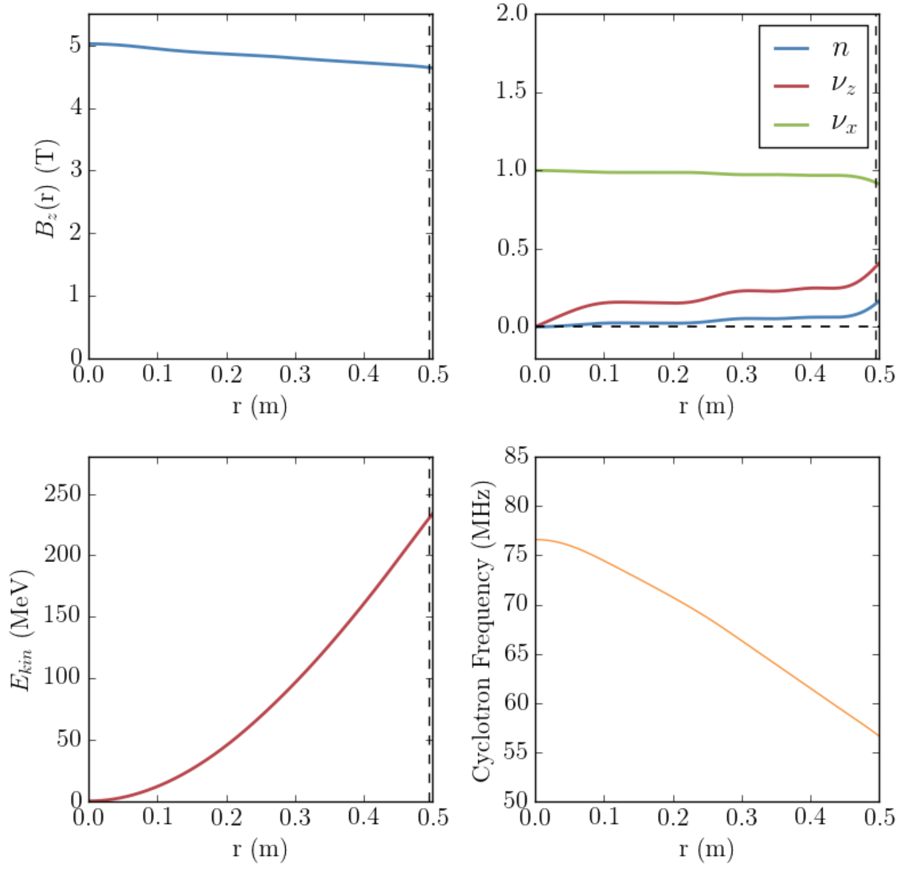


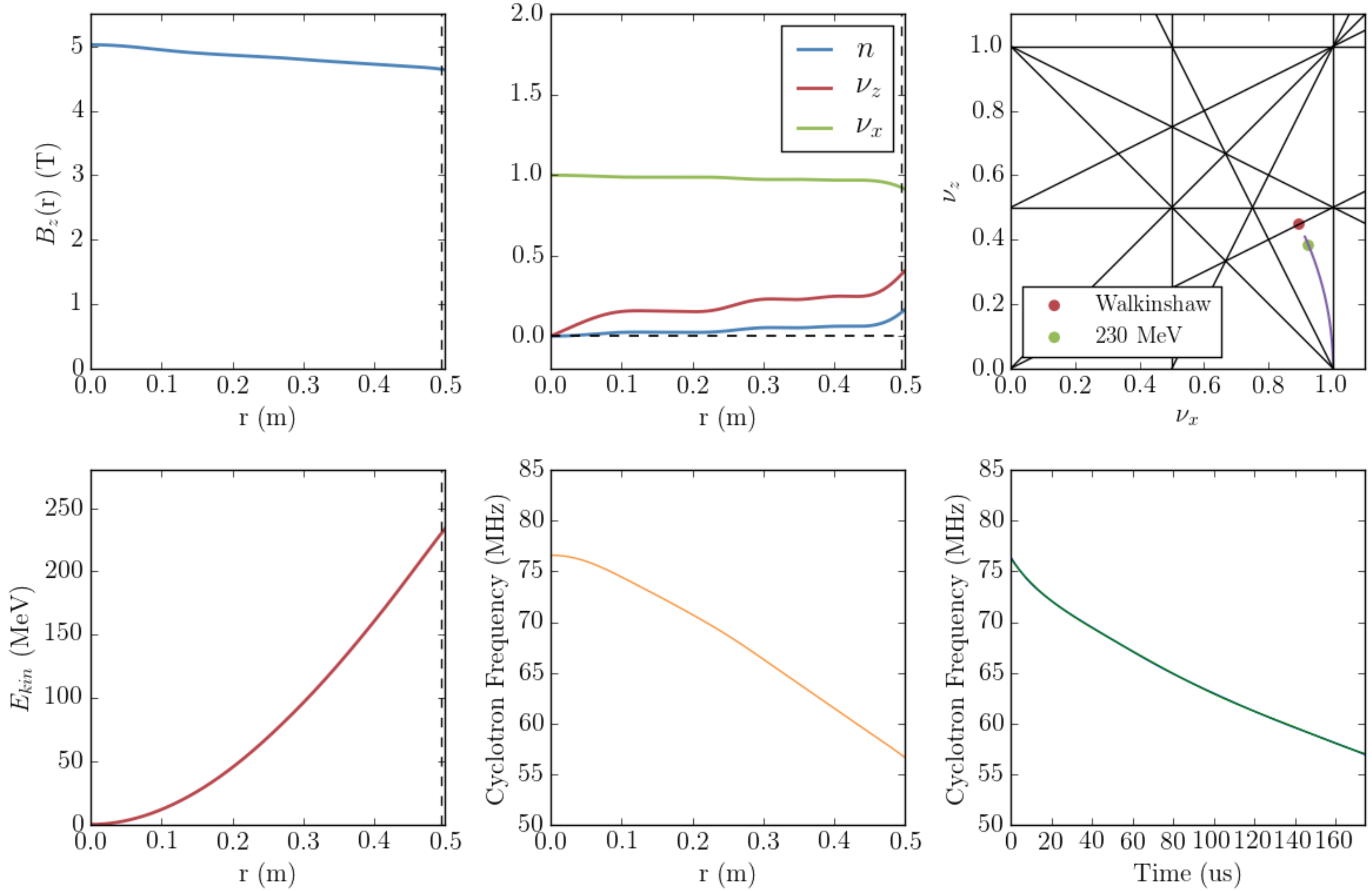
- *Phase Stability*: particles near the synchronous particle in Φ_S & E stay near the synchronous particle in Φ_S & E.

Tunes

- Synchronous particle is on equilibrium orbit. Other particles (slightly offset) oscillate around this orbit. → Radially and Vertically
- (cf. Lecture on accelerators by Elke Aschenauer)
- Example: Synchrocylotron →



Resonances - Synchrocyclotron



Beam injection

- Simplest way: Don't inject. (Internal sources, H+, H-, deuterons, He-3, He-4)
- Radial injection (almost exclusively separated sector machines, ring cyclotrons)
- Axial Injection:
  - Spiral Inflector

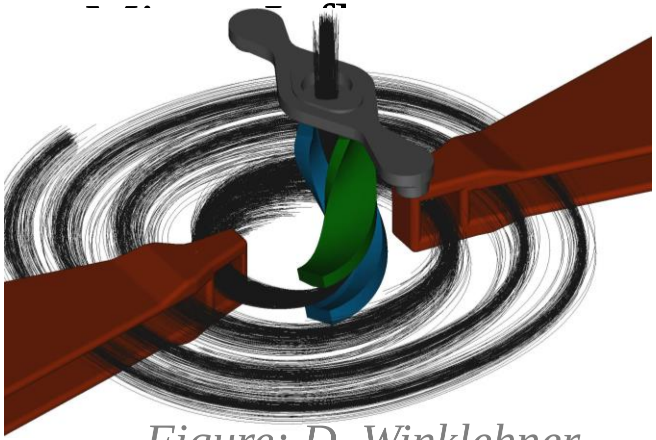


Figure: D. Winklehner

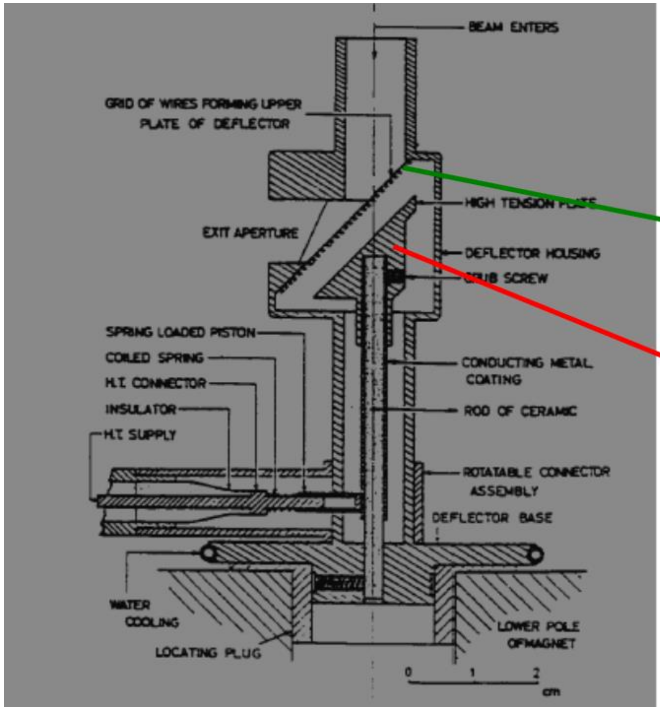
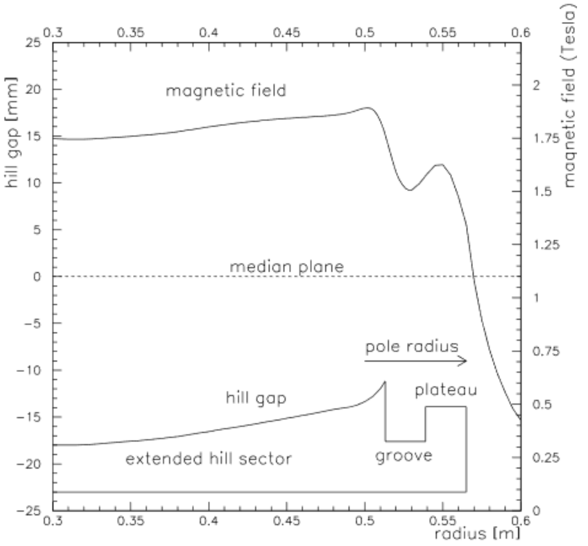


Figure: W. Kleeven

Beam extraction

- Simplest way: Don’t extract. (internal target) – Earliest cyclotrons
- Still, need to increase turn separation at the end:
  - Increase Dee voltage
  - Excite resonance (typically precessional or regenerative, both $\nu_r=1$, but…)
- Extract once turn separation is large enough:
  - Septum (electrostatic, RF pulsed)
  - Self extracting
- Once orbit is right, need extraction channel
- Or stripping extraction (H2+, H-)!



Graph: W. Kleeven

IBA compact self-extracting cyclotron

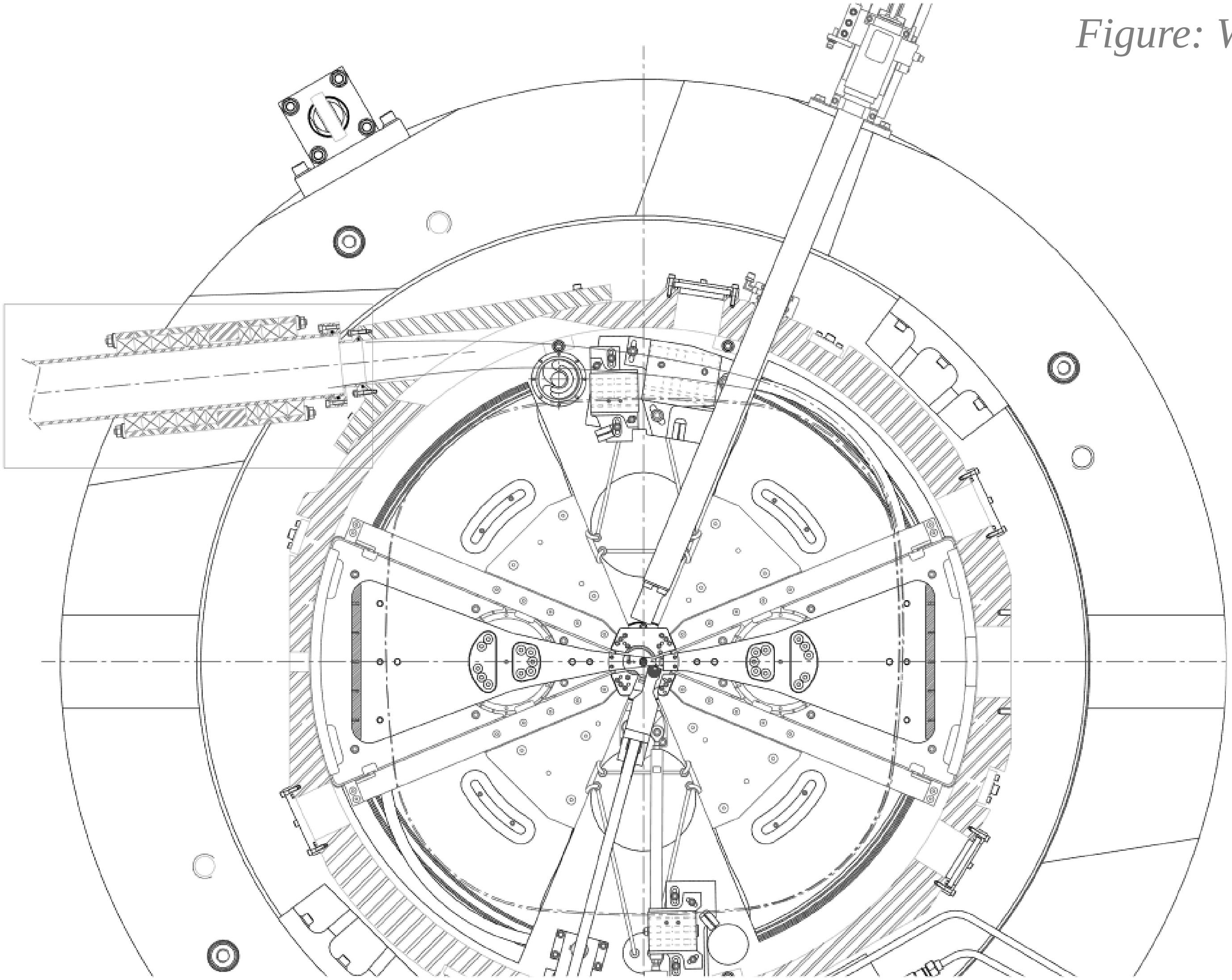
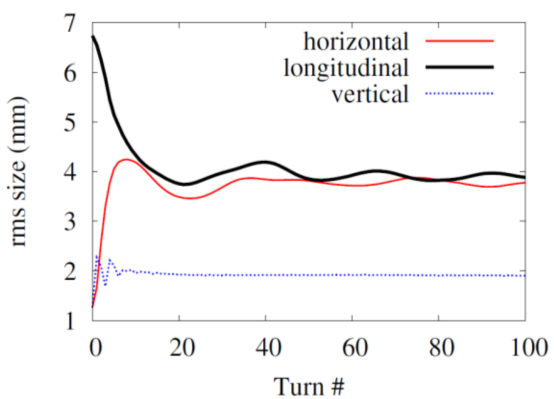


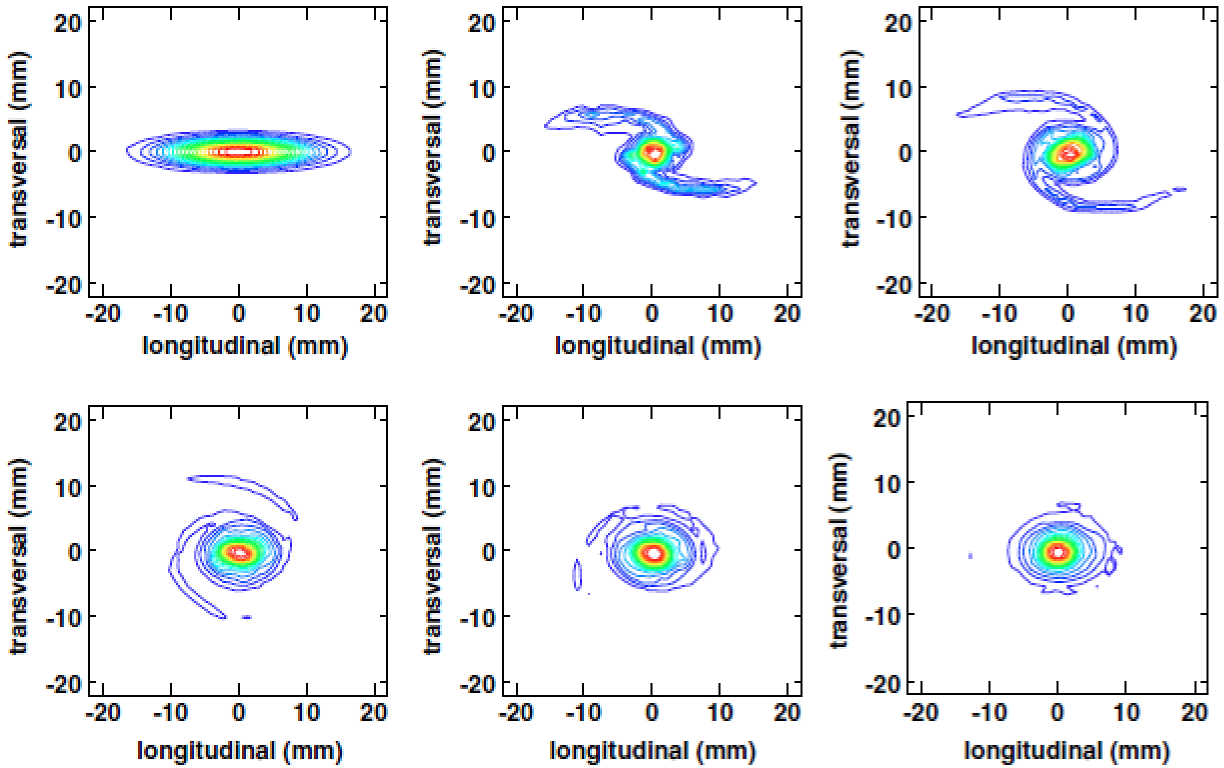
Figure: W. Kleeven

Massachusetts Institute of Technology

Vortex Motion for High Space Charge

The combination of non-linear space charge forces (outwards) and alternating gradient focusing (inwards) curls beam up into a almost perfect circle (horizontal plane)

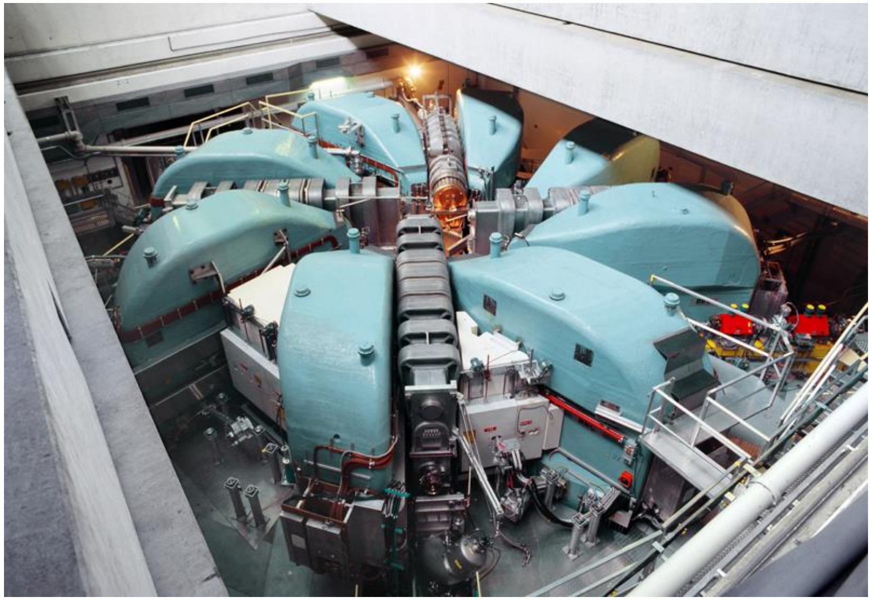




Simulation of PSI Injector 2: JJ. Yang

Simulation of proposed IsoDAR cyclotron: JJ. Yang

Short break (building RIKEN SRC)



PSI 590 MeV Ring Cyclotron, Source: www.psi.ch

Act II

CURRENT MACHINES

Cyclotron advantages

- Clearly, cyclotrons are not at the high energy frontier (anymore). However, they have certain attractive qualities:
  - Well-understood
  - Comparably cheap
  - Can be very compact
  - Can deliver fairly high cw beam currents (PSI: 2.2 mA protons)

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- Still used very successfully for:
  - Medical isotope production (PET)
  - Cancer therapy (Bragg-peak, p, carbon)
  - Nuclear physics
  - Education

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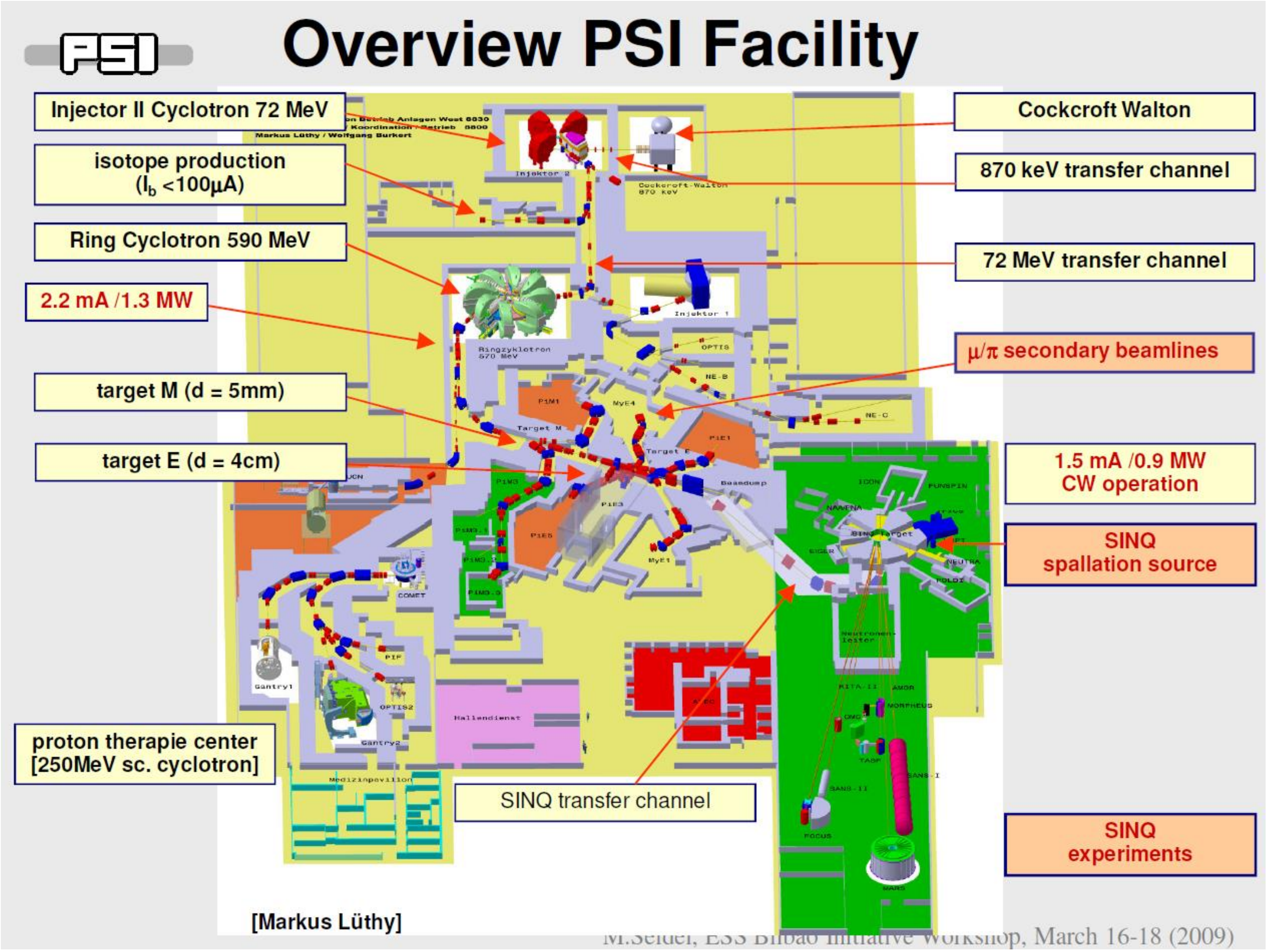
A selection of facilities using cyclotrons

- Mostly for Rare/Radioactive Isotope Experiments
  - ISOL
  - Fragmentation/In-flight separation
- Also: n, μ production
- All need driver beams
- Examples:
  - PSI
  - RIKEN
  - TRIUMF
  - NSCL

Paul Scherrer Institut (PSI) - Machines



Paul Scherrer Institut (PSI) - Machines

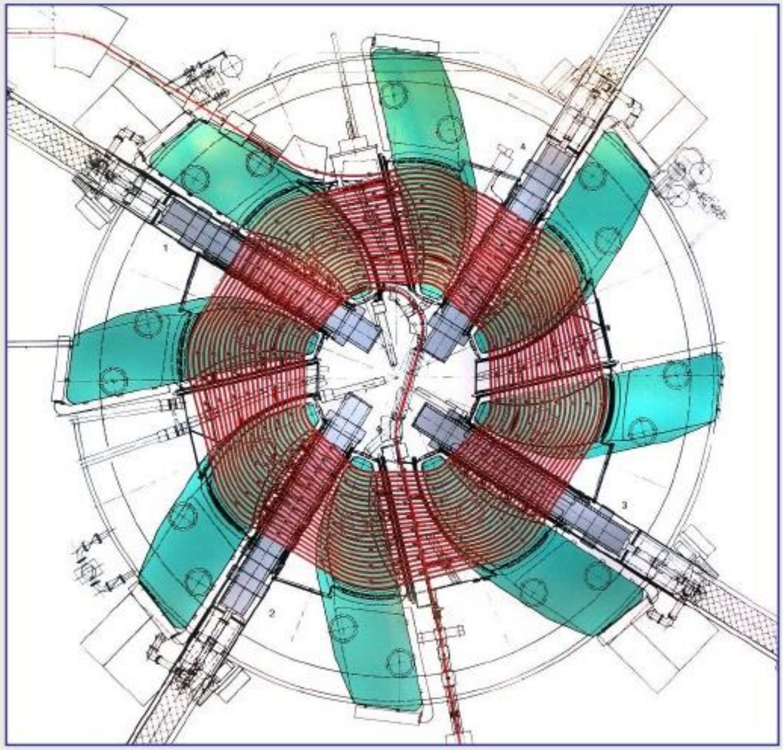
PSI

CW Acceleration using a Sector Cyclotron

590 MeV Ring Cyclotron

(magnets) in operation for 30+ years

- 8 Sector Magnets	1 T
- Magnet weight	~250 tons
- 4 Accelerator Cavities	850kV (1.2MV)
- Accelerator frequency:	50.63 MHz
- harmonic number:	6
- beam energy:	72 → 590MeV
- beam current max.:	2.2 mA
- extraction orbit radius:	4.5m
- relative Losses @ 2mA:	~1..2·10^{-4}
- transmitted power:	0.26-0.39 MW/Res.



Pro:	Con:
- CW operation is inherently stable	- inj./extr. difficult, interruptions, losses!
- efficient power transfer with only 4 resonators	- large and heavy magnets (therm. equiliblium!)
- cost effective, compact	- energy limited ~1GeV
[- no pulsed stress in target]	[- no pulsed structure for neutrons]

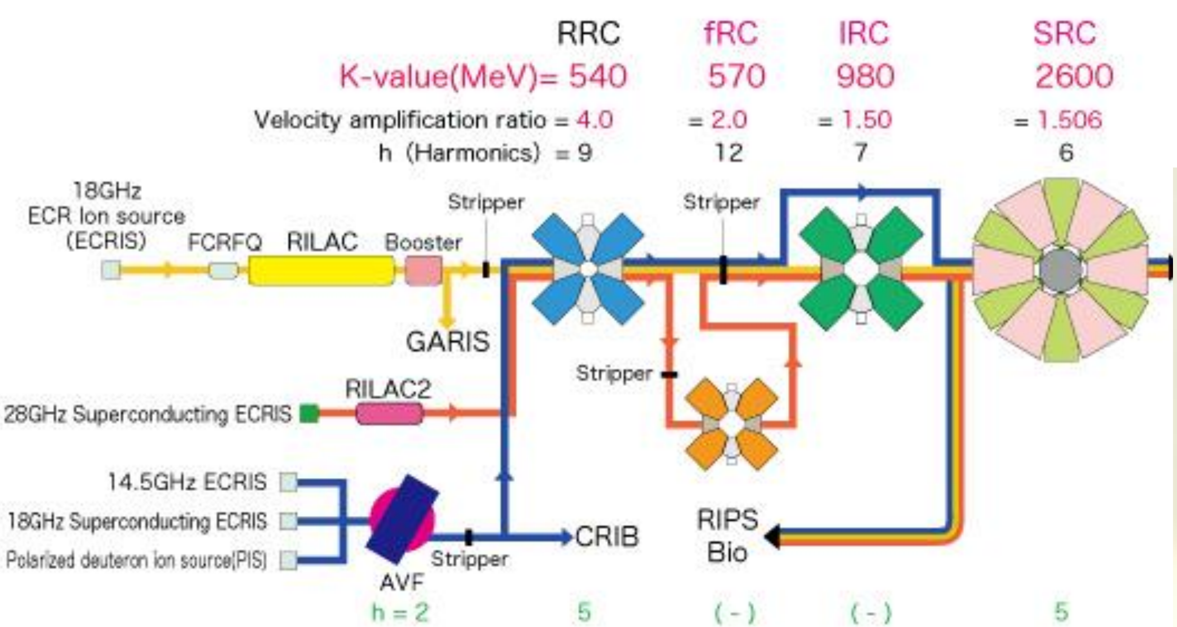
M.Seidel, ESS Bilbao Initiative Workshop, March 16-18 (2009)

Paul Scherrer Institut (PSI) - Science

- Science:
  - Neutron production (SINQ) for n scattering and imaging of molecules and atoms
  - Muon production (SμS): Muon Spin Rotation, Relaxation or Resonance: A research tool using muons as sensitive local magnetic probes in matter.
    Research at the LMU focuses mainly on magnetic properties of materials and on positive muons or muonium (bound state of a positive muon and an electron) as light protons or hydrogen substitutes in matter.

RIKEN - Machines

- RIBF at the Nishina Center
- 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions.



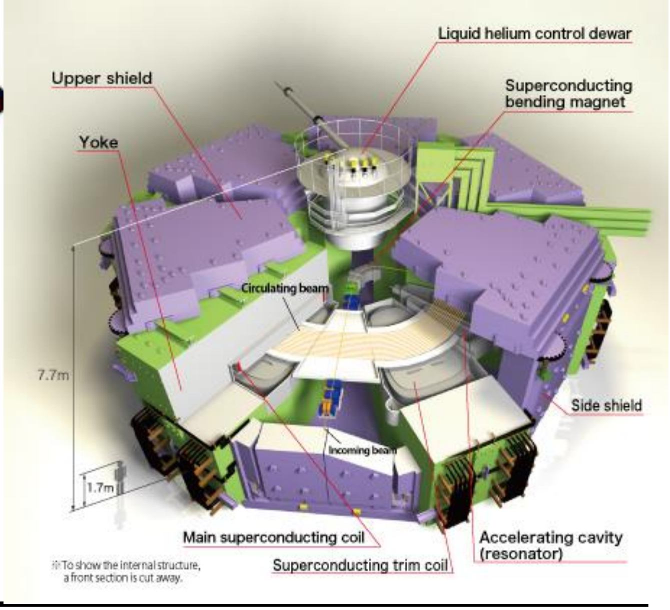


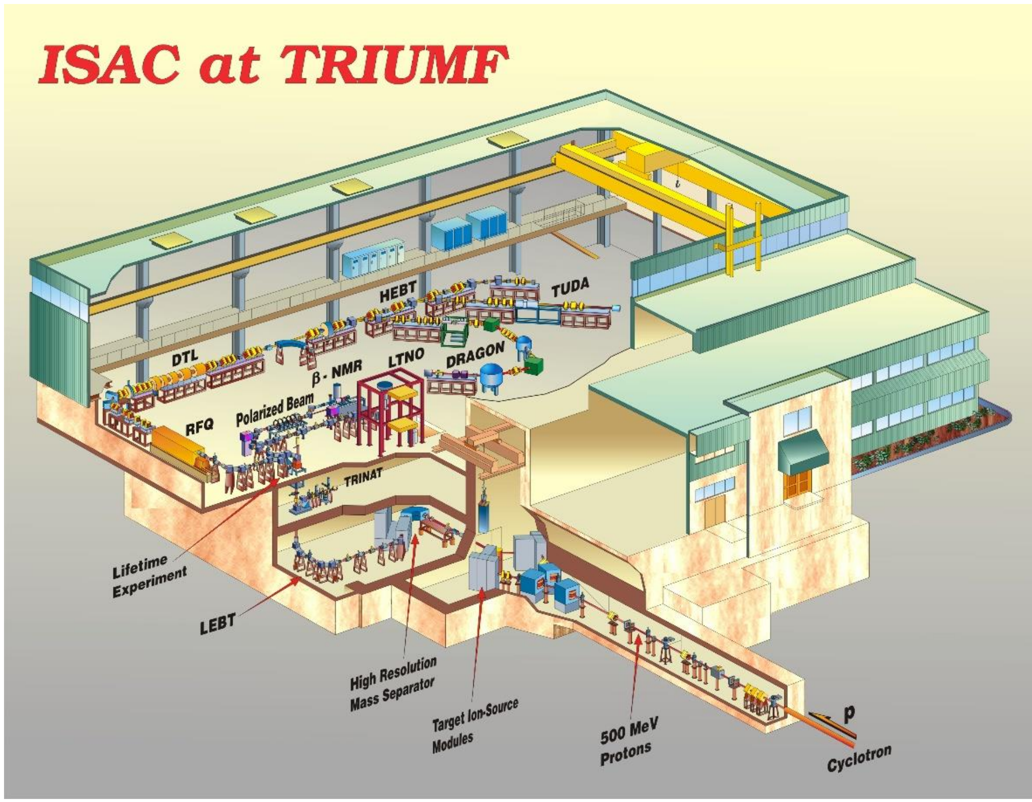
Image credit: nishina.riken.jp

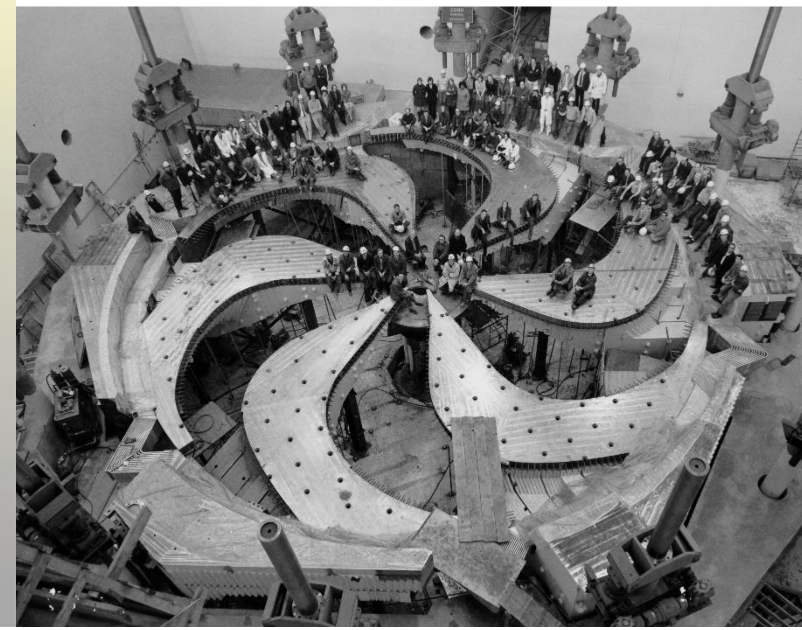
RIKEN - Science

- RIPS is an in-flight type radioactive isotope (RI) separator to produce intense RI beams via the projectile fragmentation of stable ions or the in-flight fission of uranium ions.
- Map out isotope chart, discover new elements and isotopes.
- 2004: Element 113 discovery.
- 2009: at RIBF, polarized deuteron beams are accelerated up to 440A MeV in the AVF-RRC-SRC acceleration mode.
- Three Nucleon Force Study via Few Nucleon Systems
- BigRIPS – large acceptance in-flight RI separator

TRIUMF - Machines

- 500 MeV proton cyclotron (accelerate H-, extract by stripping)
- Bombard suitable target, extract rare isotopes and re-accelerate



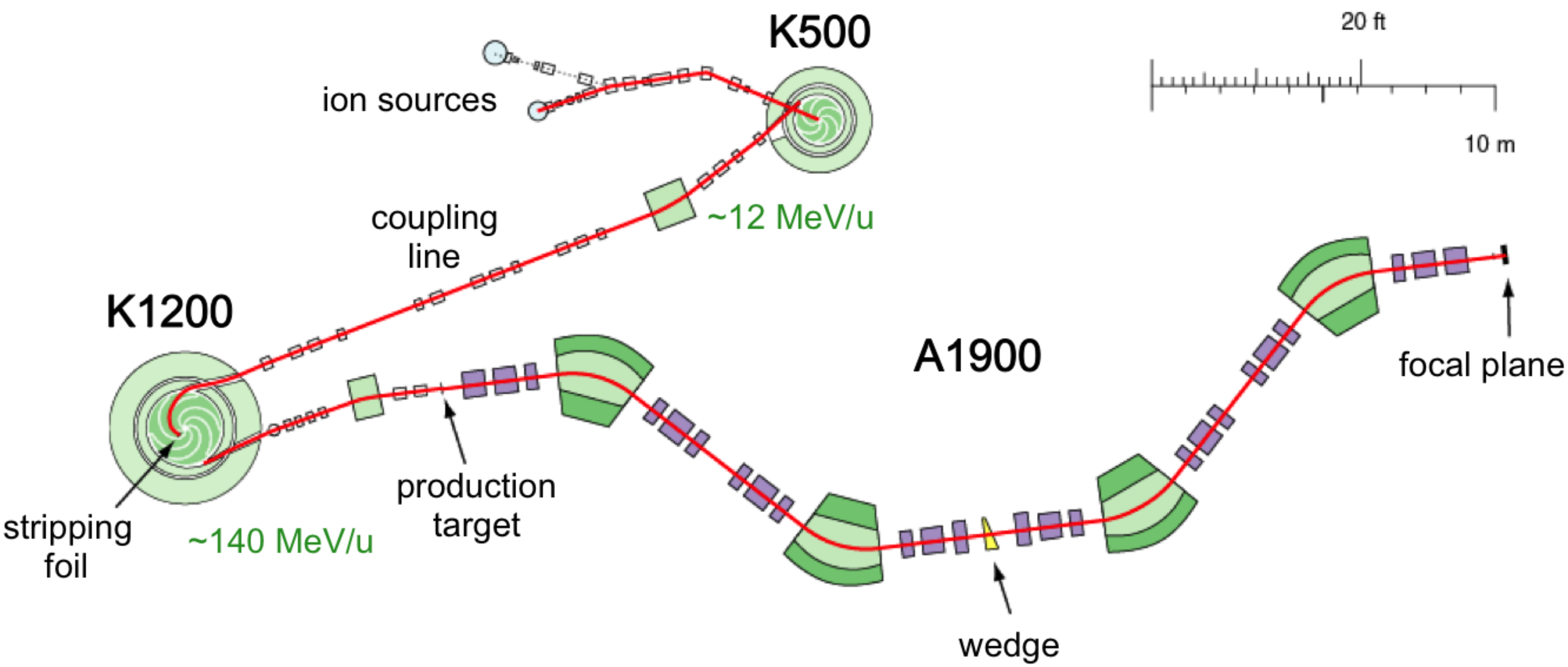


TRIUMF - Science

- Isotope Separation and Acceleration (ISAC) → linear accelerator post-accelerates separated isotopes
- Science:
  - Nuclear structure
  - Nuclear astrophysics
  - Fundamental symmetries

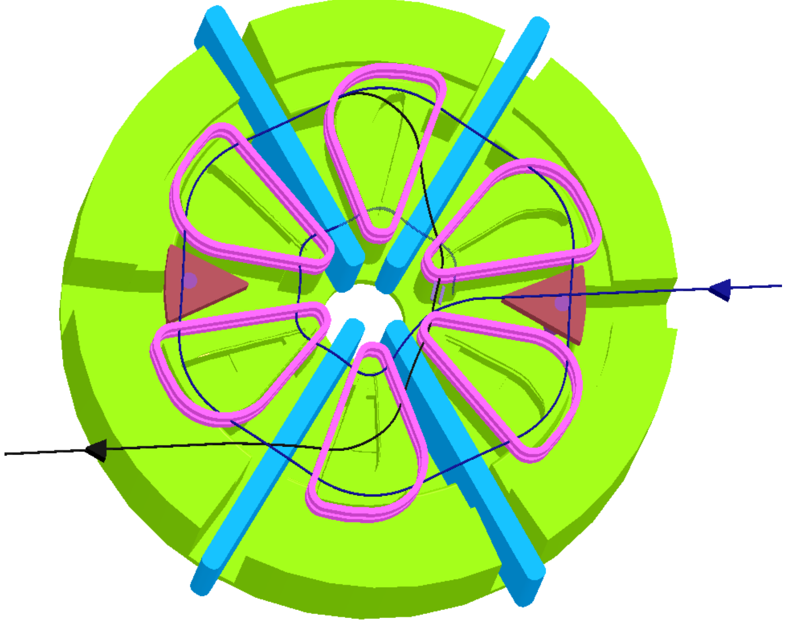
NSCL - Machines

- 2000: Coupled Cyclotron Facility starts producing beam (before only separately)
- Beam is created in ECR ion sources (SuSI and Artemis)
- K-500/K-1200: compact superconducting isochronous cyclotrons



NSCL - Science

- Fragmentation of heavy ions impinging on a thin beryllium foil
- A1900 mass spectrometer separates rare isotopes for use in experiments.
- Science:
  - Study of nuclei with extreme neutron excess
  - Quark-Gluon Plasma
  - Nuclear Astrophysics (low energy area)
  - Fundamental Symmetries
- Outlook: Construction of FRIB underway (replace cycl. with linac)



Proposed design of a 6-sector cyclotron for the DAEδALUS experiment. Source: The DAEδALUS collaboration

Act III

FUTURE CONCEPTS

Cyclotron Advantages

- Clearly, cyclotrons are not at the high energy frontier (anymore). However, they have certain attractive qualities:
  - Well-understood
  - Comparably cheap
  - Can be very compact
  - Can deliver fairly high cw beam currents (PSI: 2.2 mA protons)
- New developments:
  - Push intensity limits!
  - Lighter, more compact…Ironless?
  - Decelerator.

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  - Push intensity limits!
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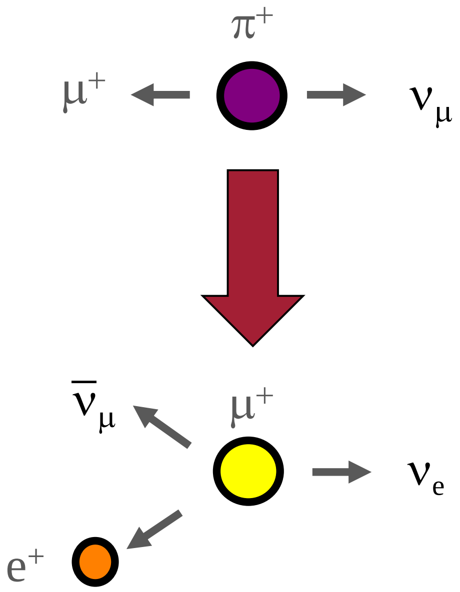
  - Decelerator.

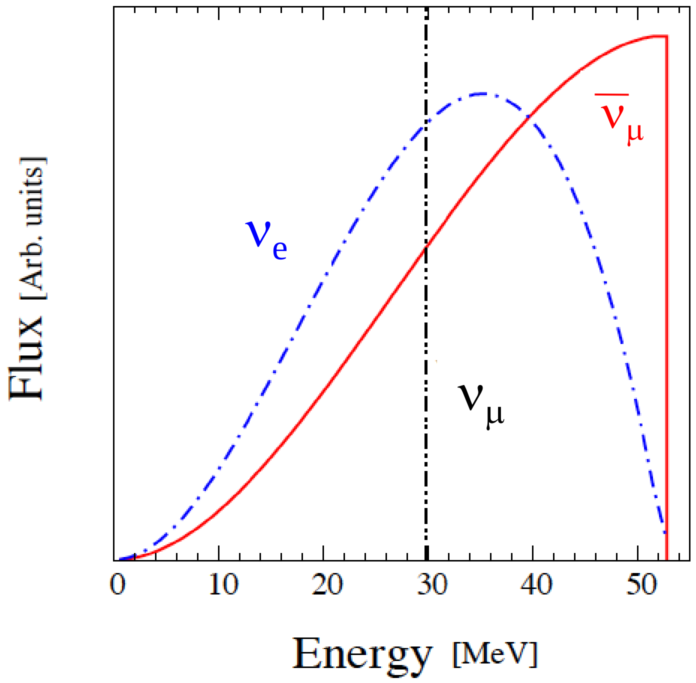
Why push intensity?

- Many experiments benefit from higher statistics.
  Higher current: Run shorter time with more particles, get better results earlier ☺
- Other processes can only be sustained with a certain influx of particles (e.g. accelerator driven subcritical reactors - ADS)
- Efficiency: More particles from one accelerator → more isotope production for medical purposes (run several targets off one accelerator)
- PSI Ring has demonstrated > 2.2 mA cw proton beams.
- Neutrino and Dark Matter group here at MIT is proposing an experiment to measure CP violation (see Neutrino talk next week), calls for 10 mA of protons… possible? See next slides…

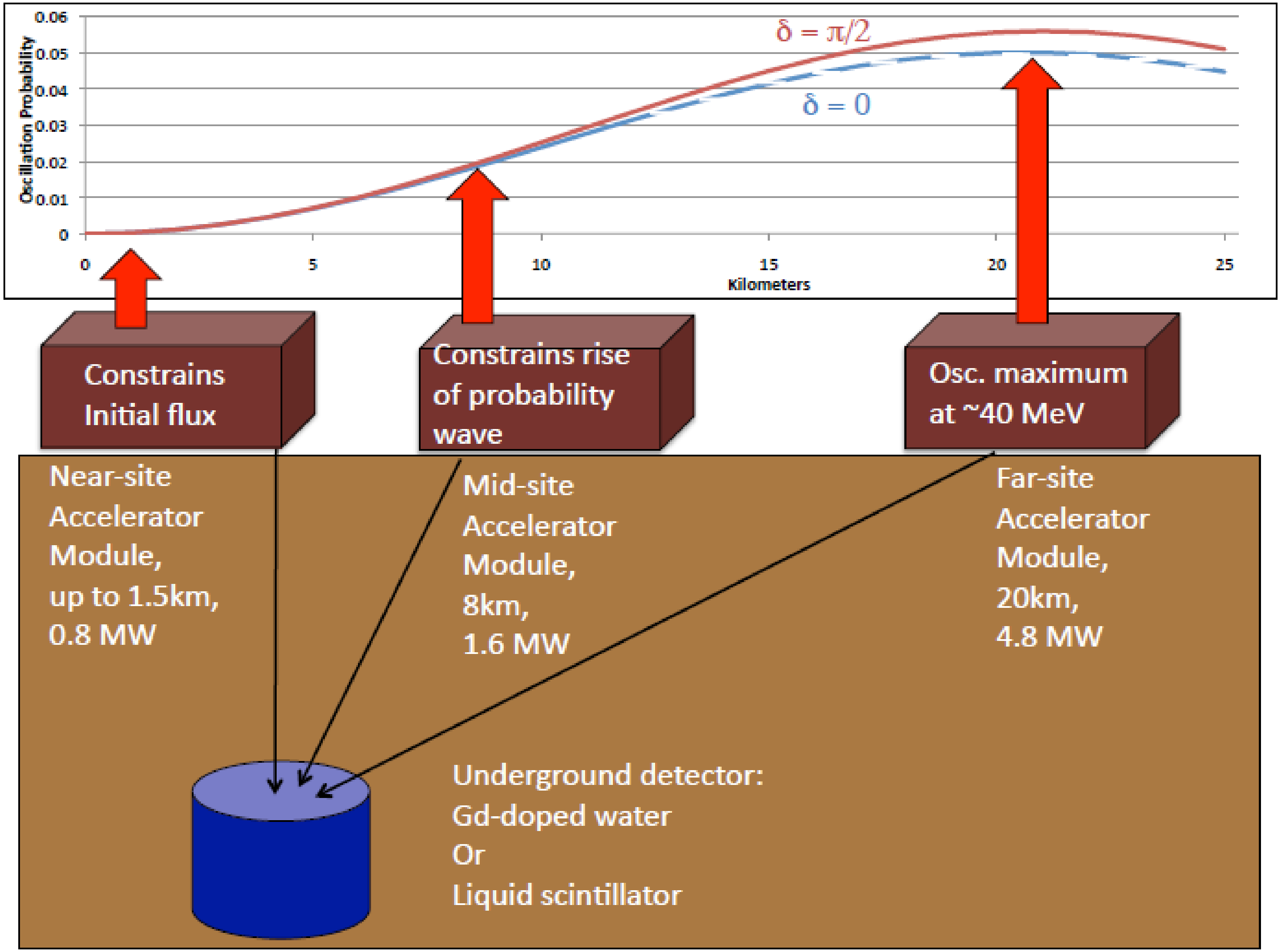
DAEδALUS Neutrino Production

- Use Pion/Muon decay-at-rest induced by 800 MeV protons for neutrino production, virtually free of $\bar{\nu}_e$
- Use inverse beta decay (IBD) to measure $\bar{\nu}_e$ appearance
- Need detector with large number of protons (free hydrogen): Scintillator or Gd doped water Cherenkov detector

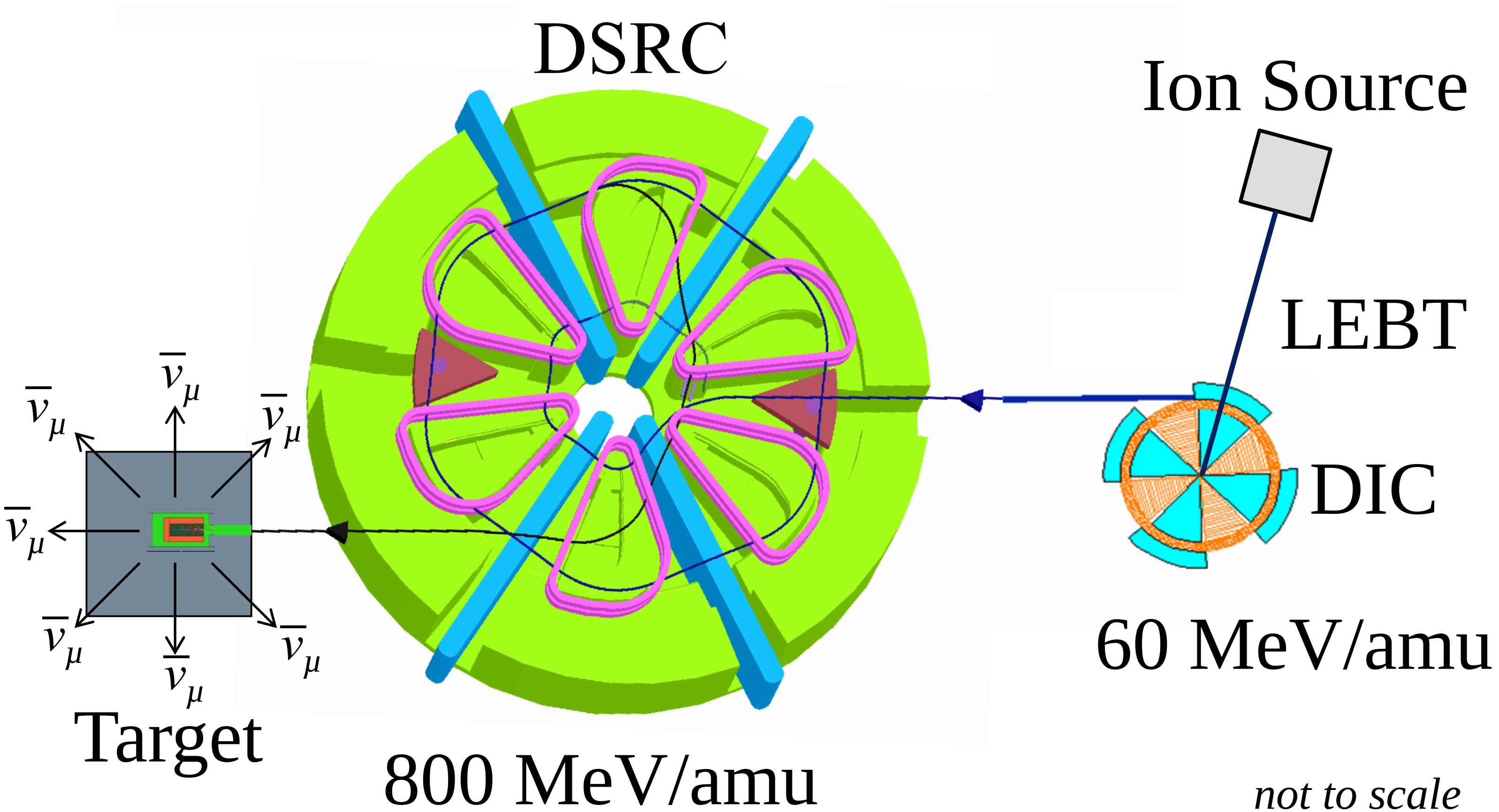




DAEδALUS – Three Accelerator Concept



How to provide the 800 MeV protons?



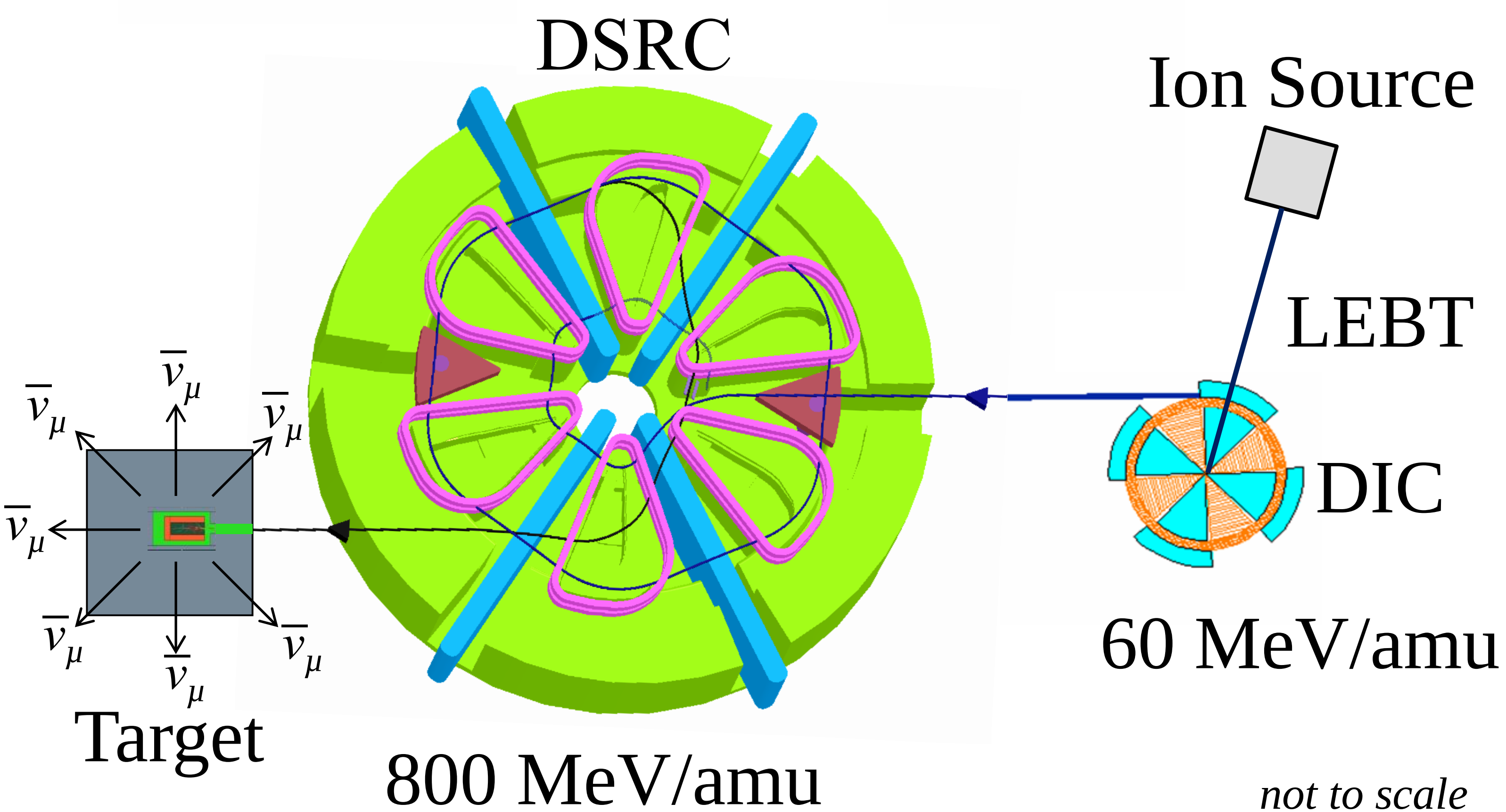
The 4 Phases of DAEδALUS

Phase			Location/Detector	
I		Produce 50 mA H_2^+ source, inflect, capture 5 mA and accelerate	BCS Inc. Teststand, Experiment at INFN-LNS Catania	Accelerator Science
II	IsoDAR	Design and build DIC, extract, produce antinu flux via ^{8}Li	WATCHMAN, KamLAND, JUNO	SBL $\bar{\nu}_e$ physics
III		Build first DSRC, Run as a “near accel.” at existing large detector	NOvA, LENA, Super K	SBL $\bar{\nu}_\mu$ physics
IV		Build the high power DSRC, Construct DAEδALUS	JUNO HyperK, LENA	~~CP~~

We are here

Can we use the injector cyclotron alone?

DAEδALUS



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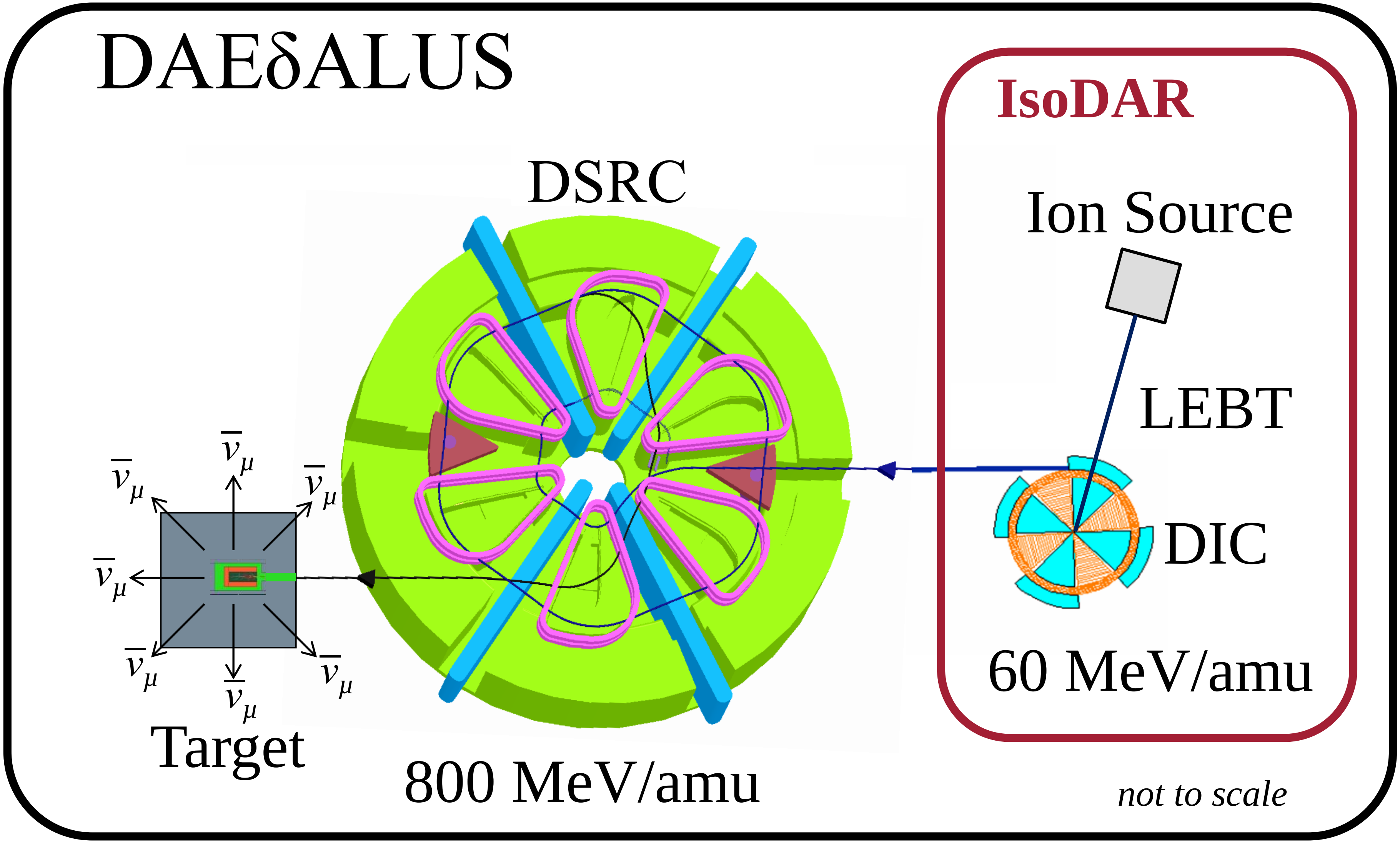
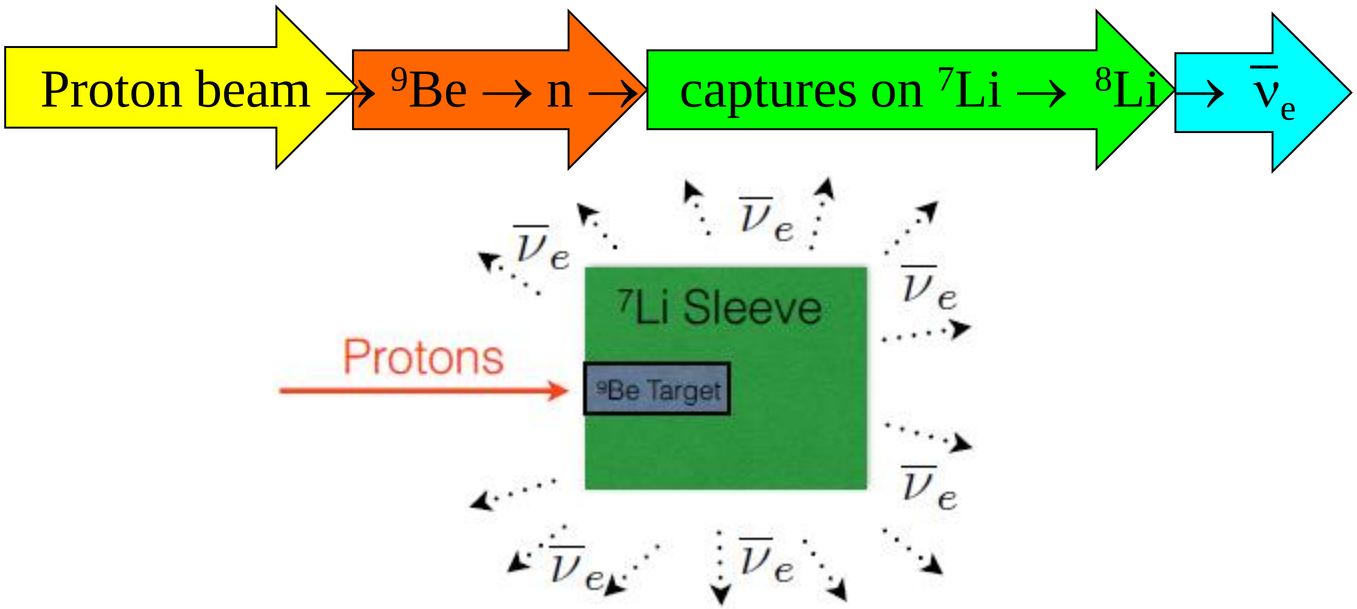


Massachusetts Institute of Technology

IsoDAR Production

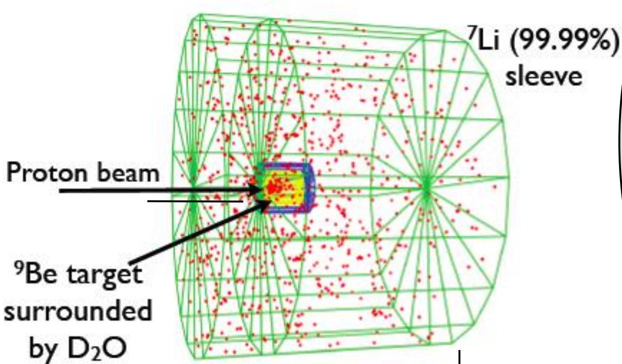
- Use beta-decay-at-rest induced by 60 MeV protons to produce very pure $\bar{\nu}_e$ beam

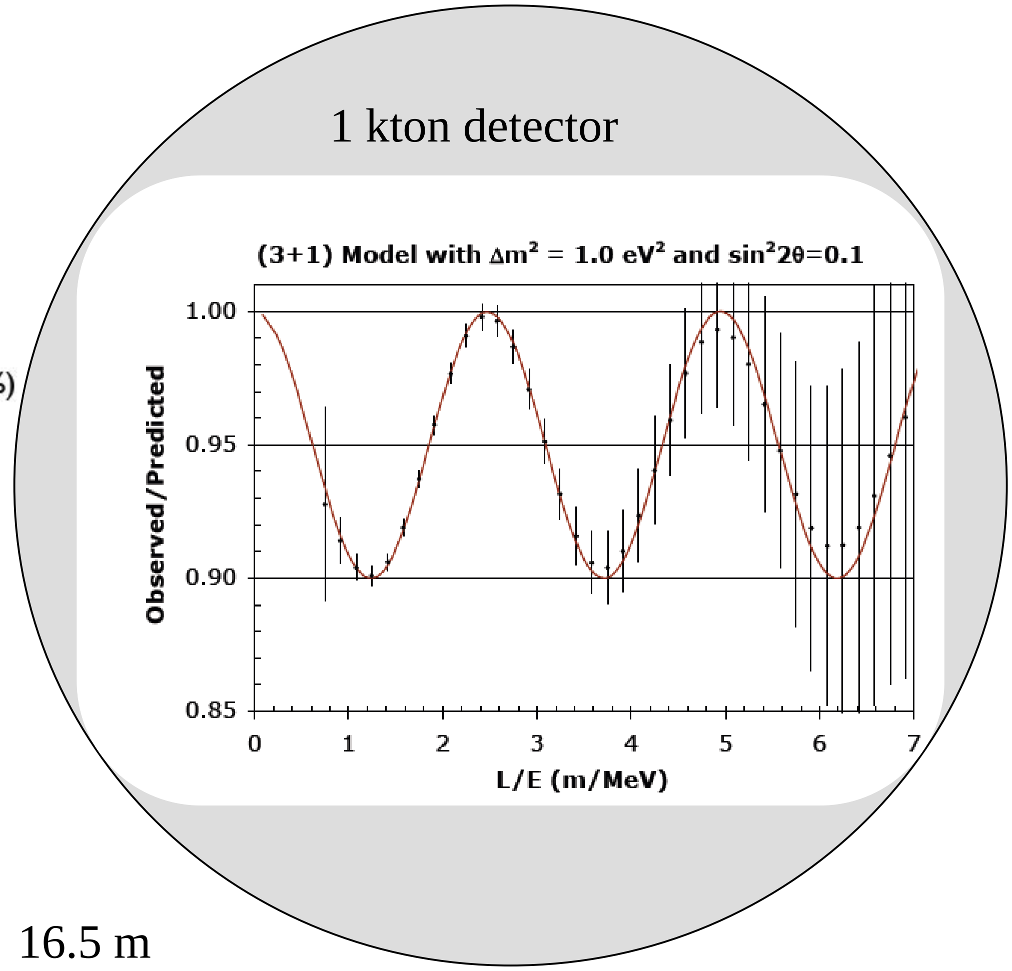


- Measure $\bar{\nu}_e$ disappearance through inverse beta decay.
- Low energy, very short baseline.

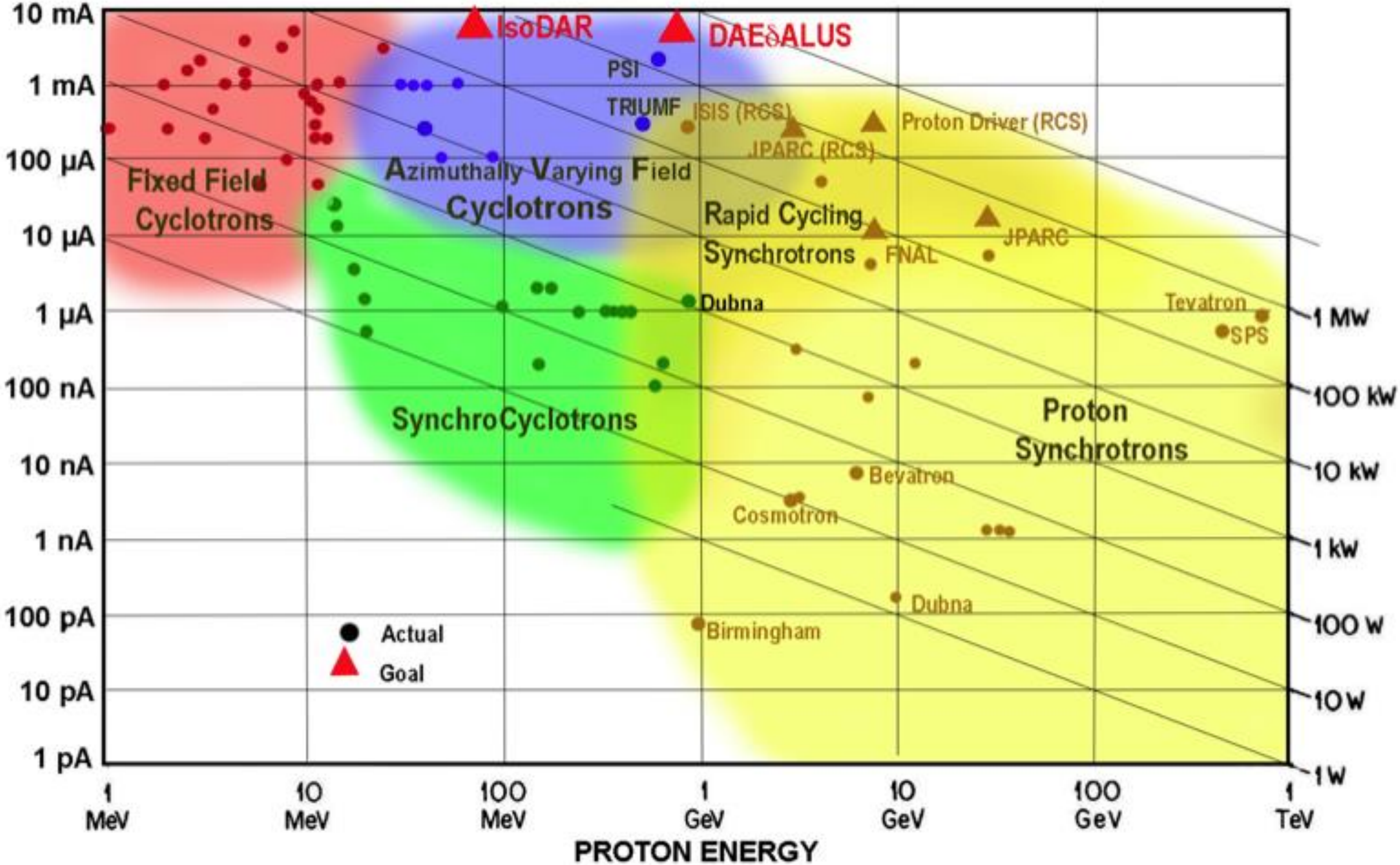
IsoDAR: Measure $\bar{\nu}_e$ Disappearance

Search for oscillations
at short distances
and low energy

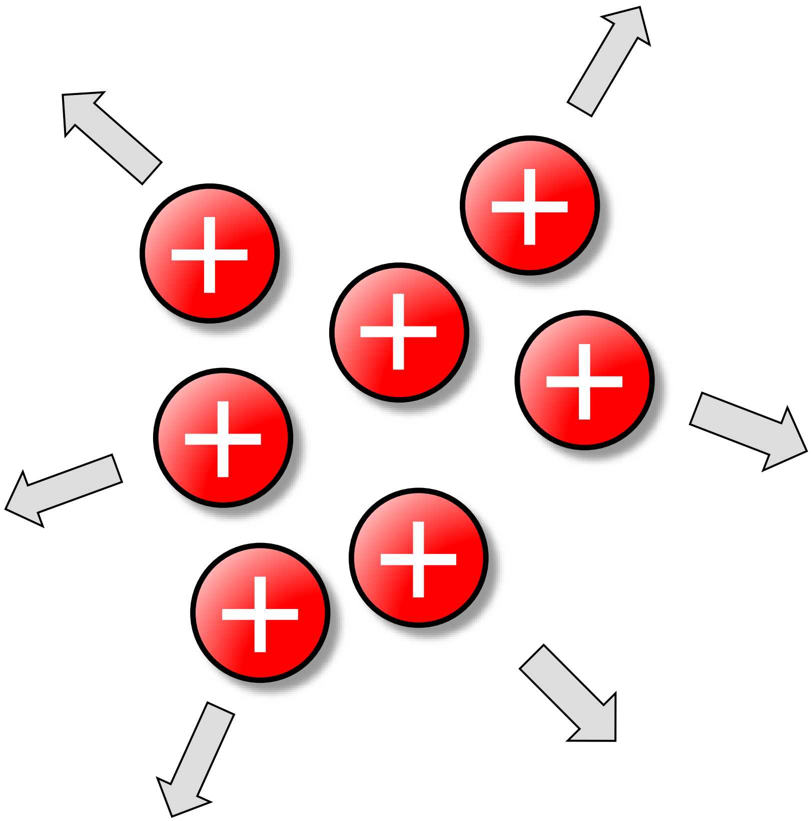


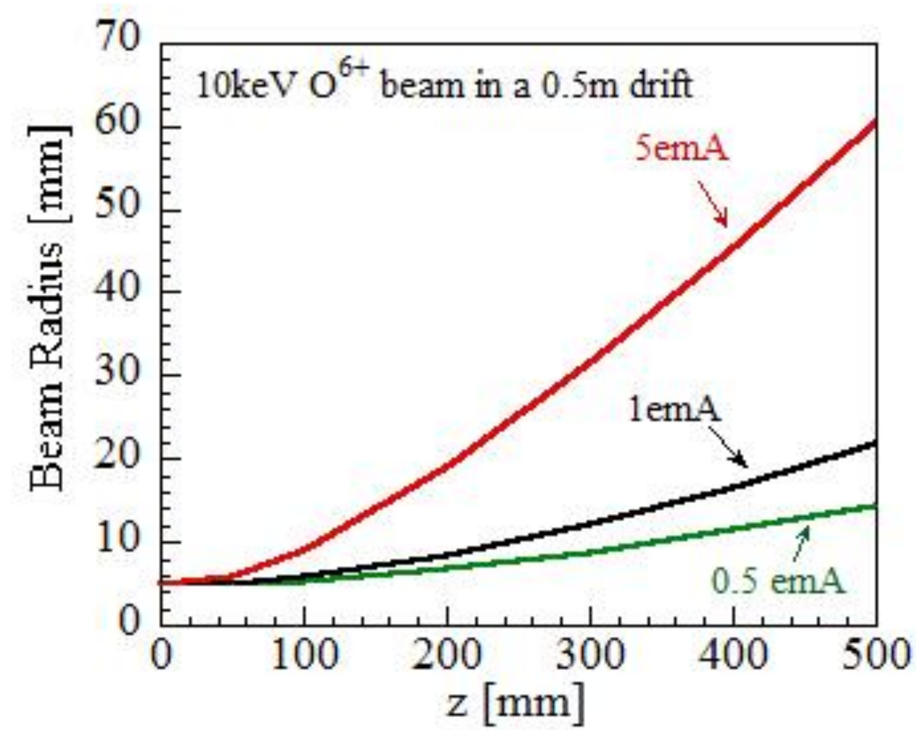


16.5 m


10 mA
1 mA
100 µA
10 µA
1 µA
100 nA
10 nA
1 nA
100 pA
10 pA
1 pA
IsoDAR
DAEδALUS
PSI
TRIUMF
ISIS (RCS)
Proton Driver (RCS)
JPARC (RCS)
Fixed Field
Cyclotrons
Azimuthally Varying Field
Cyclotrons
Rapid Cycling
Synchrotrons
FNAL
JPARC
Dubna
Tevatron
SPS
1 MW
100 kW
10 kW
1 kW
100 W
10 W
1 W
SynchroCyclotrons
Proton
Synchrotrons
Bevatron
Cosmotron
Dubna
Birmingham
Actual
Goal
1
MeV
10
MeV
100
MeV
1
GeV
10
GeV
100
GeV
1
TeV
PROTON ENERGY

Space Charge





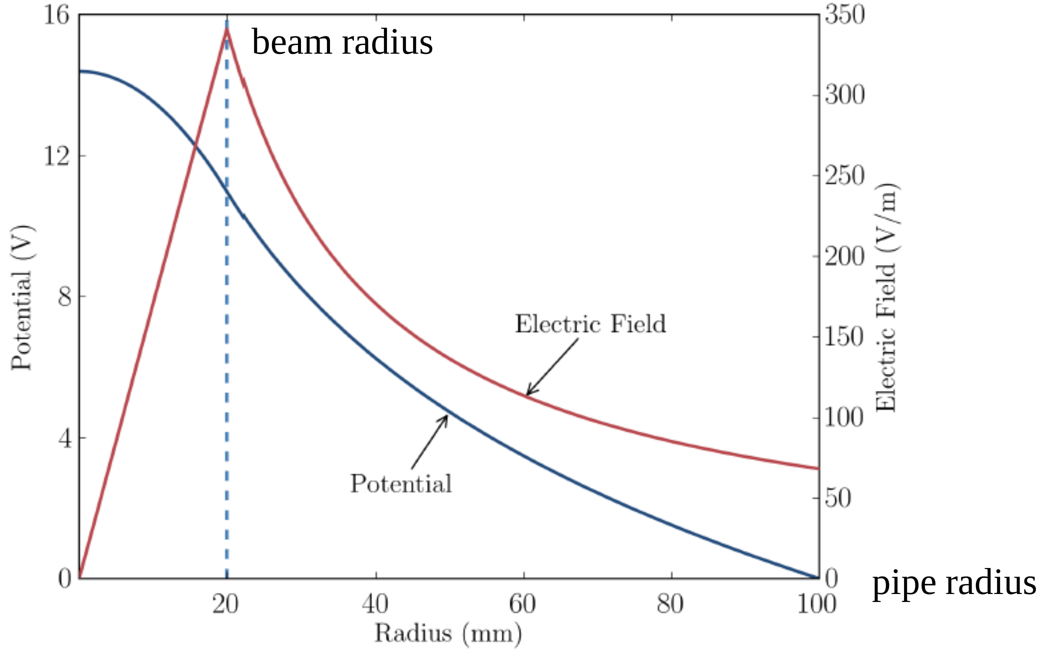
- Acts defocusing on the beam

Space Charge Potential

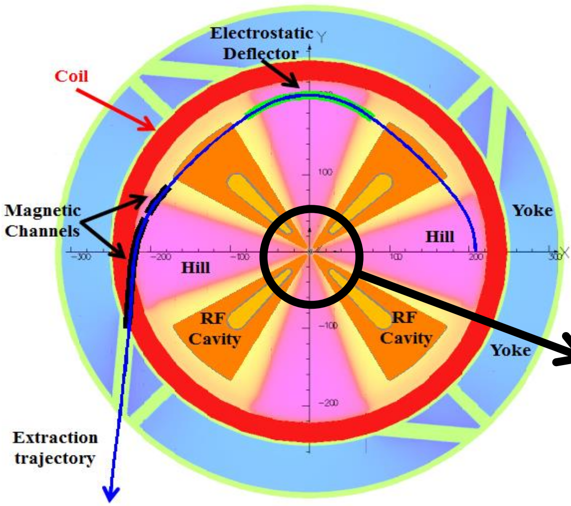
- Space charge potential of a uniform and round beam with beam radius r_b in a grounded beam pipe r_p:

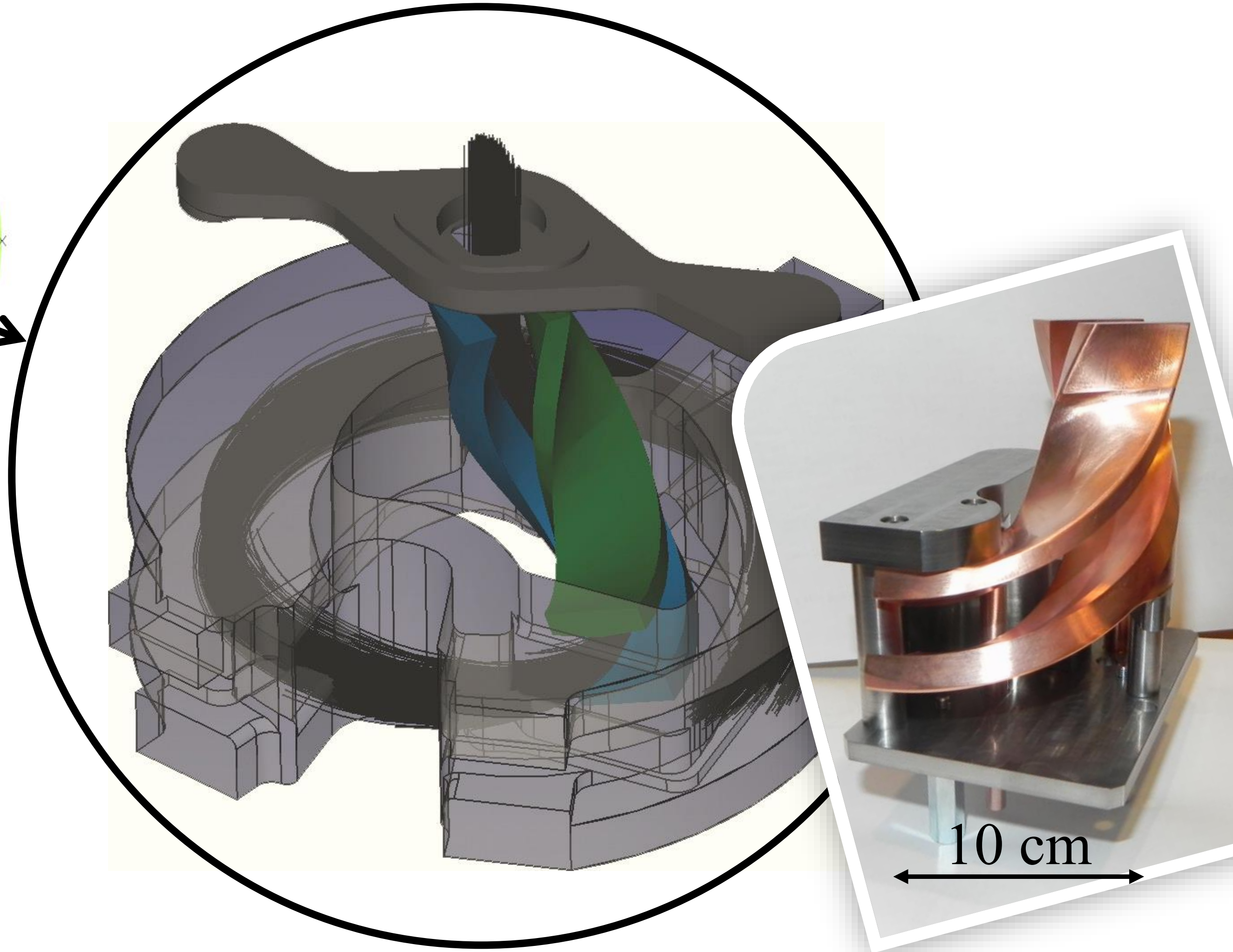
$$\phi(r) = \begin{cases} \Delta\phi \left(1 + 2\ln\frac{r_p}{r_b} - \frac{r^2}{r_b^2}\right) & \text{for } r \le r_b \\ \Delta\phi \; 2\ln\frac{r_p}{r} & \text{for } r_b \le r \le r_p \end{cases}$$

$$\Delta\phi = \frac{I}{4\pi\epsilon_0 v_b}$$



Spiral Inflector



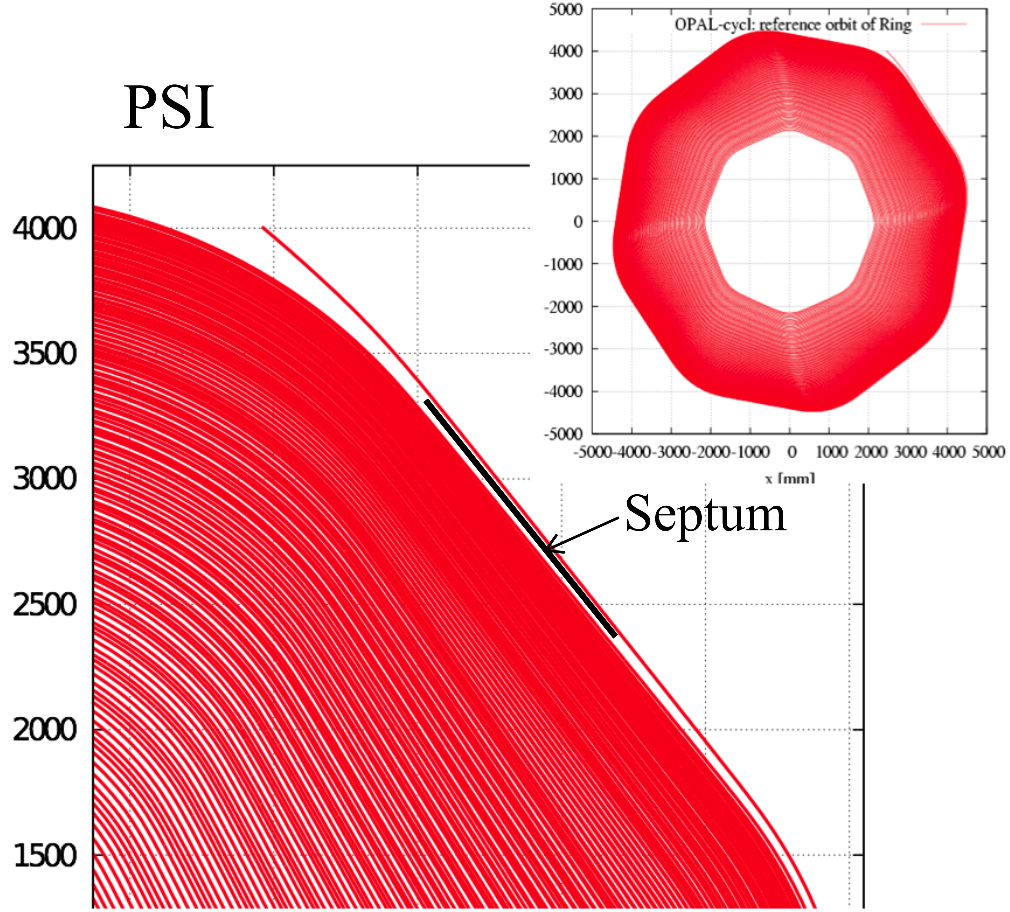


- Takes the beam from axial direction to horizontal plane
- No SCC
- Complicated Boundary Conditions

Designed by Daniela Campo

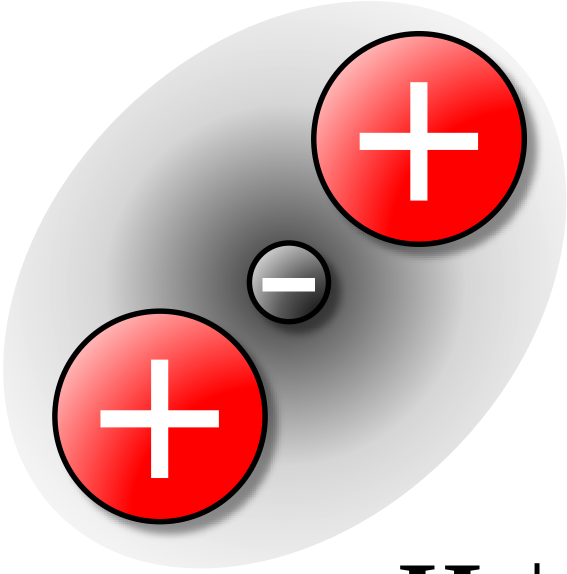
Other Problem: Extraction

- “Classical“ with Septum
- Requires extreme beam stability
- Very good turn separation
- Need to play with resonance to increase turn separation
- PSI (2.2 mA) has 99.98% efficiency, still loses 200 W of beam on septum
- Upper limit for hands-on maintenance (activation)
- No good for 10 mA beam



Accelerate H_2^+

- 2 protons for each charge state
- Reduces Space Charge in LEBT and Spiral Inflector
- Can do stripping extraction in Superconducting Ring Cyclotron for DAEδALUS
- Challenges:
  - Ion Source? Microwave or Multicusp
  - Vibrational States



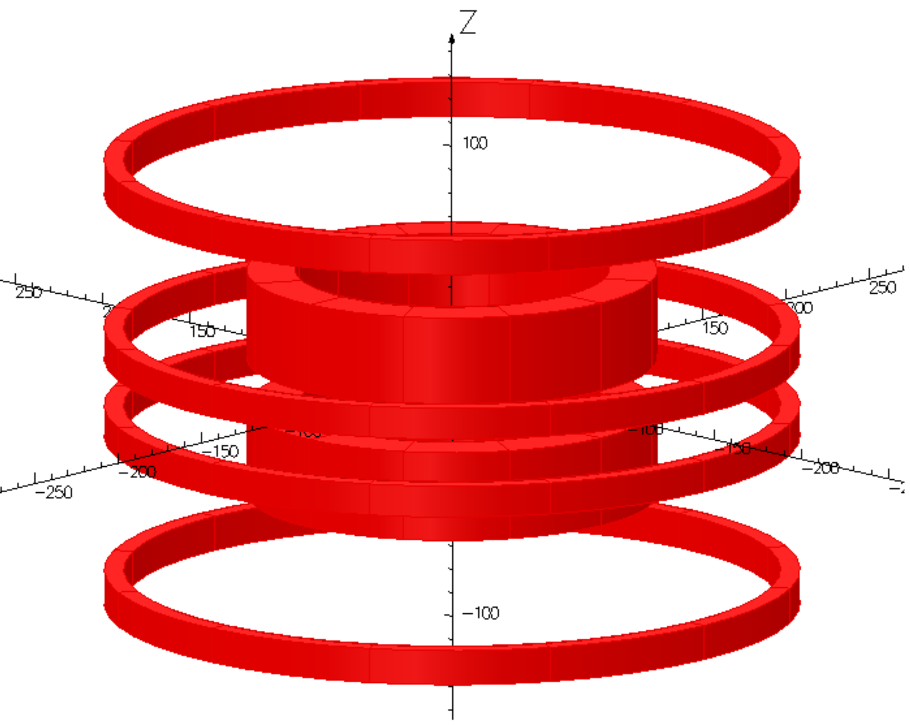
H_2^+

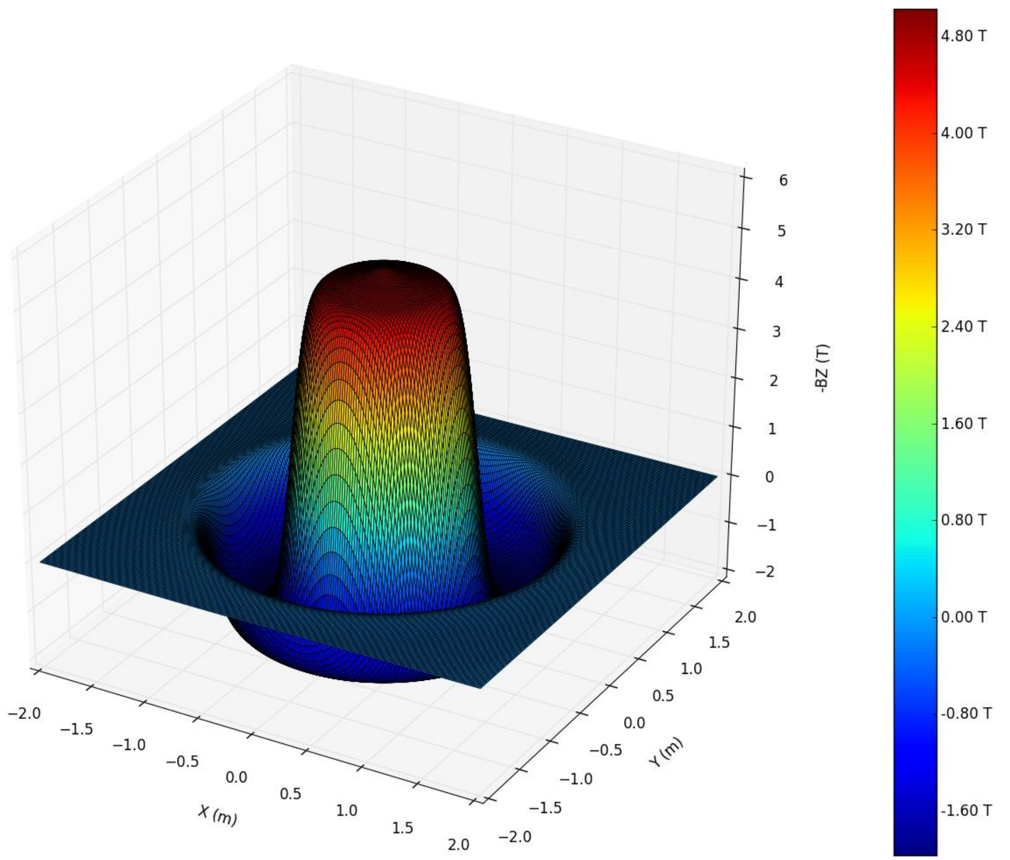
Why Ironless?

- It is very important to be able to select the particle energy to determine the depth of the Bragg peak
- This is usually done with degraders. Wedges that are inserted in the beam path. Messy.
- The connection of the gantry to the main beam line has to be rotatable, what if we can put the cyclotron on the gantry and move it together? But: Iron is heavy.
- Ironless Cyclotrons would be energy scalable!
- Much lighter!
- Ongoing research at MIT – Plasma Science and Fusion Center

Synchrocyclotron Coils

- Main Field Coils + Shaping Coils + Compensation Coils

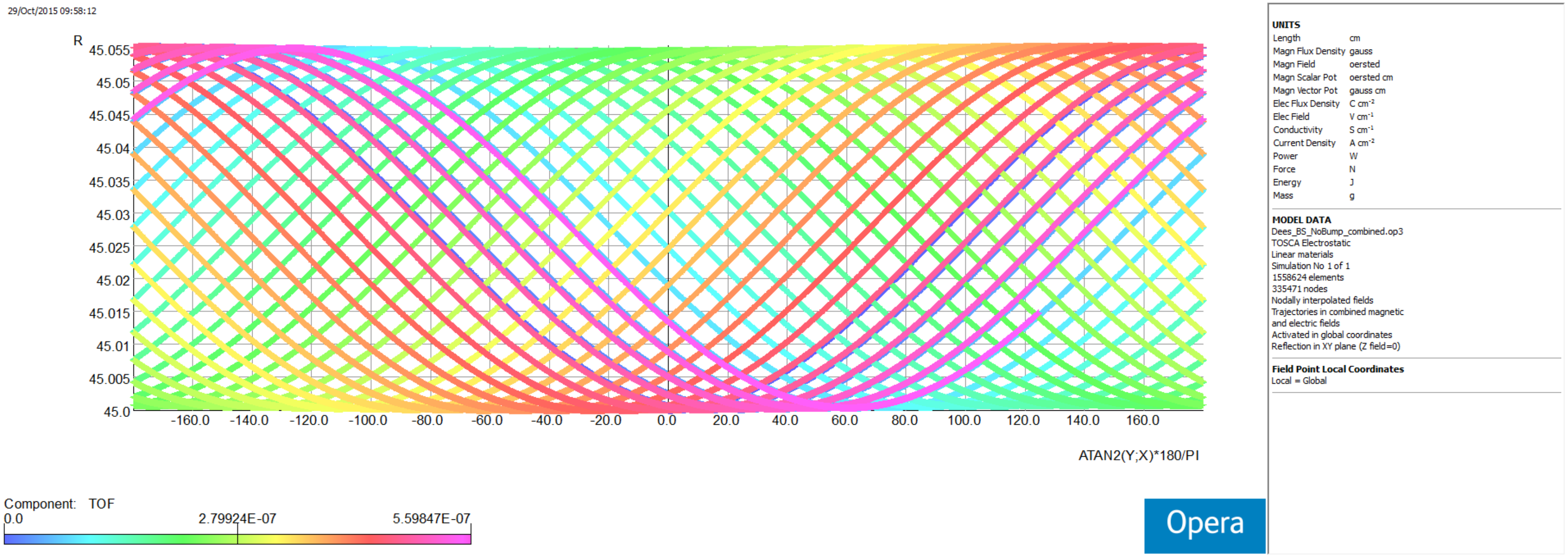




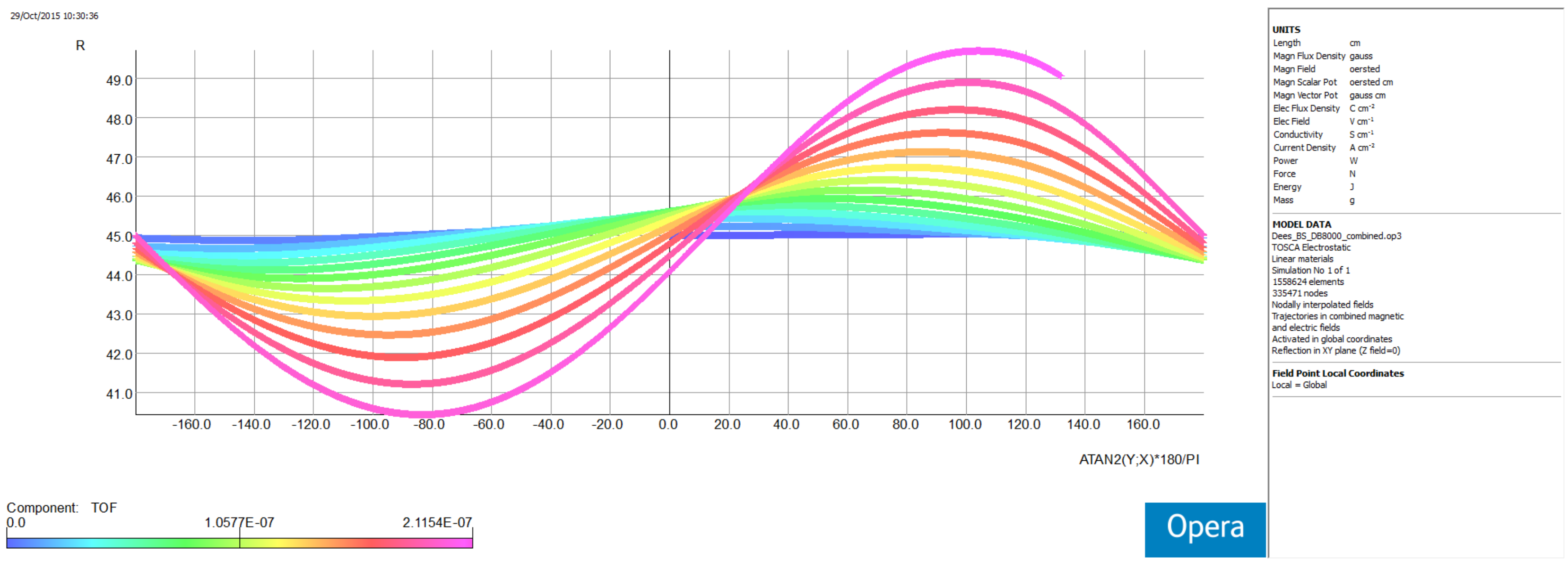
Extraction, The $\nu_r = 2/2$ resonance

- Dee voltage in a synchrocyclotron is typically 2-5 kV. That means acceleration is slow and turn separation is tiny.
- How do we get the beam out?
- If things go in circles… Resonances! Usually something we would like to avoid, but in this case we can use it.
- Use second order resonance $\nu_r = 2/2$ by introducing a field bump that increases linearly radially outwards.
- How? Coils. No iron, no permanent magnets because it needs to be scalable with final particle energy (70 – 230 MeV)

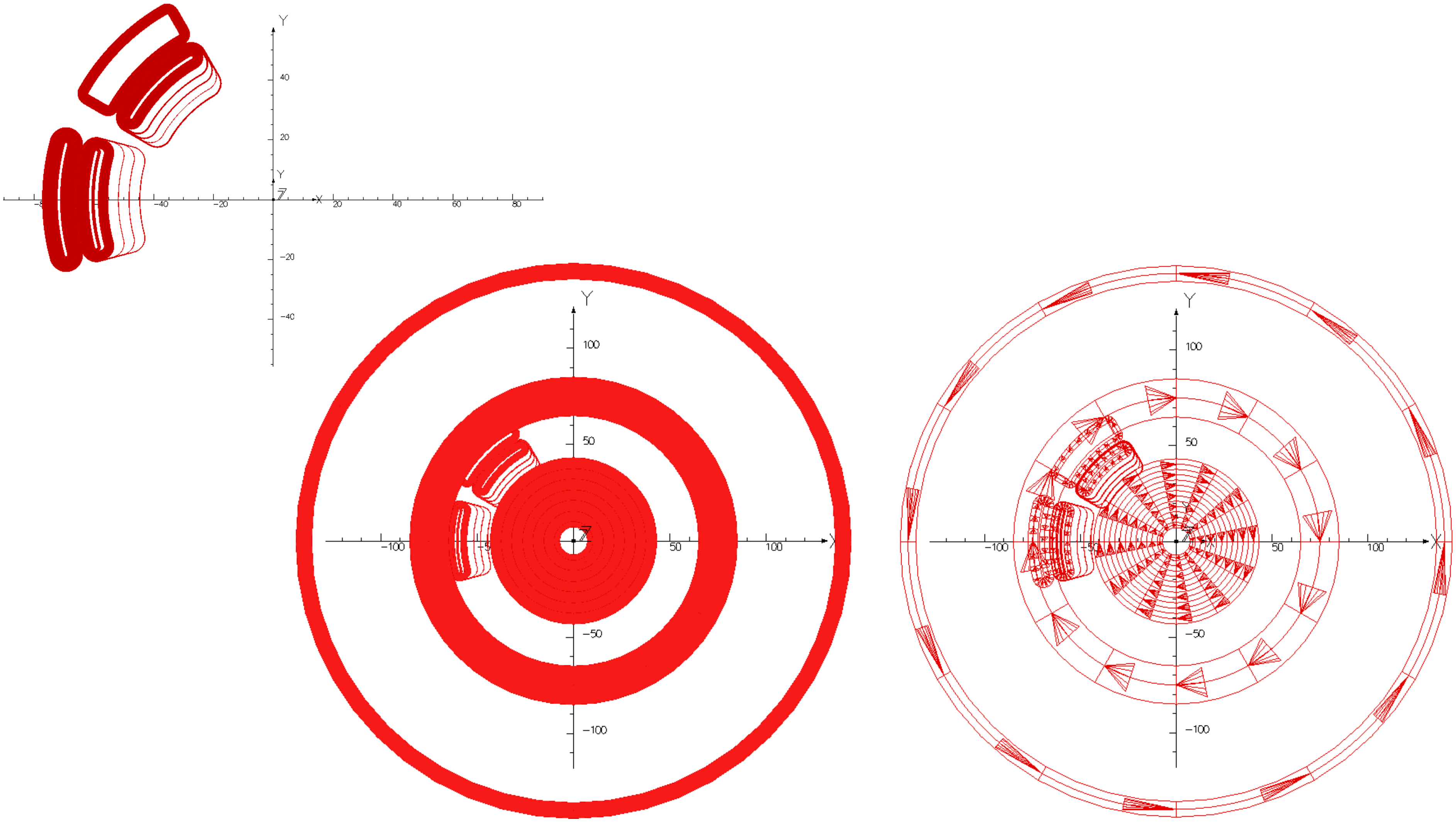
Harmonic Oscillation around r_0 with v_r
$v_r < 1$, $r_0 = 45$ cm



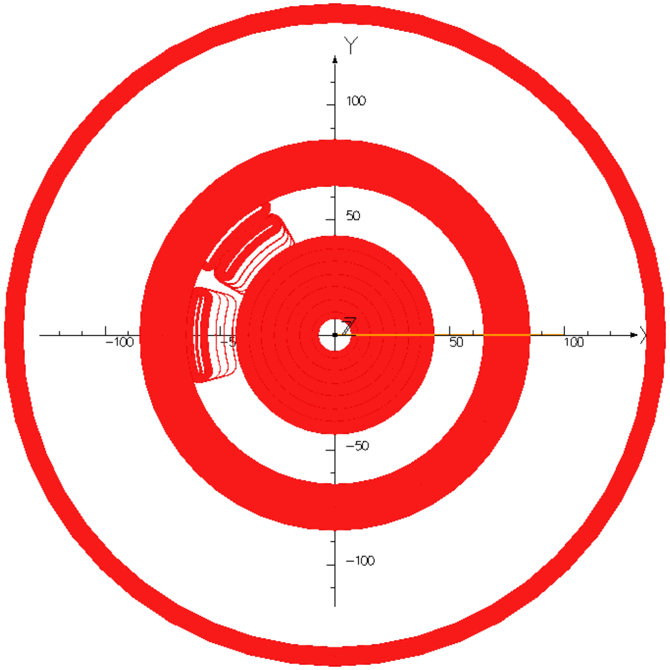
Task is to bring v_r = 1 and excite oscillation amplitude

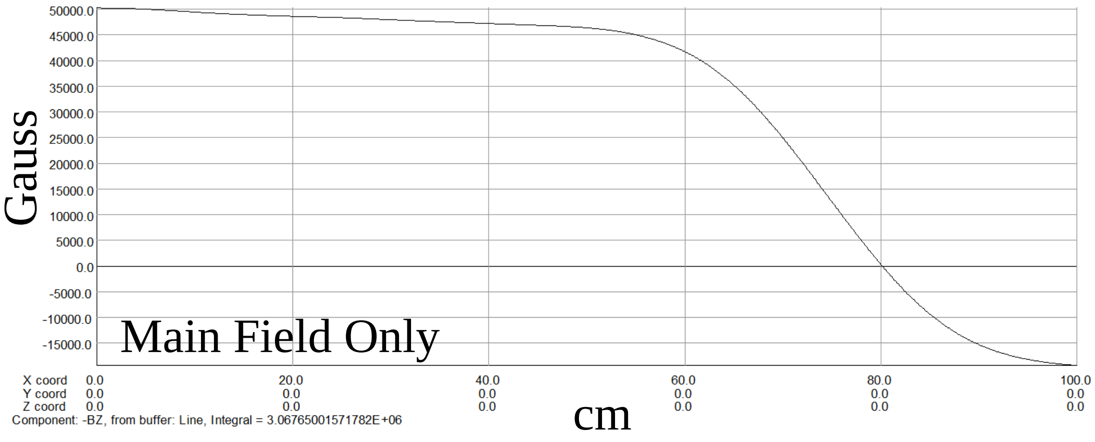


Latest Coil Model - Top View

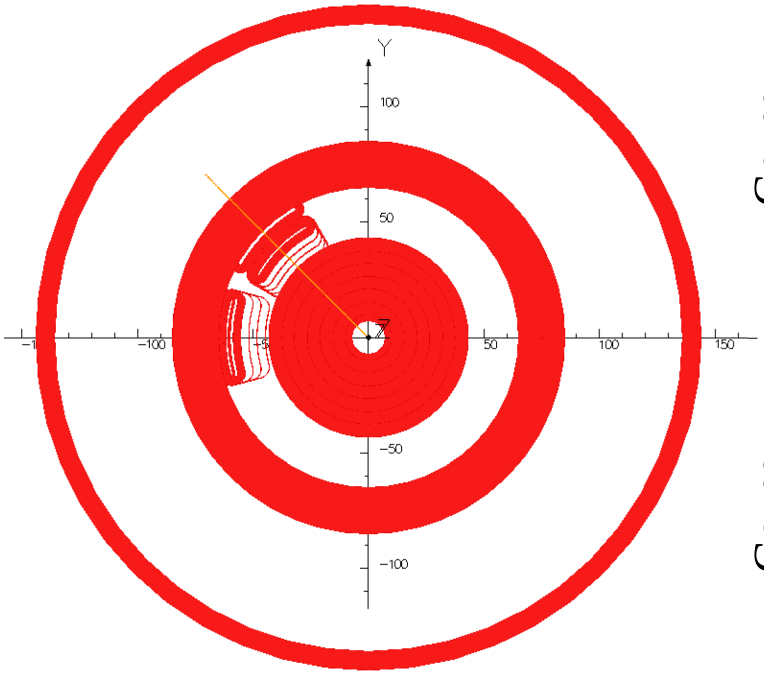


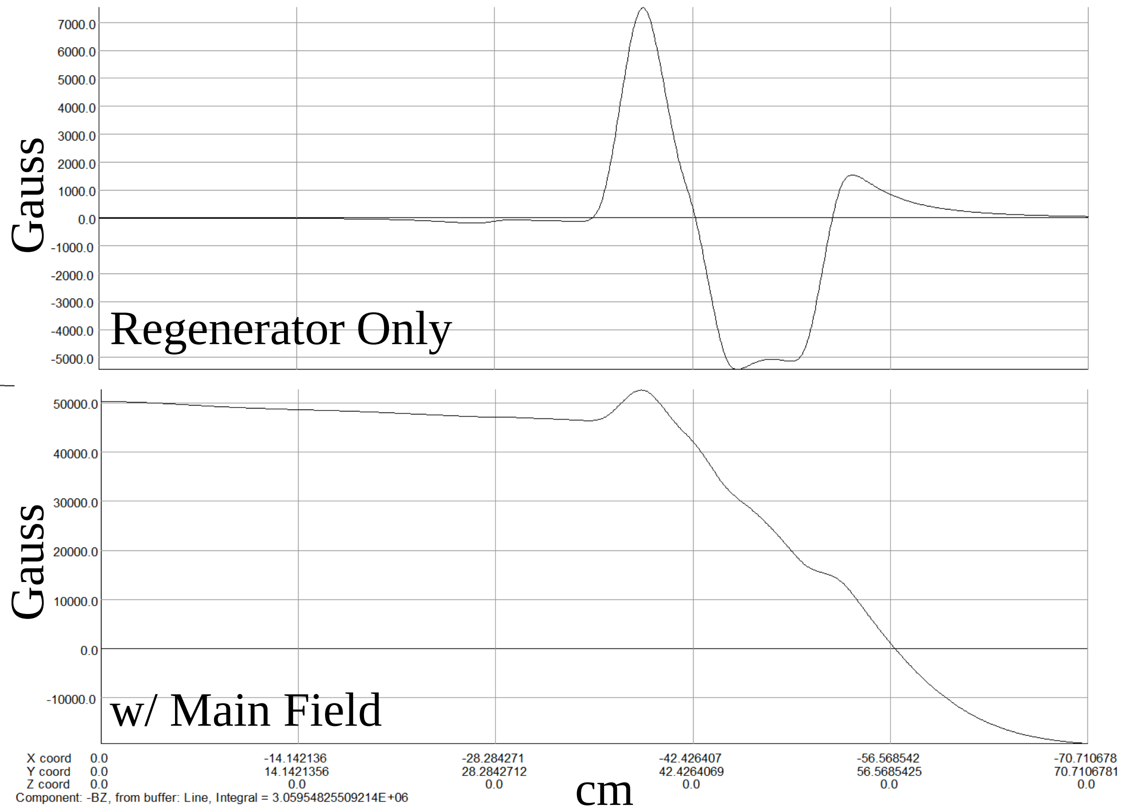
Main Field (230 MeV Field) – Option ab7a



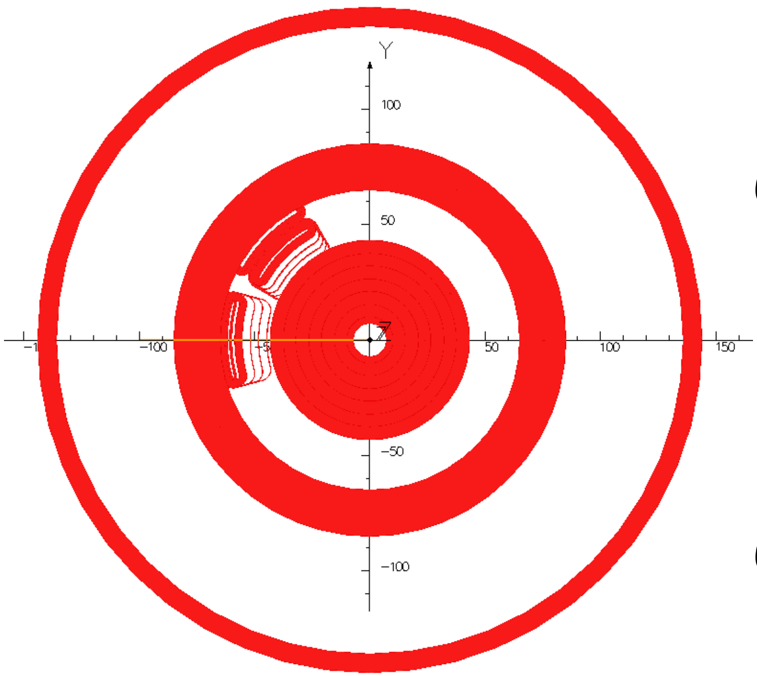


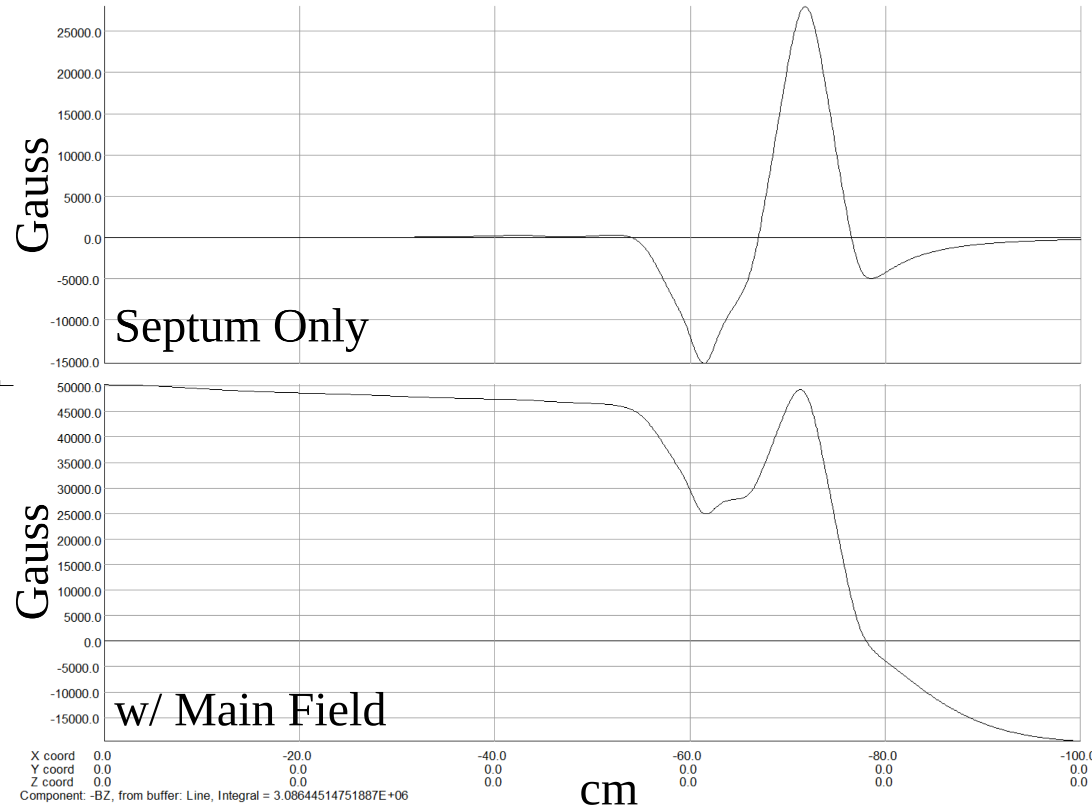
Regenerator (230 MeV Field)



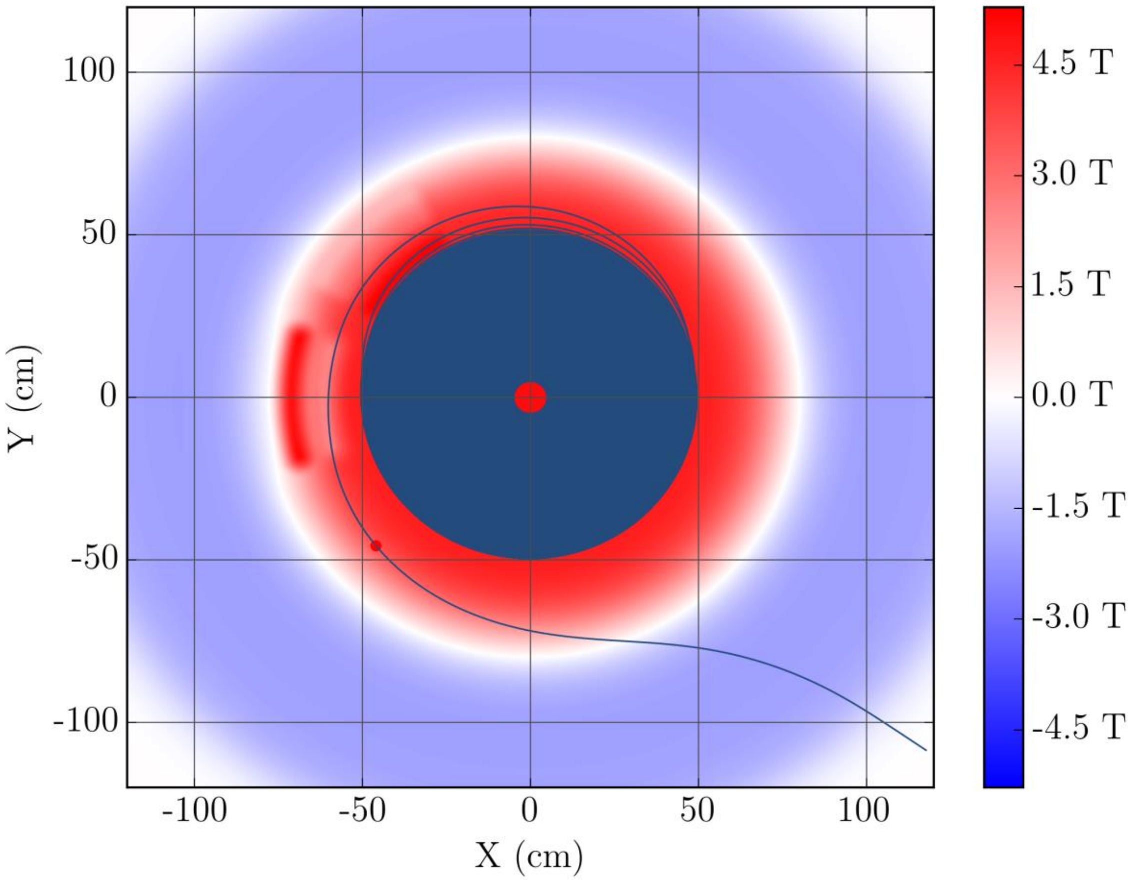


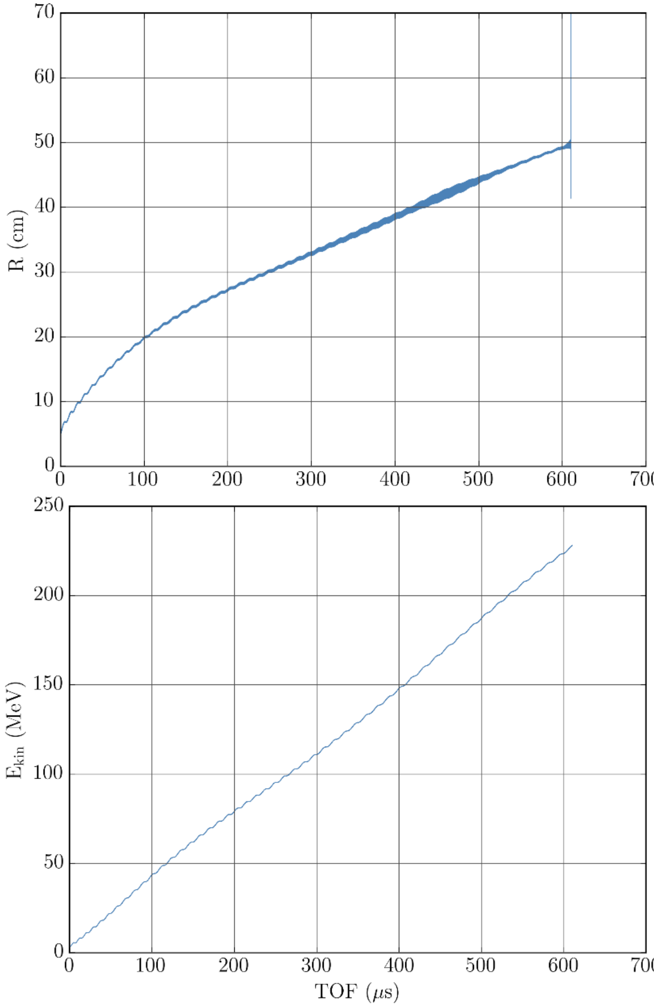
Magnetic Septum (230 MeV Field)



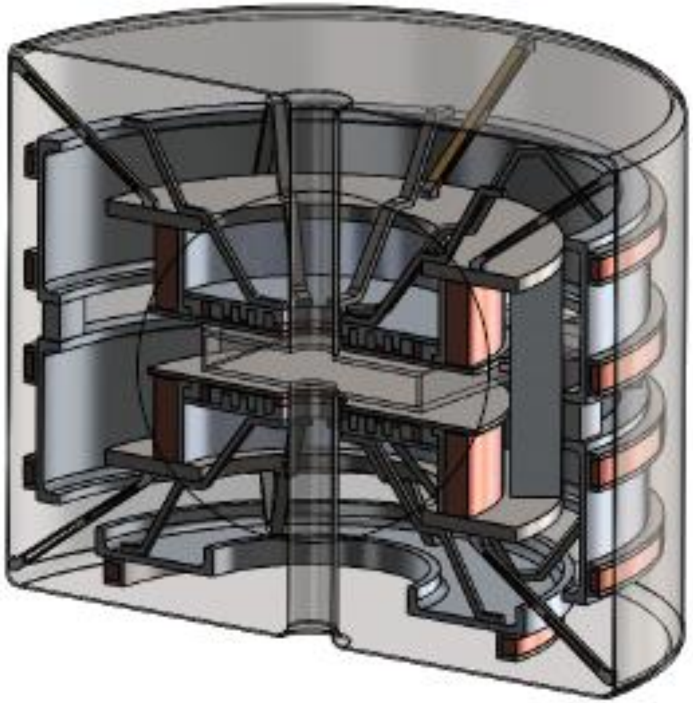


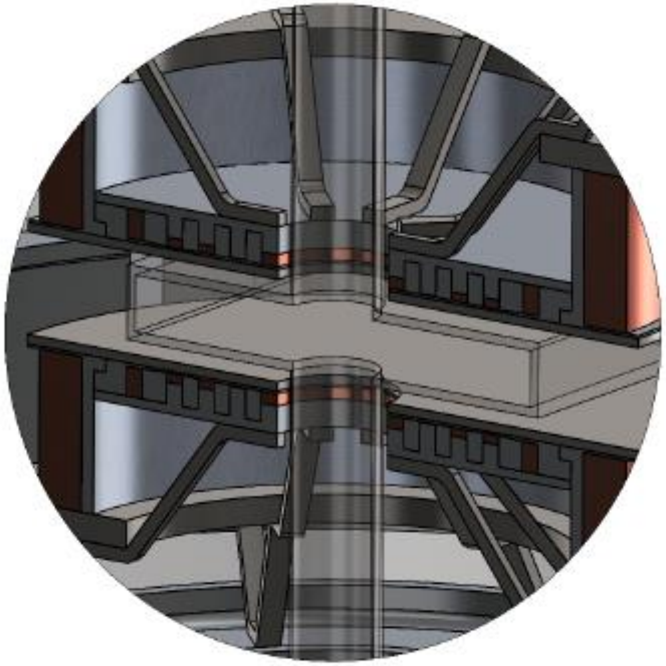
Tracking and Extraction 230 MeV





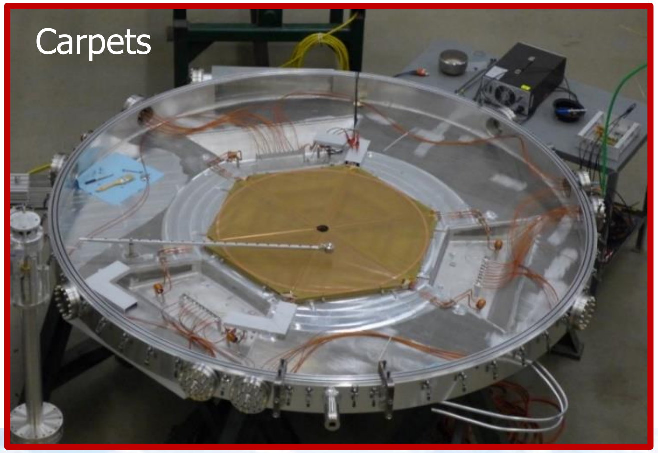
Possible Cryostat and Support Design

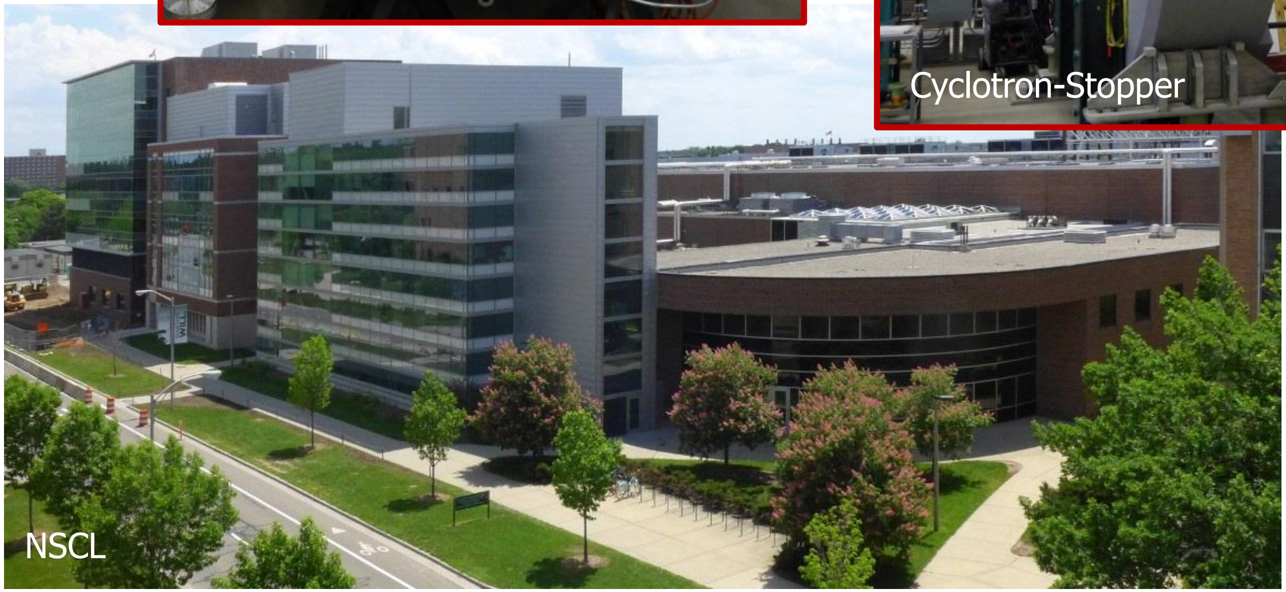




The NSCL Cyclotron Gas Stopper

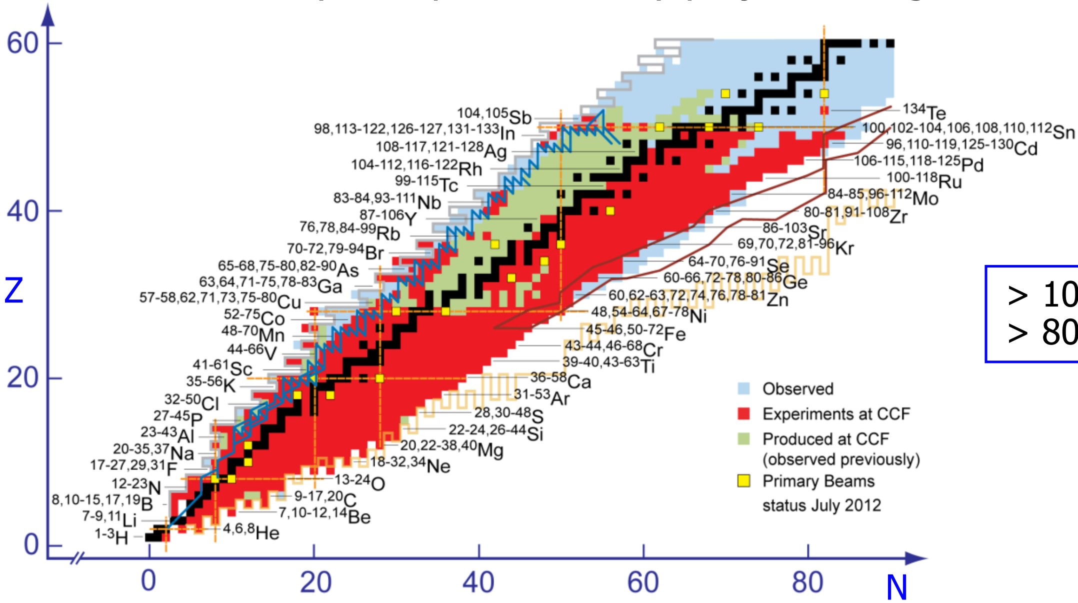
Why, What, Status & Low-energy transport





Why slow down beams at the NSCL?

NSCL: User facility, RIB production by projectile fragmentation and fission, **fast beams**



> 1000 RIBs made
> 80% RIBs used in experiments

NSCL has successful program with **stopped beams**:

– LEBIT facility for Penning trap mass spectrometry of projectile fragments

– BECOLA: laser spectroscopy coming online

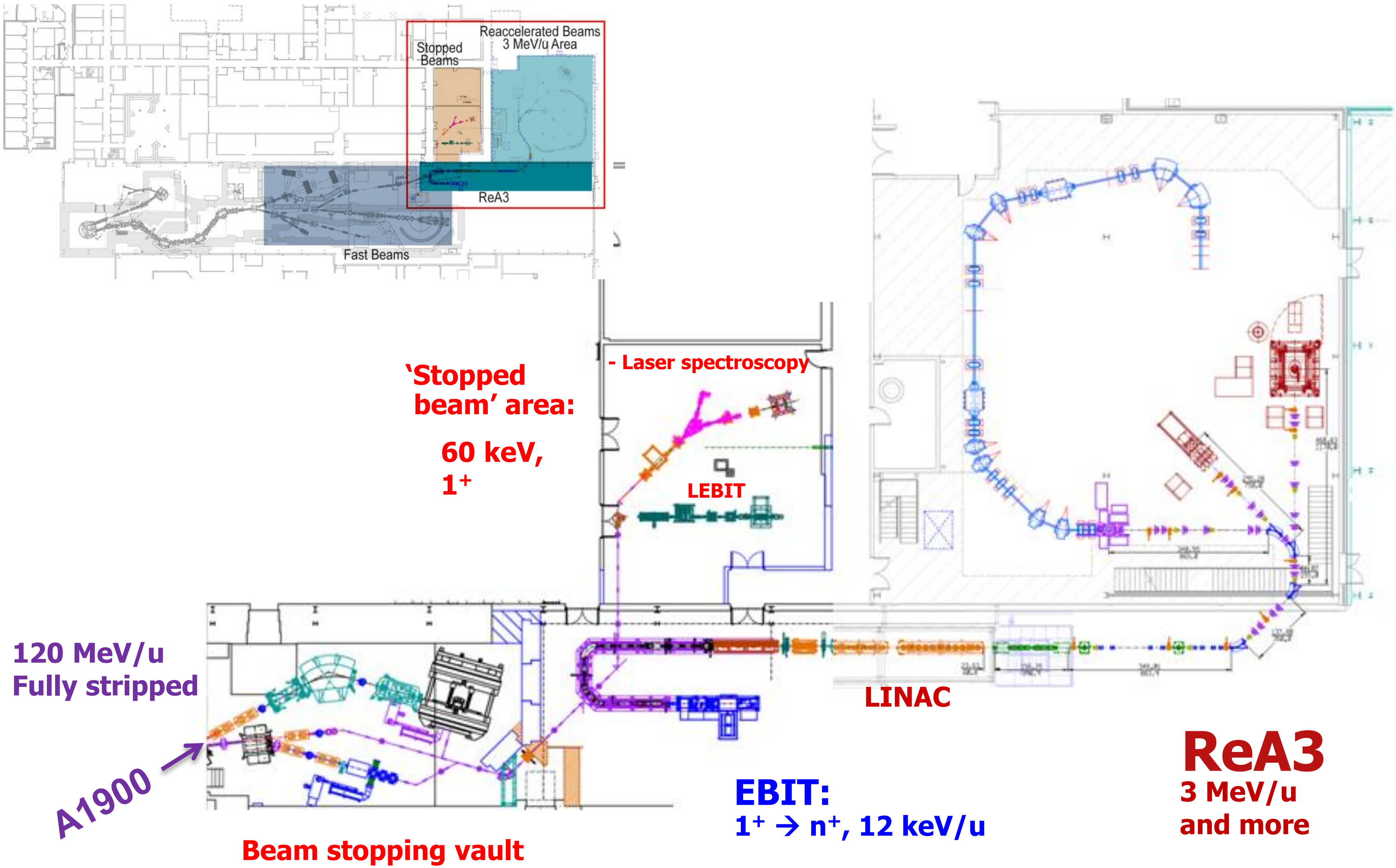
Re-accelerator ReA, new science opportunities with rare isotopes from projectile fragmentation

- Nuclear astrophysics: key reactions at near-stellar energies
- Nuclear structure via Coulomb excitation or transfer reactions

FRIB: fast, **stopped and reaccelerated beams**

Slide Credit: Stefan Schwarz, NSCL

From fast to not-so-fast



Slide Credit: Stefan Schwarz, NSCL

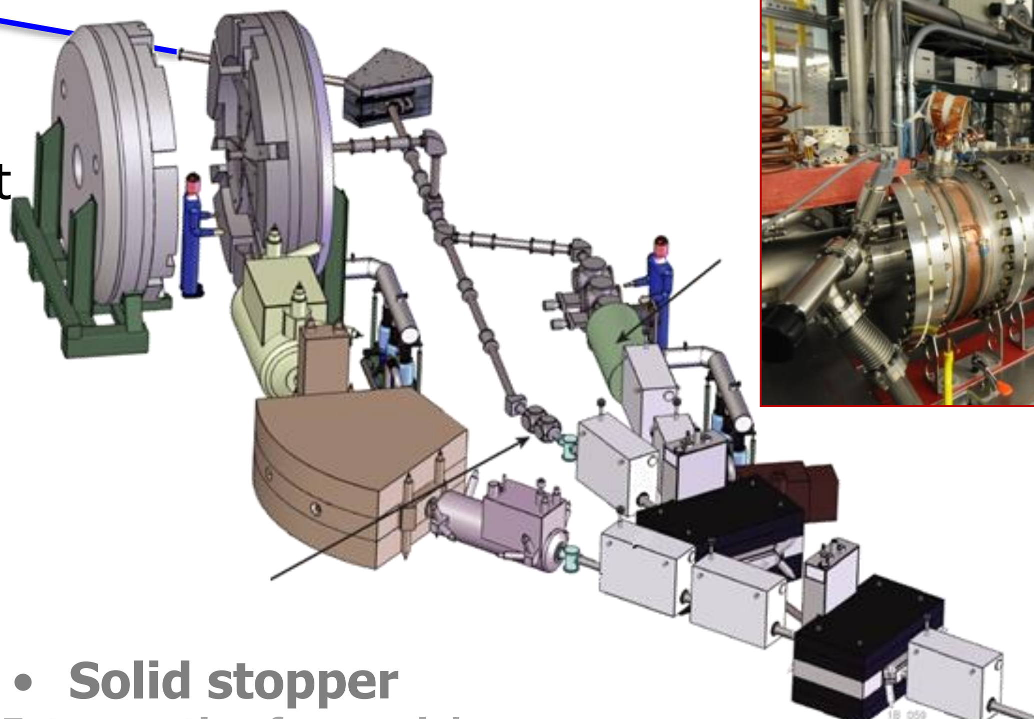
Complementary
stopper options:

← ReA,
'Stopped' Beam area
<60keV

Linear gas stopper (v2/v3)
- Low-pressure with RF carpets / wires
- ANL gas cell / Cryogenic gas cell

Cyclotron stopper
- Cyclotron-type magnet
- Low-pressure + RF ion guiding

→ ***Light ions***



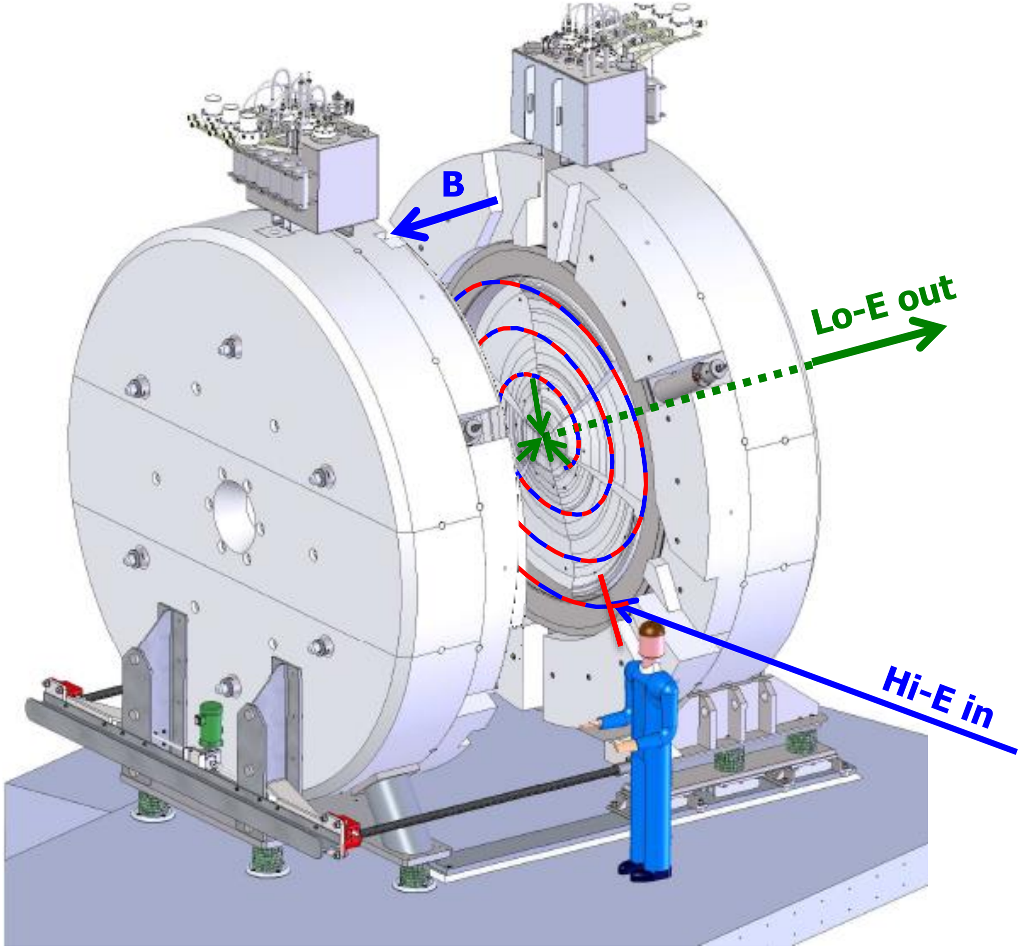
- **Solid stopper**

Future option for special elements and very high beam rates
Example: ^{15}O, I >10^{10}/s

← CCF,
100 MeV/u

Slide Credit: Stefan Schwarz, NSCL

Cyclotron stopper – the idea



1 Confine:

- **Magnetic field, <2.6 T**
    - 'wind up' trajectory in central chamber
        → confinement in radial direction
    - Cyclotron-type **sector field**:
        → axial focusing

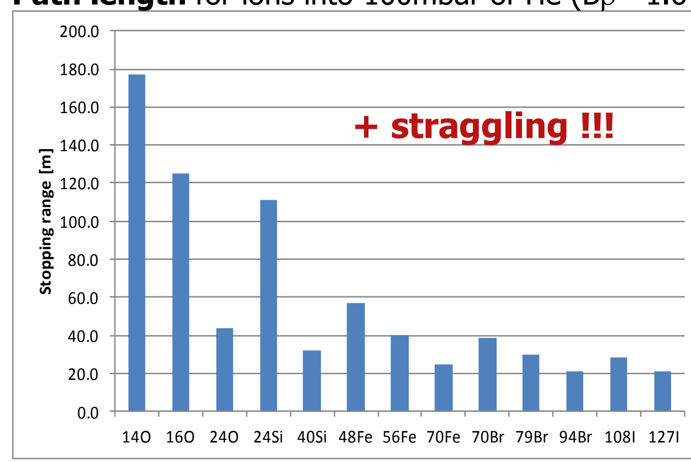
2 Thermalize:

- **Low-pressure gas in cryogenic chamber**
  ions lose energy, spiral towards center

3 Extract:

- Use **HF/RF ion guiding techniques**
  to move thermalized ions to center and out
  within a few 10 ms

Path length for ions into 100mbar of He ($B\rho$ =1.6 Tm)

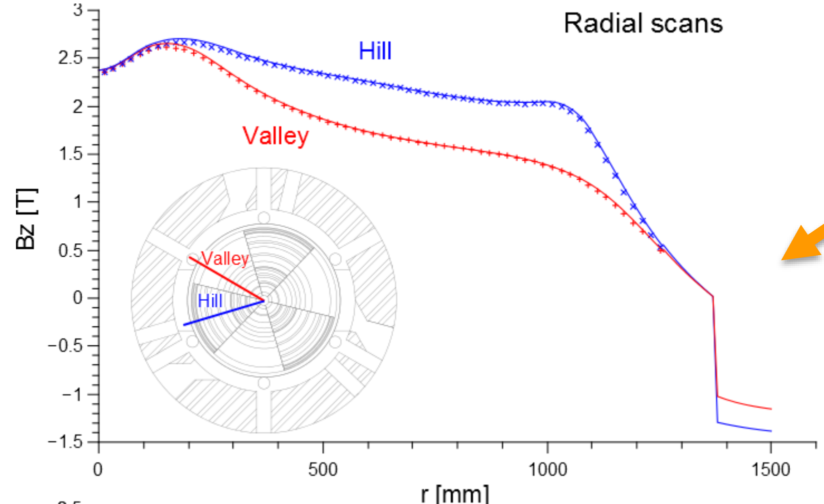


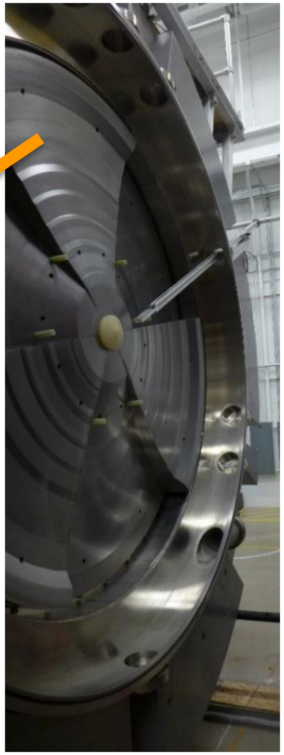
Origins:
- Decelerate antiprotons: J. Eades and L. M. Simons, NIM A 278 (1989) 368
- Proposal to stop lighter ions: I. Katayama et al., HI 115 (1998) 165

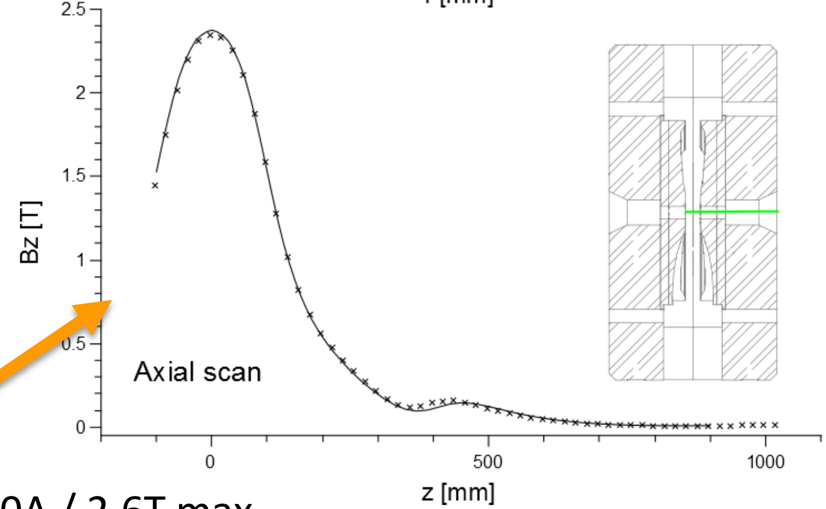
NSCL-Cyc-stopper:
- Bollen et al. NIM A550 (2005) 27, NIM B266 (2008) 4442,
- Guenaut et al HI 173(2006)35 … Schwarz et al NIM B376(2016)256

Slide Credit: Stefan Schwarz, NSCL

Magnet test



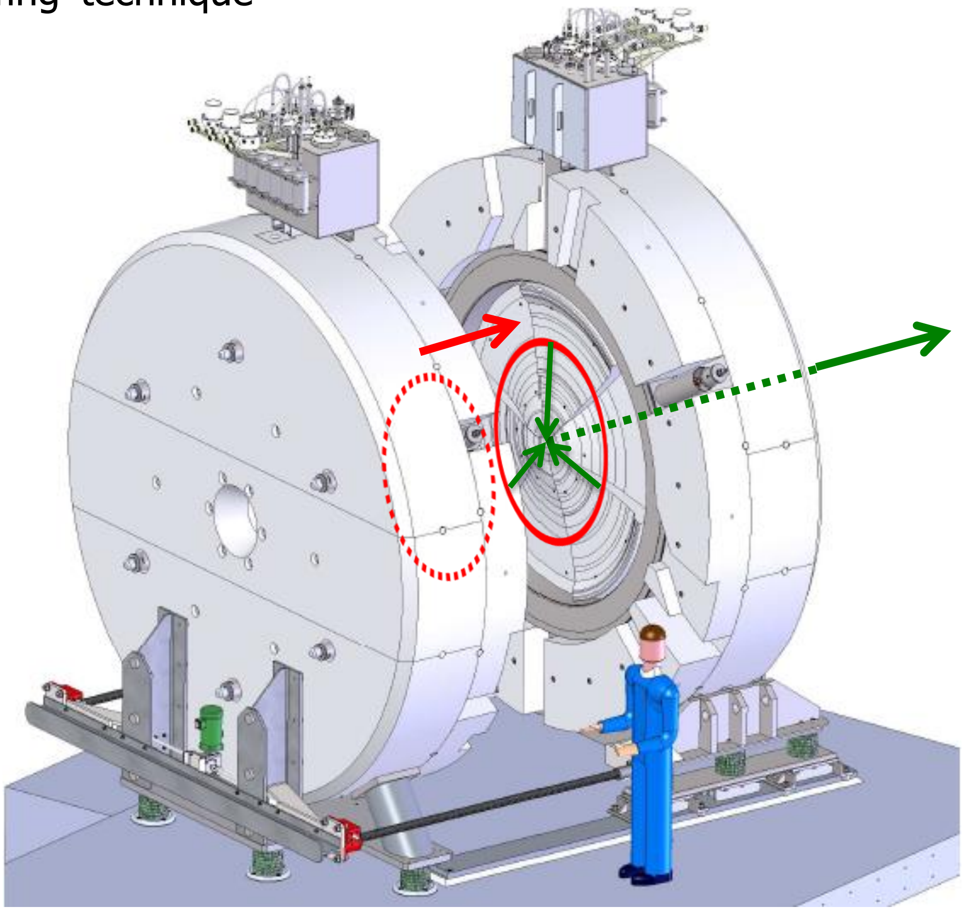


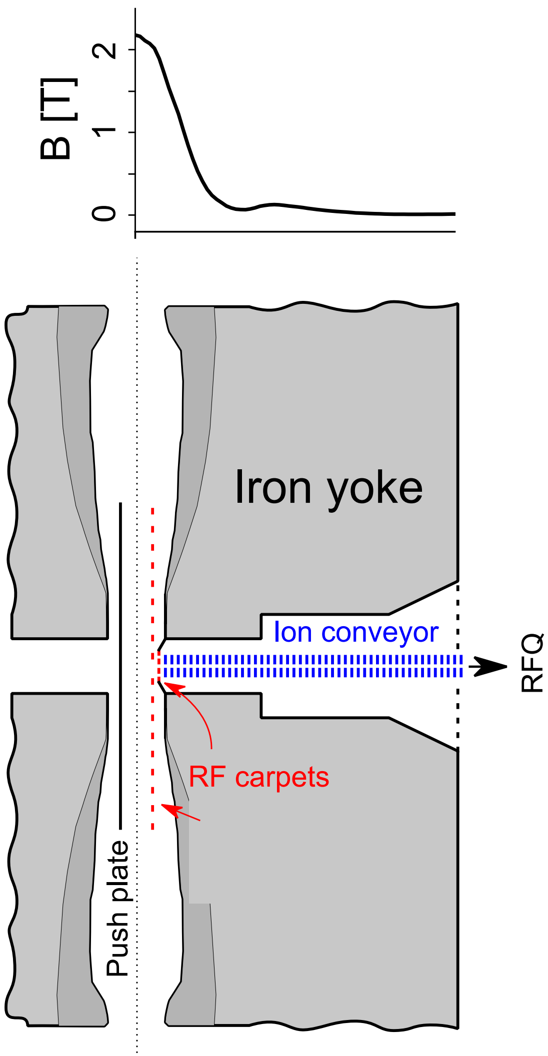


- Energized to nominal field at 180A / 2.6T max
- Measured profiles agree with expectations
  → Important for efficient stopping!

Slide Credit: Stefan Schwarz, NSCL

Ion transport to center:
- Large **RF ion carpet**, ~1m diameter
- 6-fold segmented (C, size limitations)
- 'Surfing' technique





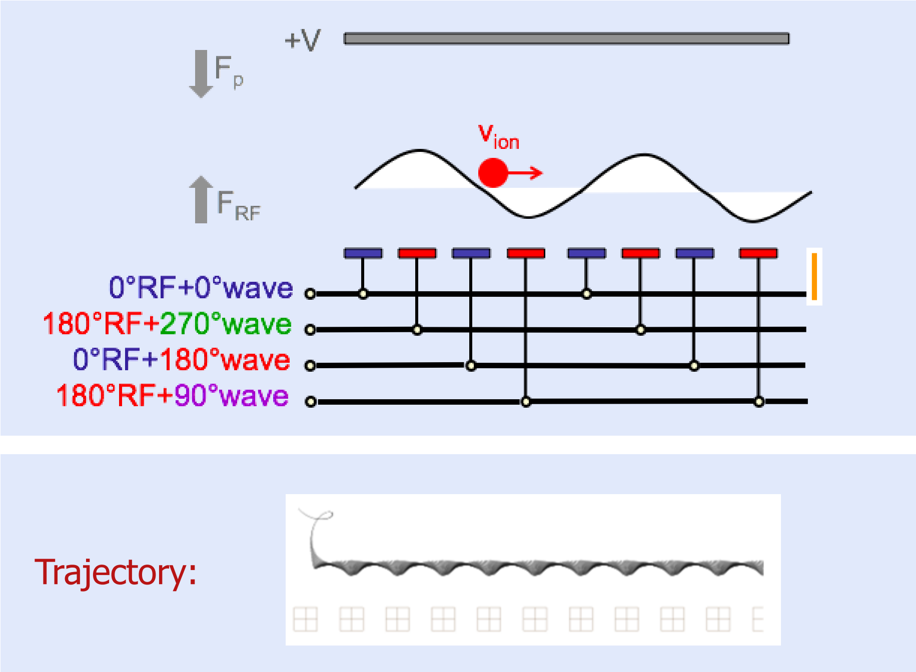
Ion extraction through axial hole on fixed side:
- RFQ ion guide + B-field = bad
  ➔ Use **ion conveyor**

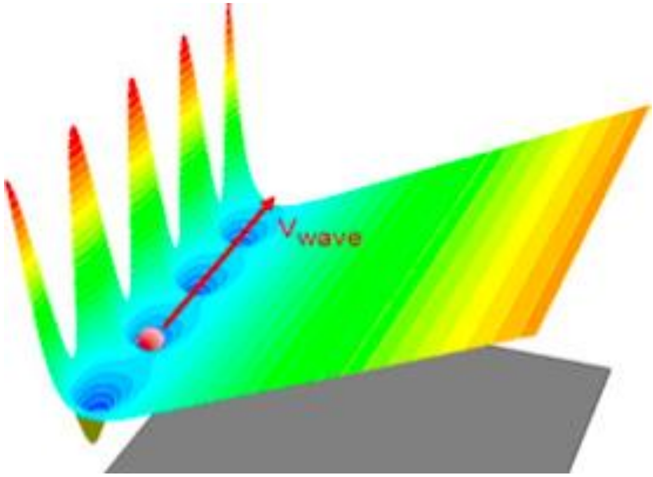
Slide Credit: Stefan Schwarz, NSCL

Centering: surfing carpet

'Surfing' RF carpet:

- Push field → move ions to carpet
- Electrode stripes with RF → keep ions above carpet
- **Low-frequency electric wave** moves ions along carpet



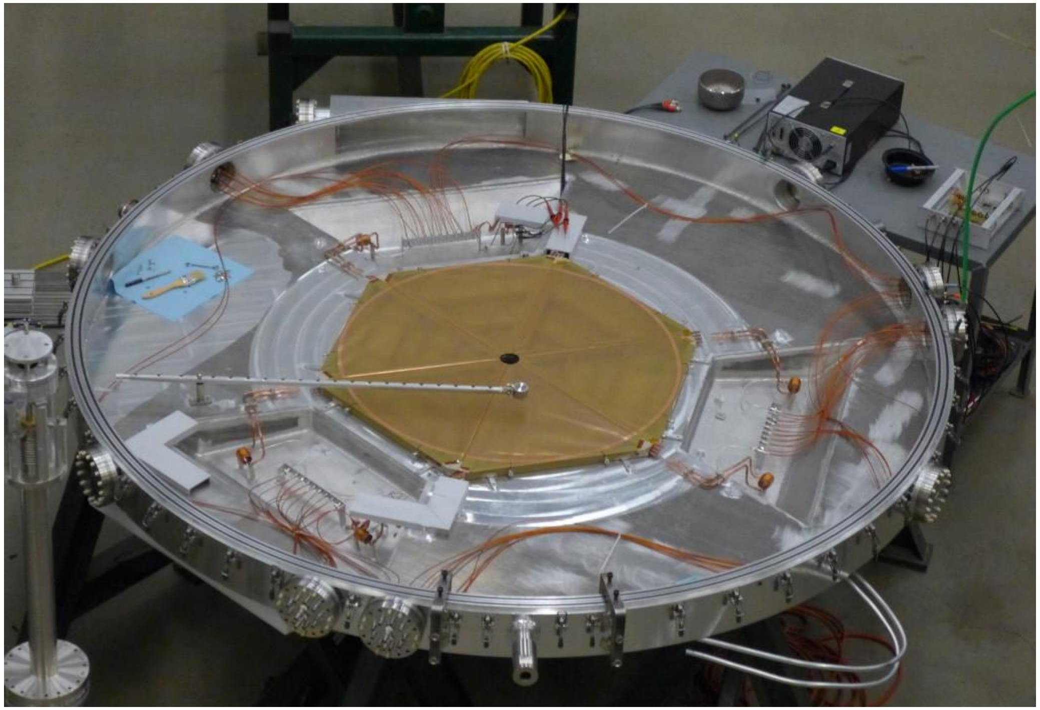


Effective potential
with moving buckets

G. Bollen, IJMS 299 (2011),131
S. Schwarz, IJMS 299 (2011),71
M. Brodeur et al., IJMS 336 (2013) 53
A. Gehring, PhD thesis 2013

Slide Credit: Stefan Schwarz, NSCL

The real deal



Carpets:

- 6 segments, pitch ~0.47 mm, Kapton backed, radius: 42cm.
- 6 'vacuum-compatible' RF resonant circuits
- 3 pockets fit in pole valleys,
  → RF circuits accessible,
  but hidden from hi-energy beam
- HF: a few 10kHz, a few V
- RF load: 4 nF each
- RF/HF cabling: Kapton isolated

- Support structure: PEEK

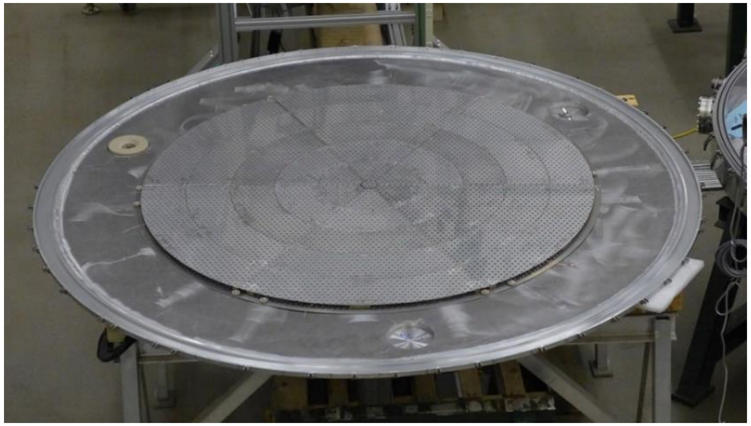
- Push field: segmented plate on lid

RF tests:

- Two carpets set up: 7.5 / 8.4 MHz
- At ~60Vpp, need about 16-20W per carpet.

Ion tests:

- Use degrader drive to move ion source across carpet
- To start ... after this workshop



Slide Credit: Stefan Schwarz, NSCL

Status

Magnet:
- tested to full field

Stopped-ion transport:
- stopping chamber in place, initial pressure tests at RT passed
- 90° prototype RF carpets tested
- 60° RF carpets: Electronics working
- Conveyor: Offline tests promising

Next:
- Install carpet + conveyor
- Test ion transport with magnetic field
- Cool chamber with LN

Move to dedicated vault: 2018 ?

G. Bollen, M. Brodeur, M. Gehring, K. Lund, N. S. Joshi, C. Magsig, D. J. Morrissey, J. Ottarson, SCS, S. Chouhan, J. DeKamp, J. Ottarson, A. Zeller … and many more!

MICHIGAN STATE UNIVERSITY

NSF Cyclotron stopper grant PHY-09-58726, PHY-11-02511

Slide Credit: Stefan Schwarz, NSCL

Conclusion – Take Home Message

- Cyclotrons brought us a long way in the early days by overcoming the limitations of linear electrostatic accelerators.
- They are ultimately limited by relativistic mass increase, even though to a certain extent this can be mitigated by ramping the RF frequency or radially changing the B-field.
- Main usage nowadays is in medical isotope production and cancer therapy, but
- There are a number of facilities world-wide using cyclotrons for nuclear physics (rare/radioactive isotope facilities)
- There are interesting ideas for future cyclotron development/usage that go beyond the state-of-the-art (neutrino physics, ADS, ironless cyclotrons, cyclotron gas stopper)

Thank you for your attention!

QUESTIONS?