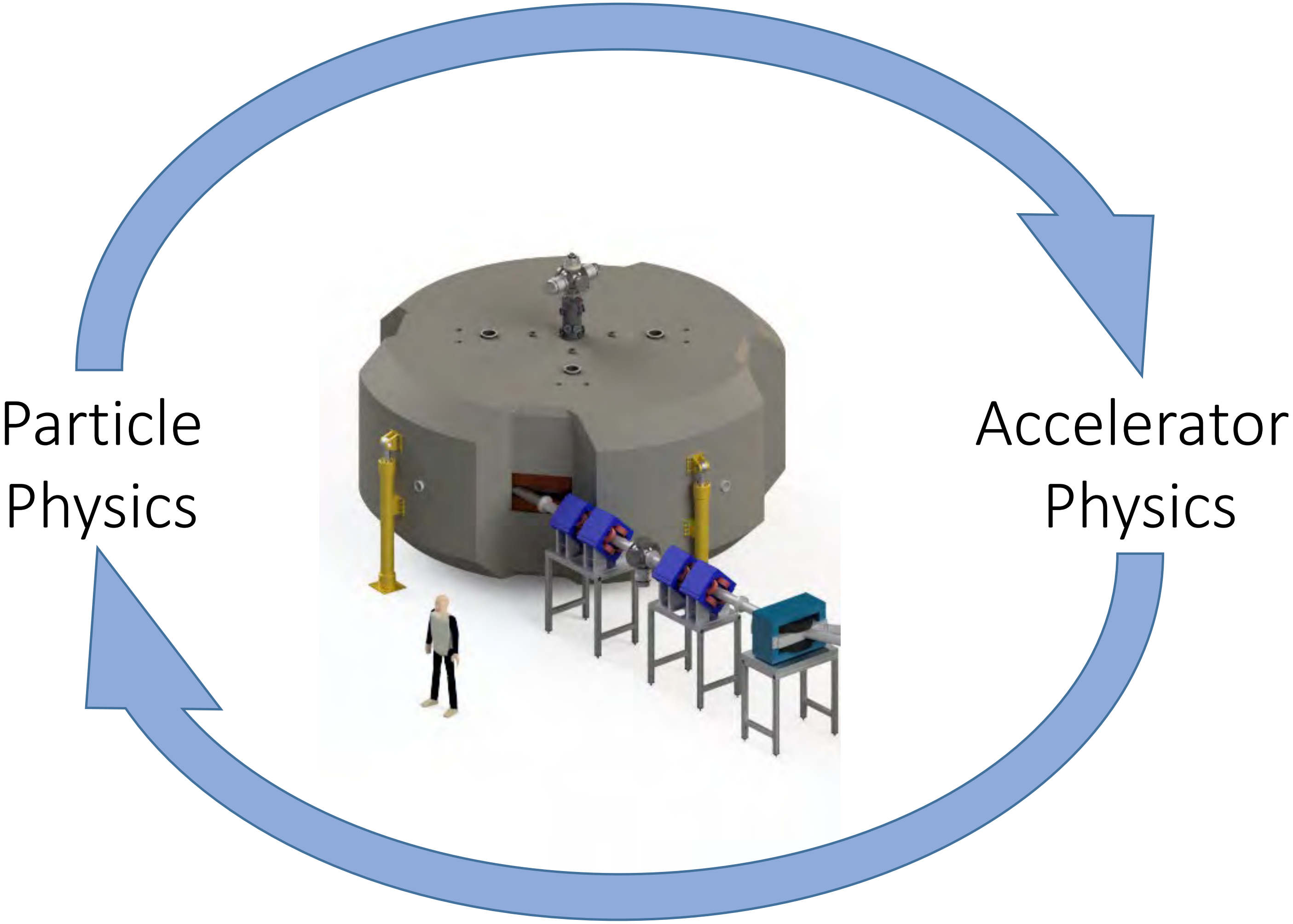
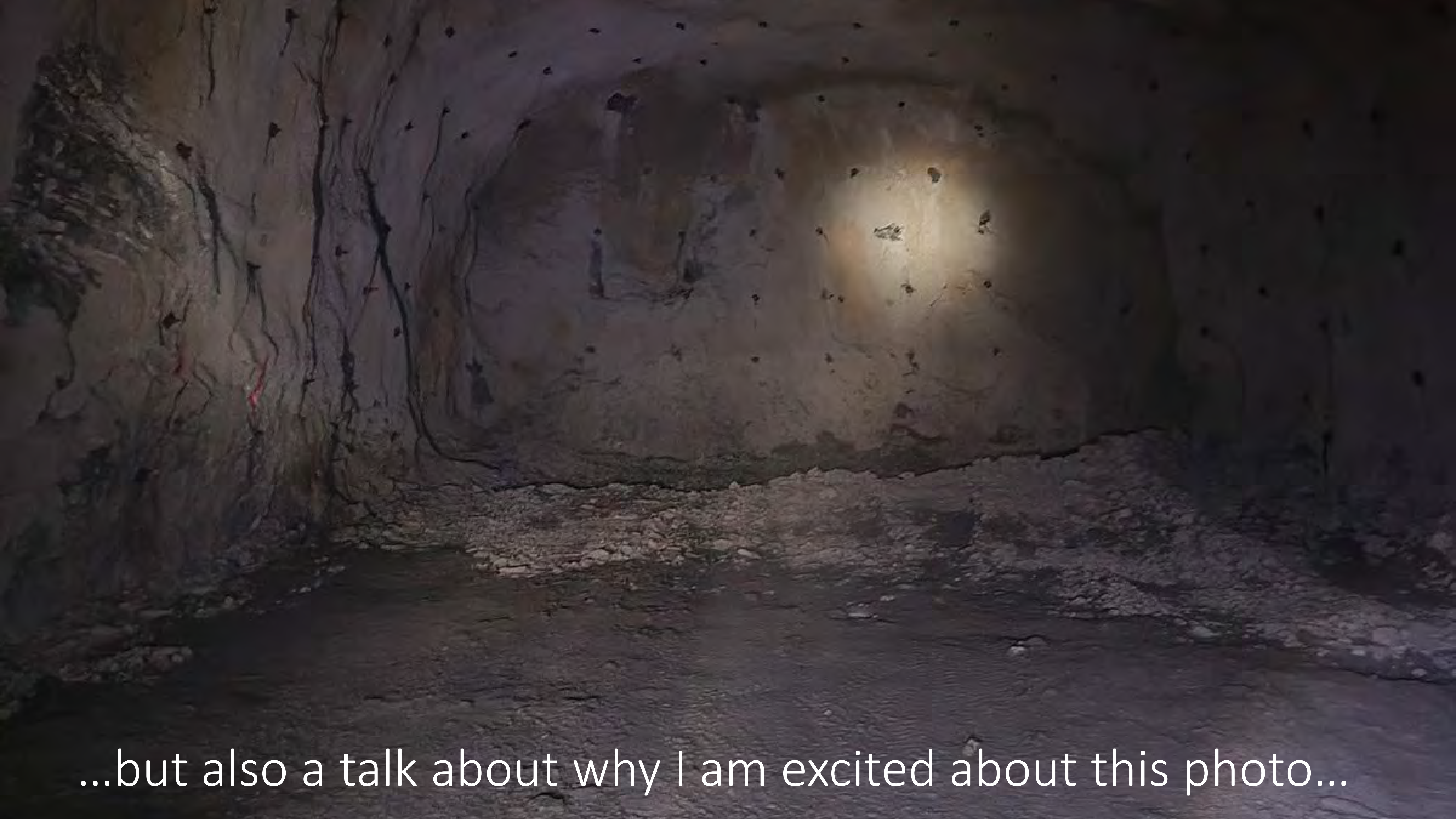
High-Current H_2^+ Compact Cyclotrons for Particle Physics and Beyond

Daniel Winklehner, MIT
PSI Colloquium – May 12th, 2022

This is a talk about synergy between particle physics and accelerator physics…





…but also a talk about why I am excited about this photo…

Outline

- Original Motivation: IsoDAR neutrino physics
  → In a few years this will yield very exciting particle physics

- Cyclotrons "101"
- The physics challenges of high intensity beams
  → How we are changing the game

- More Applications:
  - Medical Isotopes, Materials, …
  - Multi-Megawatt beams for Particle Physics and ADS

Lingo
Typical accelerator parlance

IsoDAR Collaboration

Co-spokesperson: Josh Spitz (spitzj@umich.edu)
Co-Spokesperson: Daniel Winklehner (winklehn@mit.edu)

MIT
University of Michigan
Columbia University in the City of New York

University of Huddersfield
INFN
Institute for Basic Science (ibs)
Paul Scherrer Institut PSI
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Industry Partners

AIMA Developpement
Best Cyclotron Systems
Bevatech
iba
Bartoszek Engineering

Thanks to all postdocs, postbachs and students!

- Postdocs: Jungbae Bahng, Daniel Koser, Medani Sangroula, Matthias Frey,
- Graduate Students: Spencer Axani, Jakob Jonnerby, Sonali Mayani
  Joseph Smolsky, Loyd Waites, Philip Weigel,
- Postbachs: Devin Schoen, Thomas Wester
- Undergraduate Students: Patrick Bedard, Anastasia Bershanska, Monica Busza,
  Jesus Corona, Frances Hartwell, Abutalib Namazov, Janette Park,
  Aashish Tripathee, Maria Yampolskaya, Ryan Yang

Outline

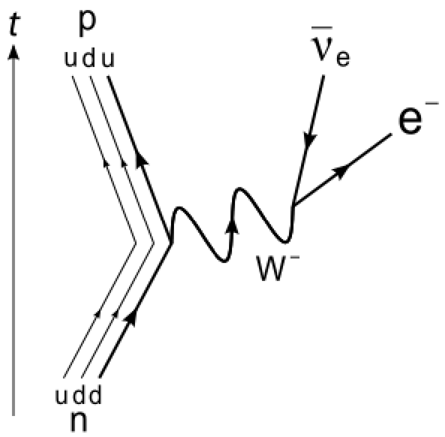
- Original Motivation: IsoDAR neutrino physics
  → In a few years this will yield very exciting particle physics

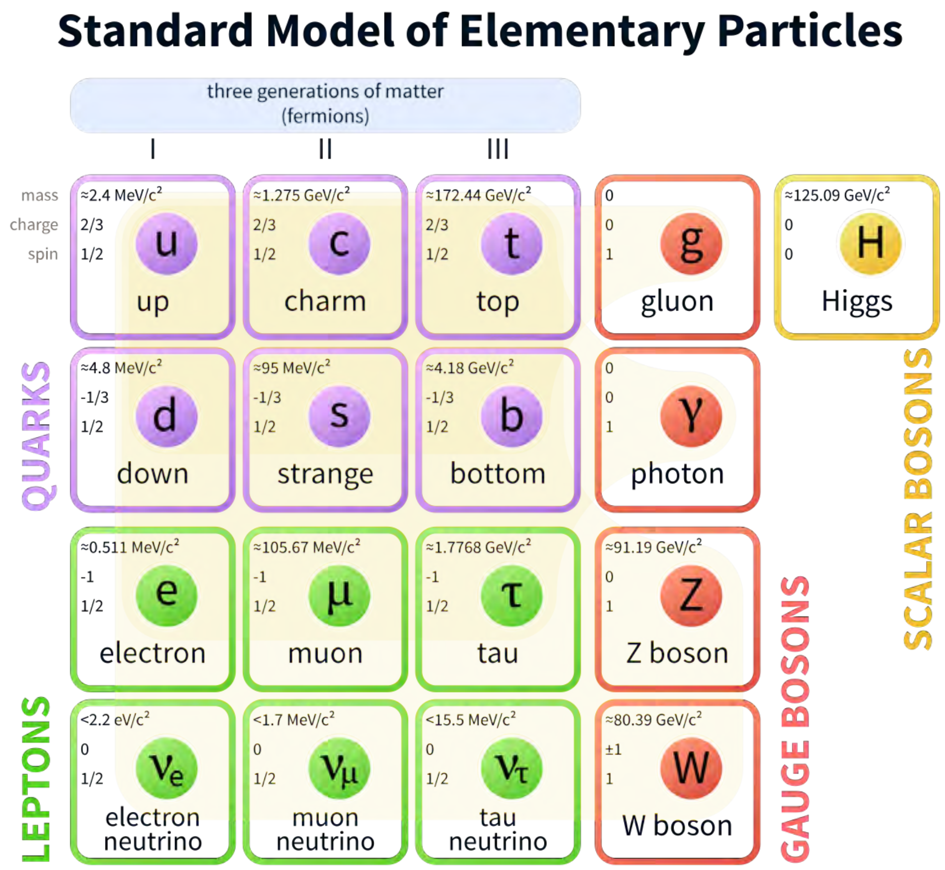
- Cyclotrons “101”
- The physics challenges of high intensity beams
  → How we are changing the game

- More Applications:
  - Medical Isotopes, Materials, …
  - Multi-Megawatt beams for Particle Physics and ADS

Three “massless” neutrinos in the Standard Model

- Three “known” neutrino flavors
- Part of the lepton weak doublets
- Only interact via weak force
- Example: Beta-Decay:



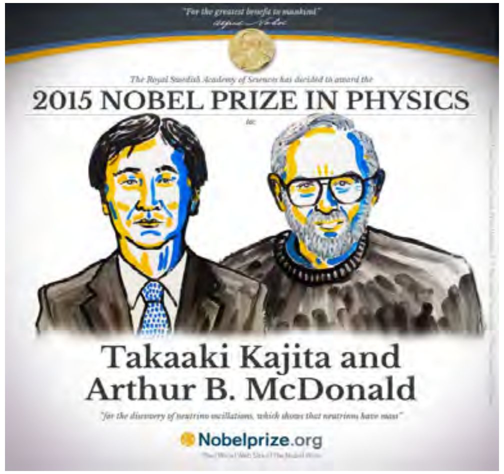

Standard Model of Elementary Particles

three generations of matter (fermions)

	I	II	III		
mass charge spin	≈2.4 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈172.44 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c^2 -1 1/2 e electron	≈105.67 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	
				GAUGE BOSONS	

Source: wikipedia.org

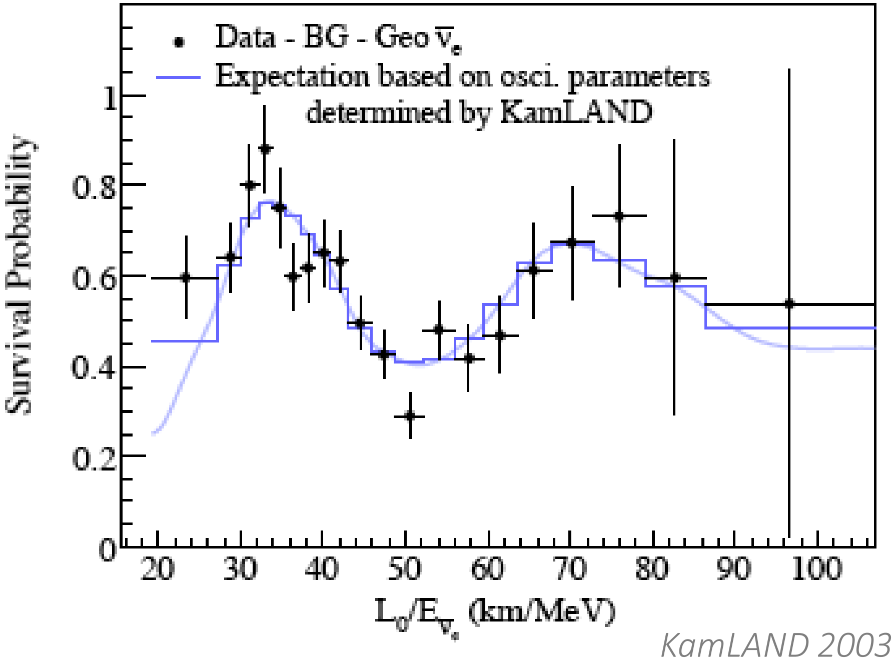
We now know neutrinos have mass and mix!



- Confirmed in SuperK and SNO for solar & atmospheric neutrinos.
- Mass and Flavor Eigenstates are not aligned → Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

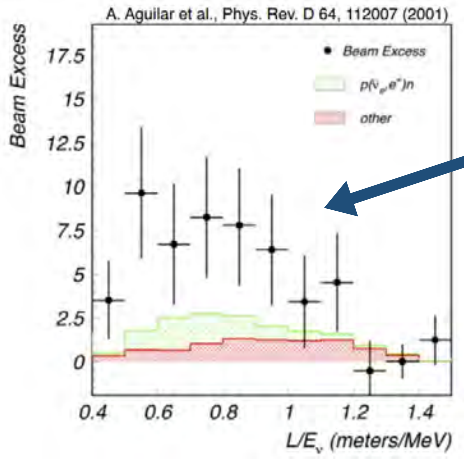
Now observed in many consistent experiments



KamLAND 2003

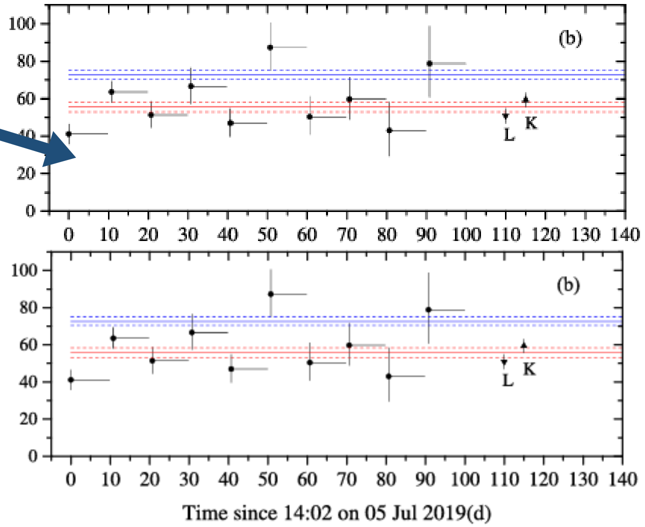
"Wave" in Rate vs L/E (distance/energy)
Only observed across multiple cycles in KamLAND

But the picture is not tidy → New Physics?



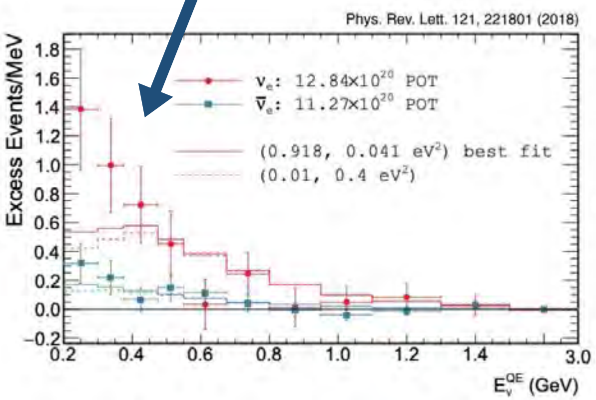
What is this bump?

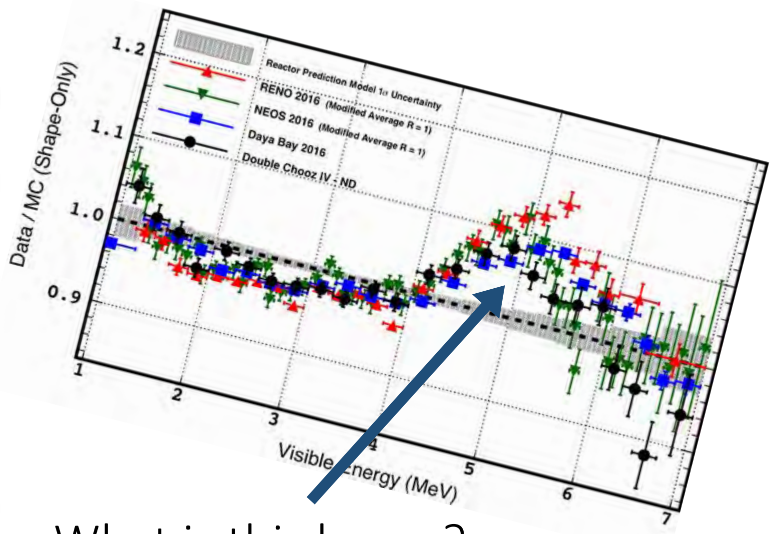
What is this deficit?



Experiments with "short baseline"

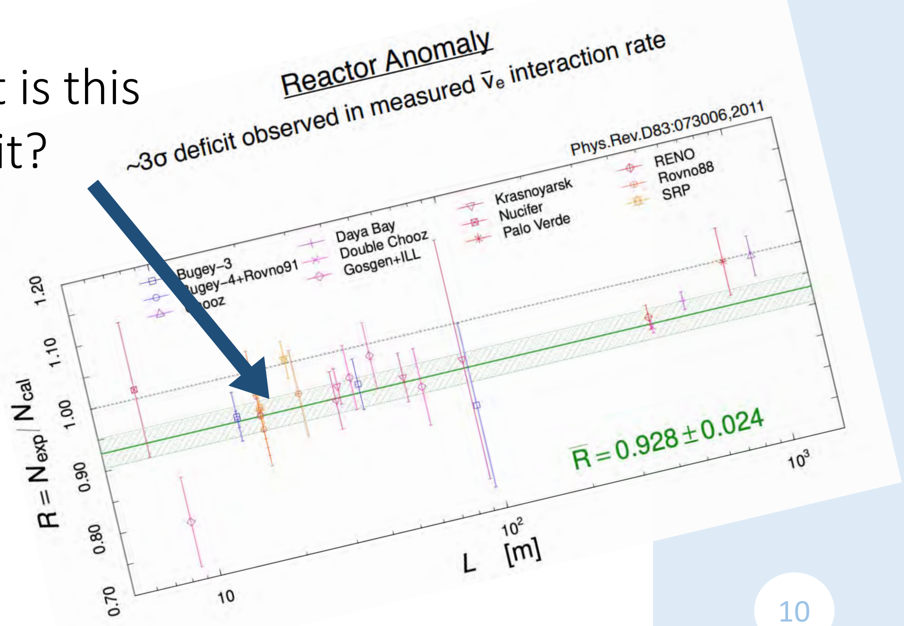
What is this bump?





What is this bump?

What is this deficit?

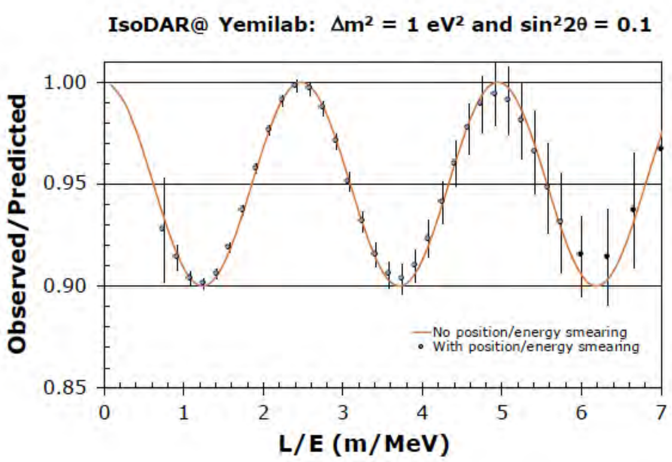


We need a really decisive follow-up!

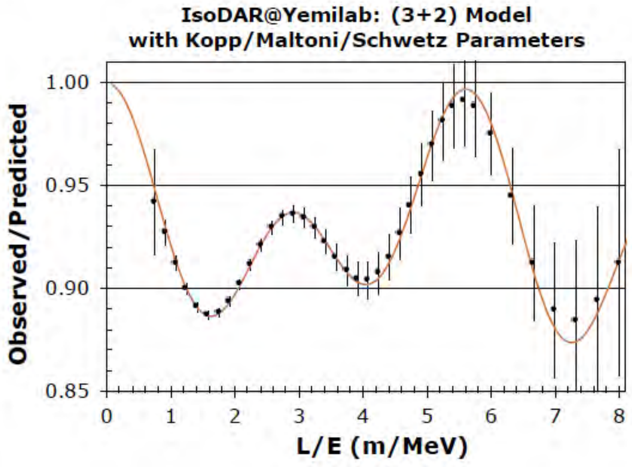
If it is oscillation related
then it will produce some kind of wave in L/E

If there is....

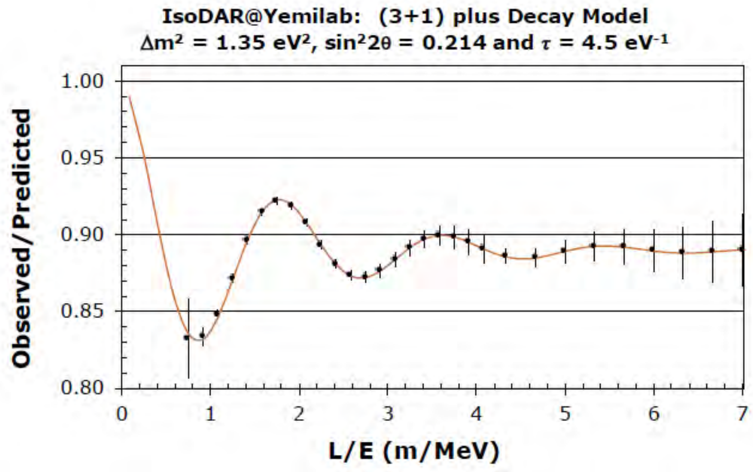
One exotic neutrino



two exotic neutrinos



one that decays...

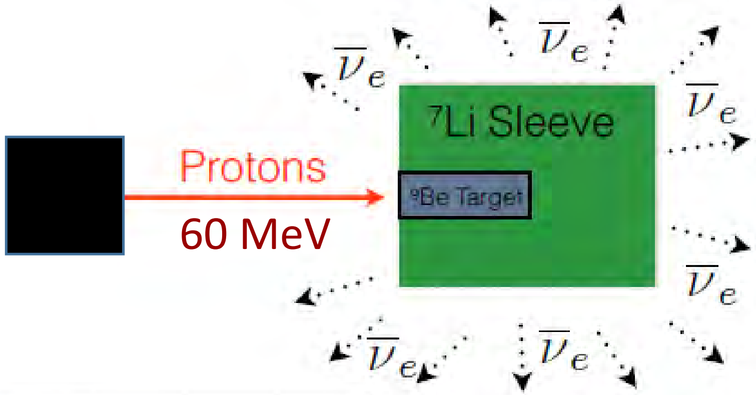


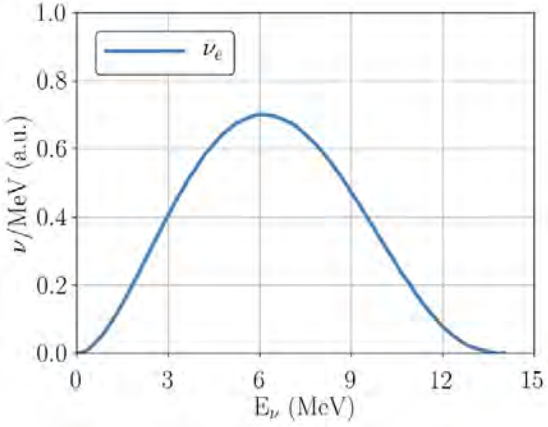
Requires: Very high statistics, well understood neutrino flux

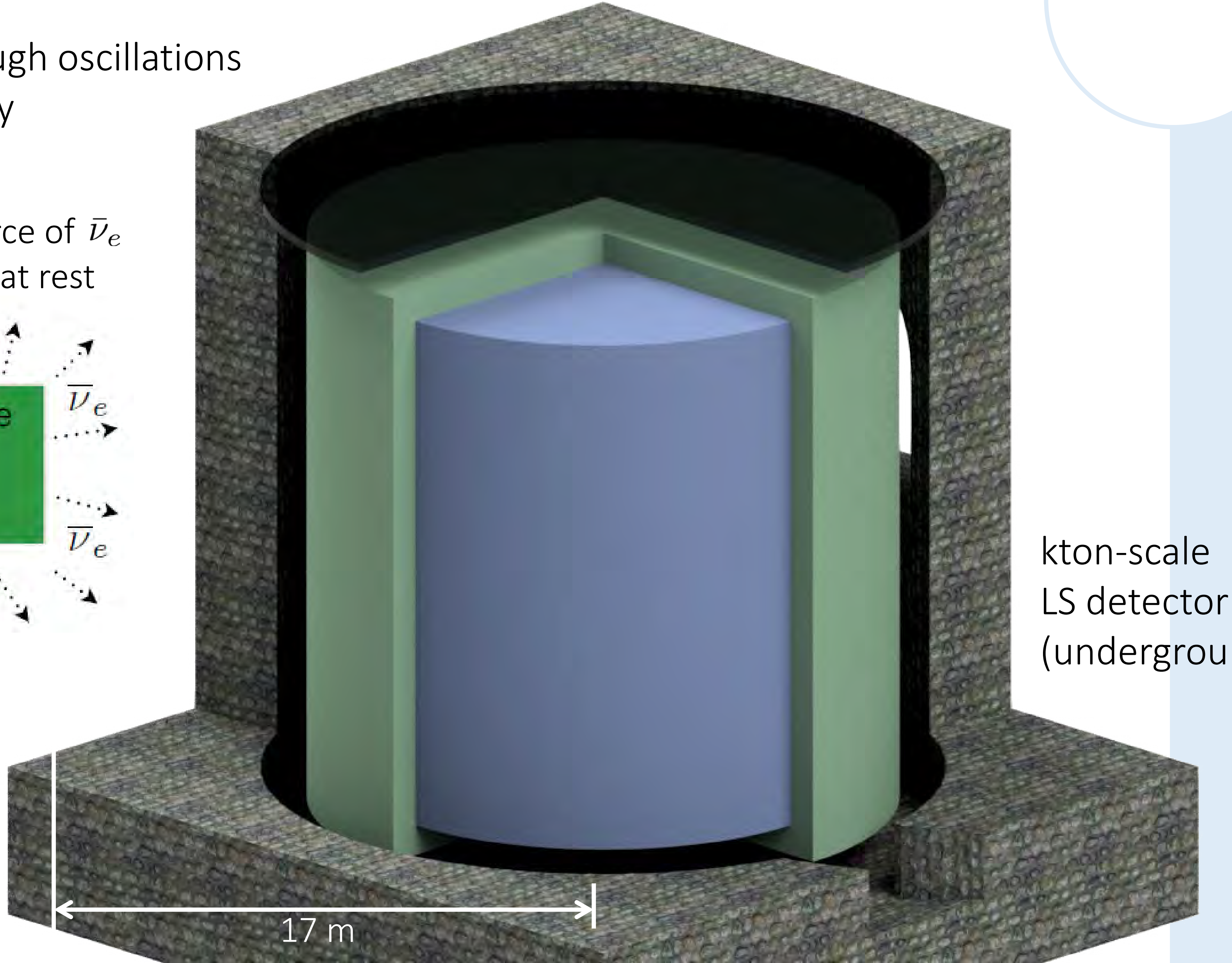
IsoDAR – Isotope Decay At Rest @ Yemilab

Search for sterile neutrinos through oscillations at short distances and low energy

Isotropic source of $\bar{\nu}_e$ through decay at rest





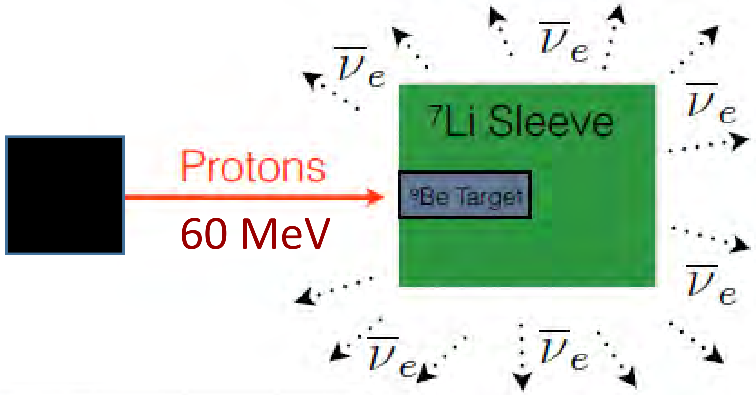


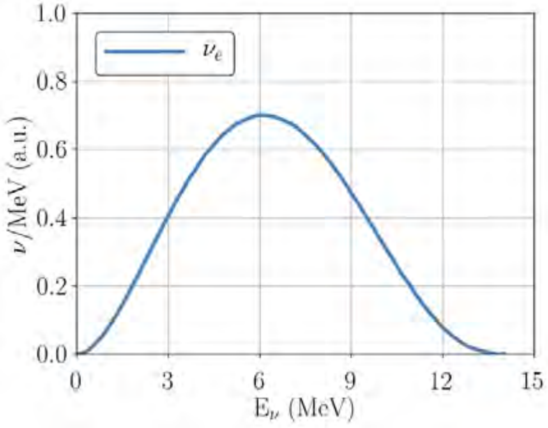
kton-scale
LS detector
(underground)

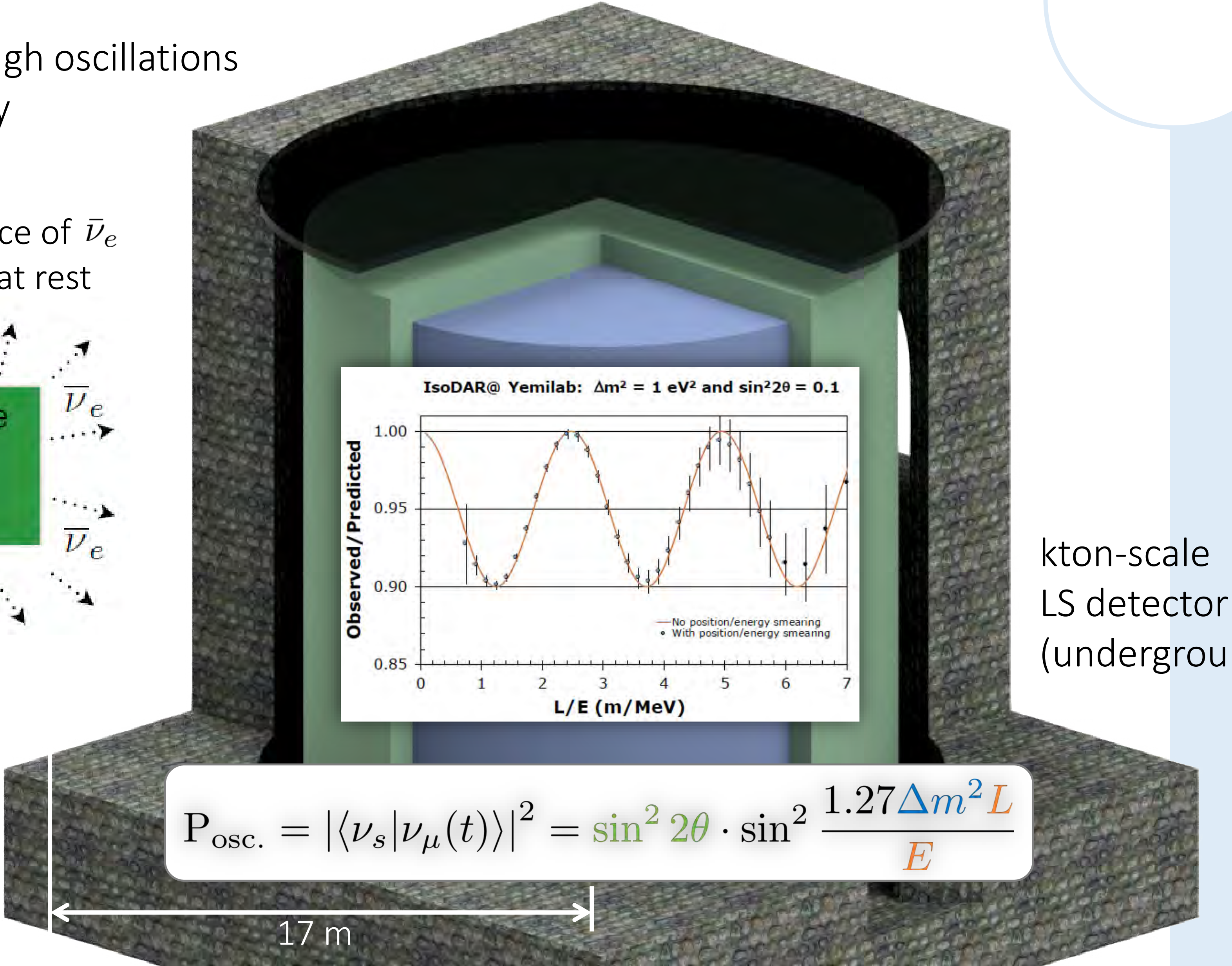
IsoDAR – Isotope Decay At Rest @ Yemilab

Search for sterile neutrinos through oscillations at short distances and low energy

Isotropic source of $\bar{\nu}_e$
through decay at rest



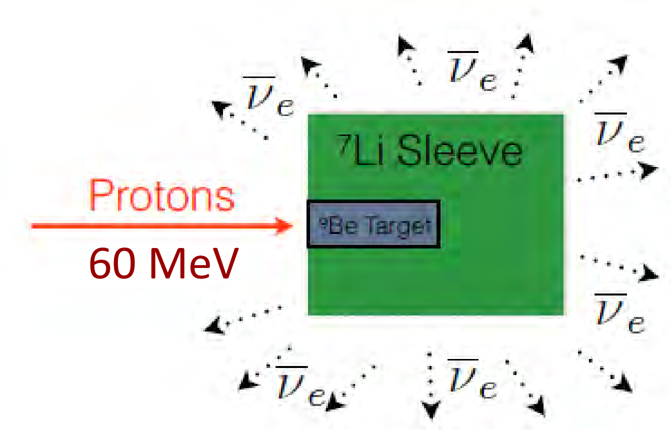




$$\mathrm{P}_{\mathrm{osc.}} = |\langle \nu_s | \nu_\mu(t) \rangle|^2 = \sin^2 2\theta \cdot \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

kton-scale
LS detector
(underground)

All of this is great, but…



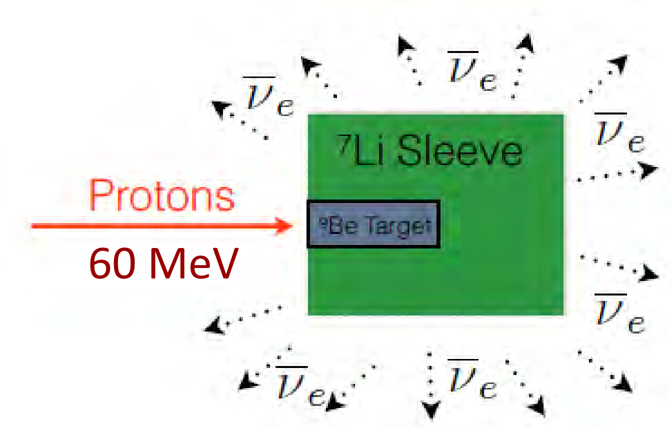
- Where do the protons come from?

- High intensity neutrino sources require high intensity proton sources 10 mA = 10x more than commercial machines!

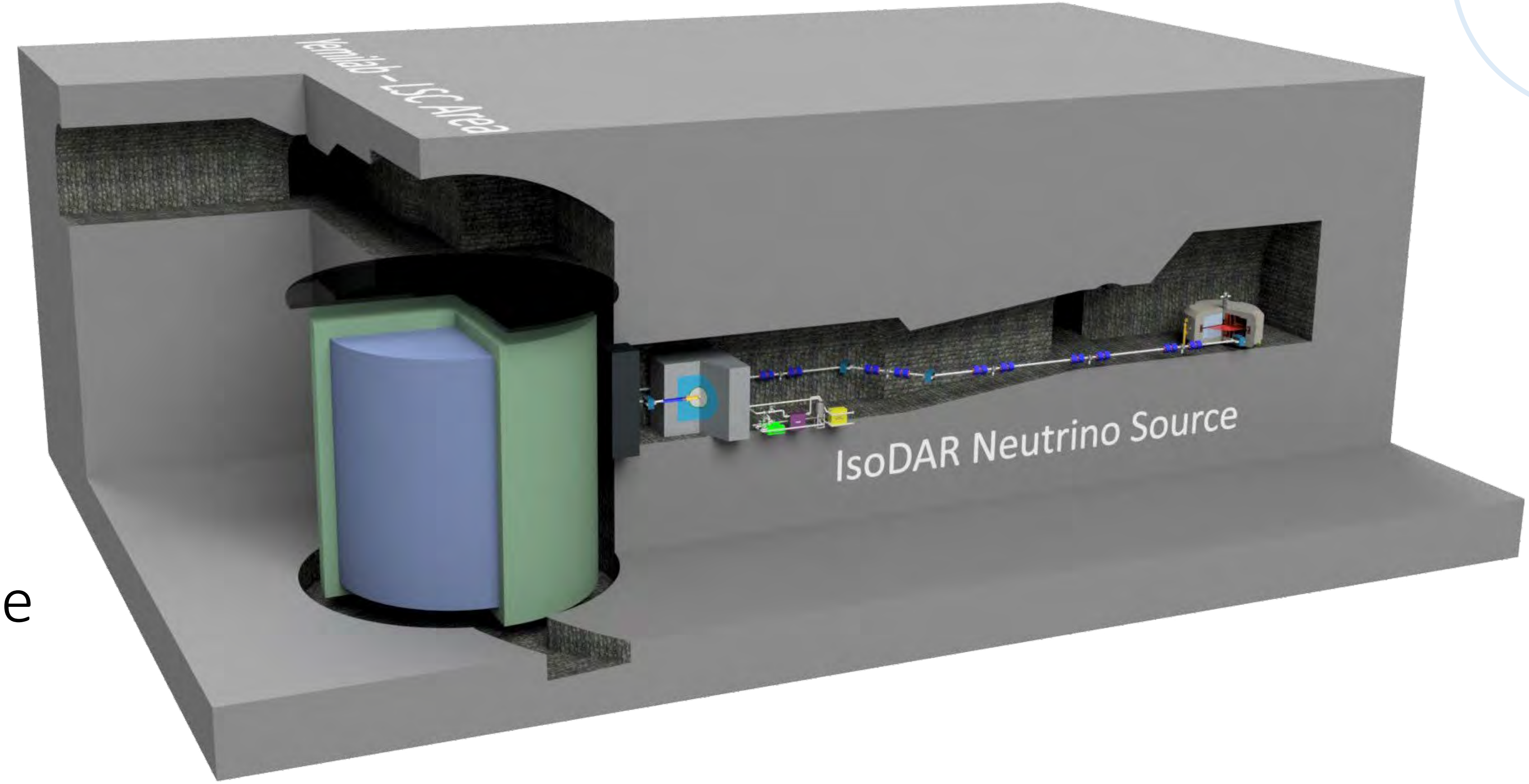
- Even more, this one has to be built underground at a reasonable cost

All of this is great, but…

- Where do the protons come from?
- High intensity neutrino sources require high intensity proton sources 10 mA = 10x more than commercial machines!
- Even more, this one has to be built underground at a reasonable cost

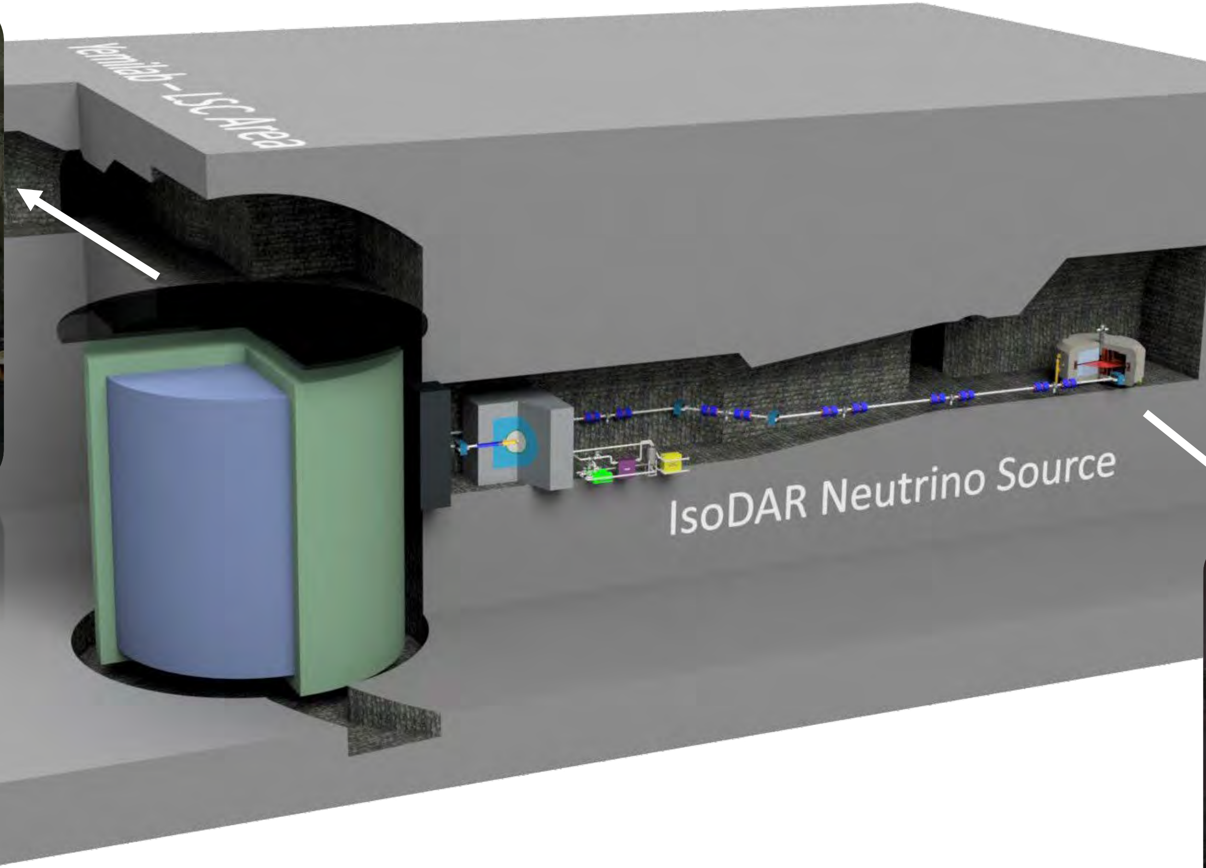


Cyclotrons are the best suited accelerators



- Cost-effective
- Compact
- Alternatives:
  - Linac (Linear Accelerator): Long, Expensive
  - FFA (Fixed-Field Alternating-Gradient): Larger Ring, Pre-accelerate, High-Intensity not established

Success! → Pre-approval to run at Yemilab in Korea



Caverns are already constructed
Now we need to put the cyclotron in it

Outline

- Original Motivation: IsoDAR neutrino physics
  → In a few years this will yield very exciting particle physics

- Cyclotrons "101"
- The physics challenges of high intensity beams
  → How we are changing the game

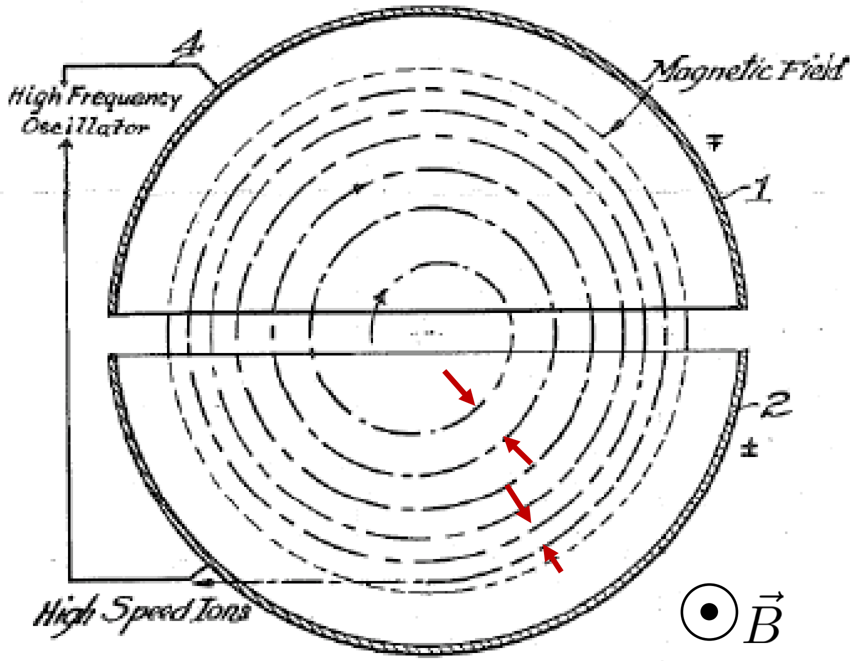
- More Applications:
  - Medical Isotopes, Materials, …
  - Multi-Megawatt beams for Particle Physics and ADS

The cyclotron as seen by the inventor

- B-field forces particles on circular orbit:

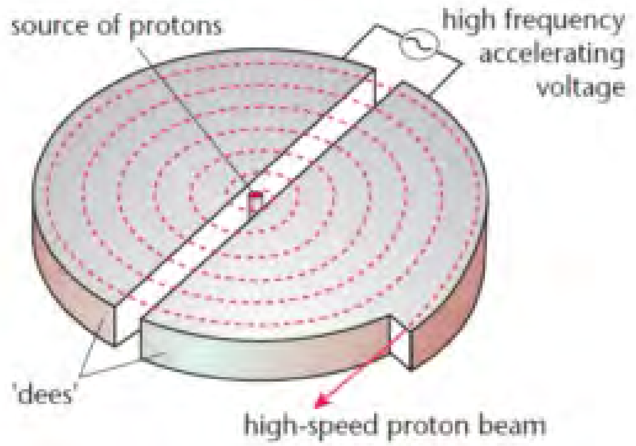
$$r = \frac{mv}{qB}$$

$$\omega_{RF} = 2\pi f = \frac{qB}{m}$$



- Oscillating “Dee” voltage accelerates

$$\mathrm{V}(t) = \mathrm{V}_{\max} \cdot \cos(\omega_{\mathrm{RF}} \cdot t - \Phi_S)$$



The cyclotron as seen by the inventor

- B-field forces particles on circular orbit:

$$\cancel{r = \frac{mv}{qB}}$$

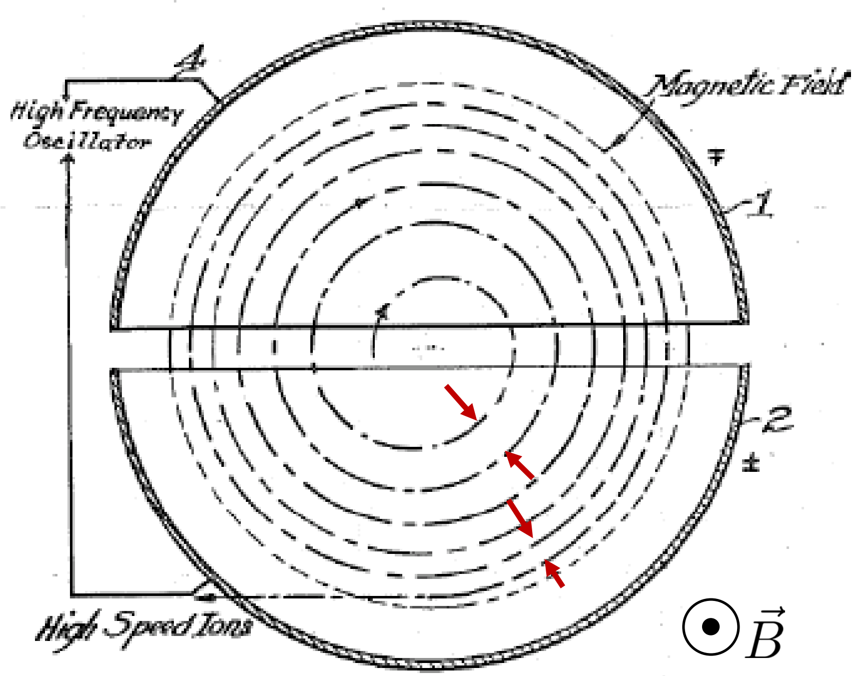
$$\cancel{\omega_{RF} = 2\pi f = \frac{qB}{m}}$$

$$r = \frac{\gamma\beta m_0 c}{qB}$$

$$\omega_{\mathrm{RF}} = \frac{qB}{\gamma m_0}$$

- Oscillating "Dee" voltage accelerates

$$\mathrm{V}(t) = \mathrm{V}_{\max} \cdot \cos(\omega_{\mathrm{RF}} \cdot t - \Phi_S)$$

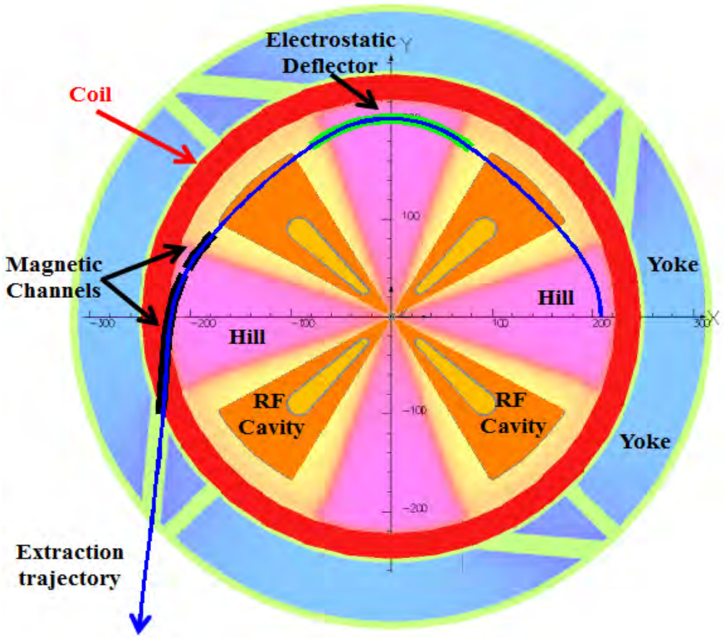


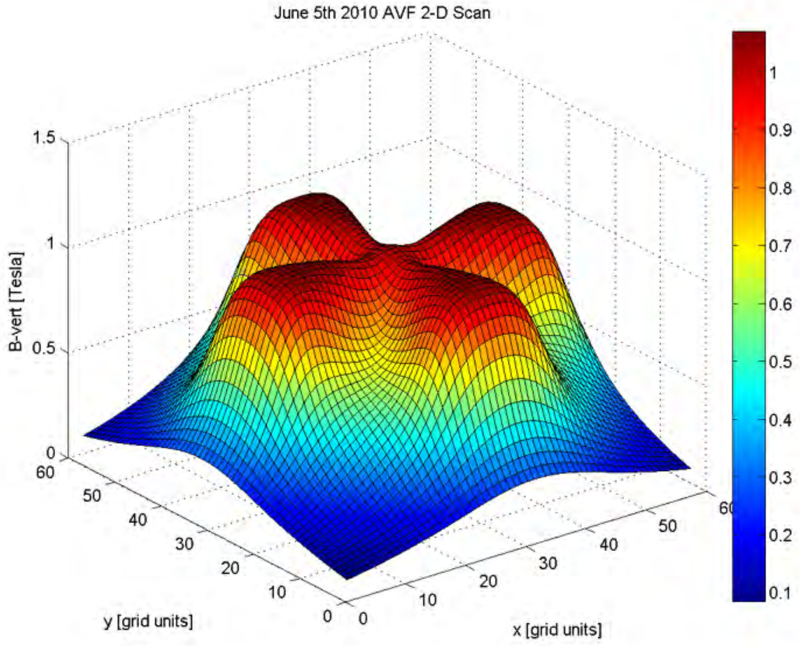
Turn Separation
Distance between neighboring turns

Synchronicity
How close the design particle stays to the synchronous phase

Most modern cyclotrons are isochronous

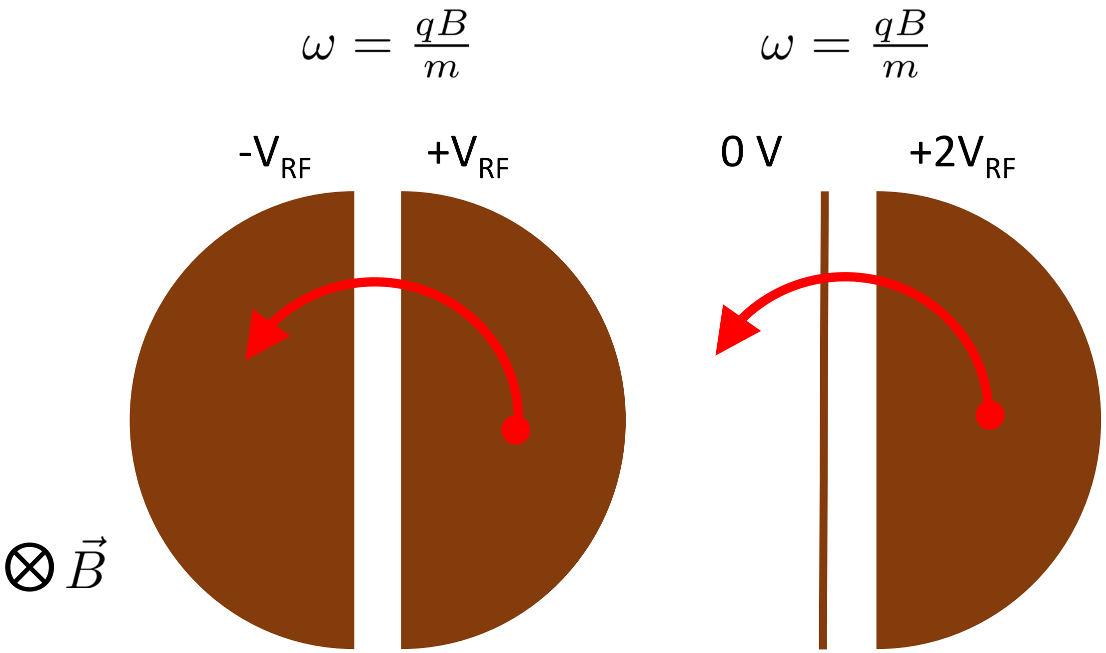
- Increase B-Field with radius to counter relativistic effects
- Use Azimuthally Varying Field (AVF) for vertical focusing





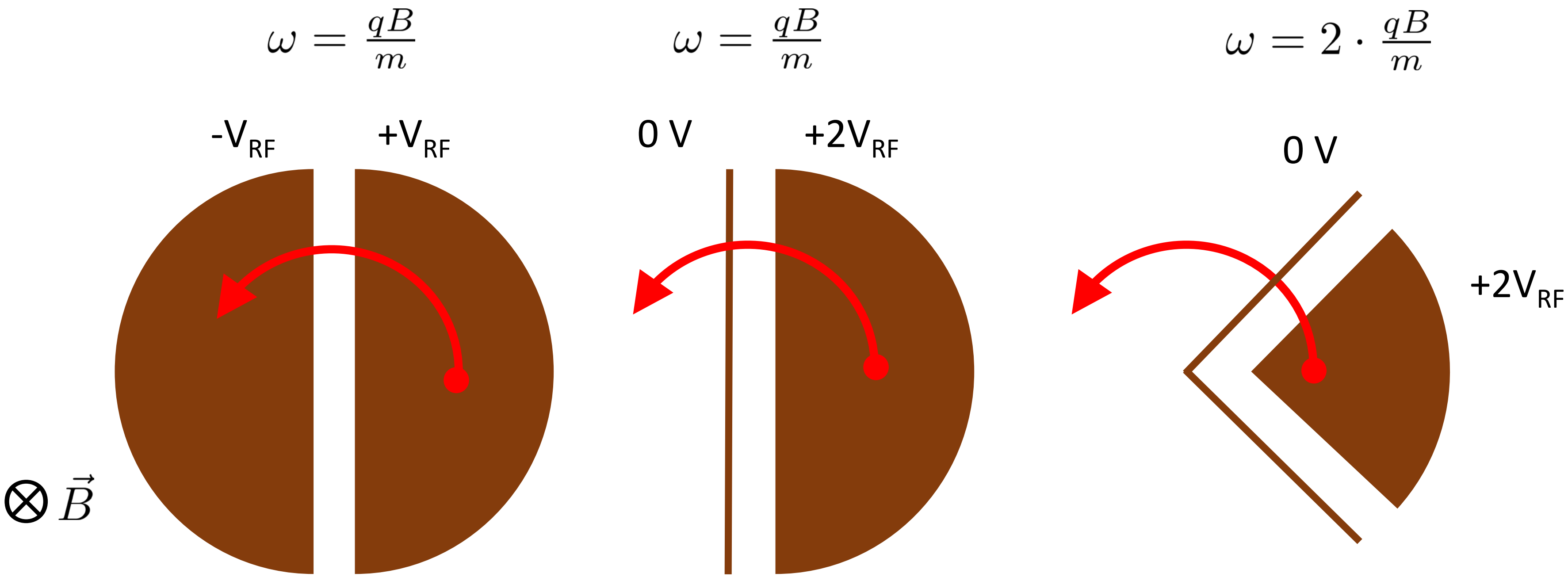
Higher energy gain per turn with harmonics

- Dee doesn't have to be "D"-shaped:



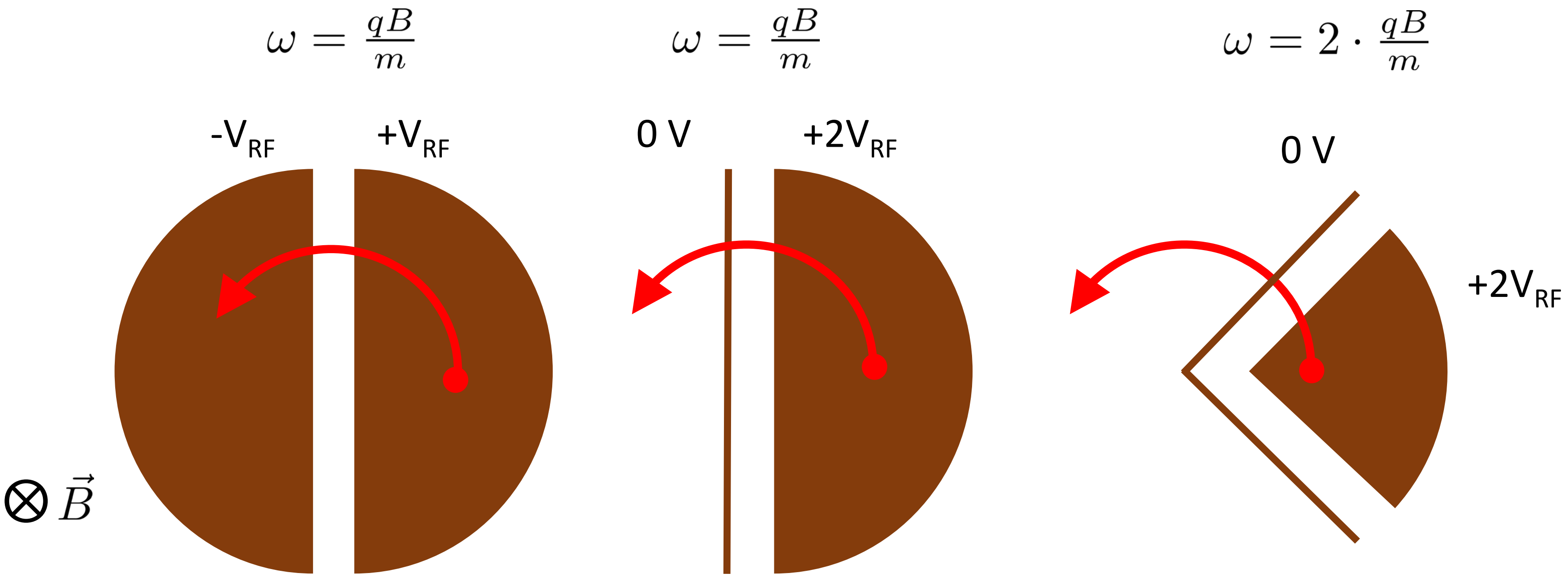
Higher energy gain per turn with harmonics

- Dee doesn't have to be "D"-shaped:



Higher energy gain per turn with harmonics

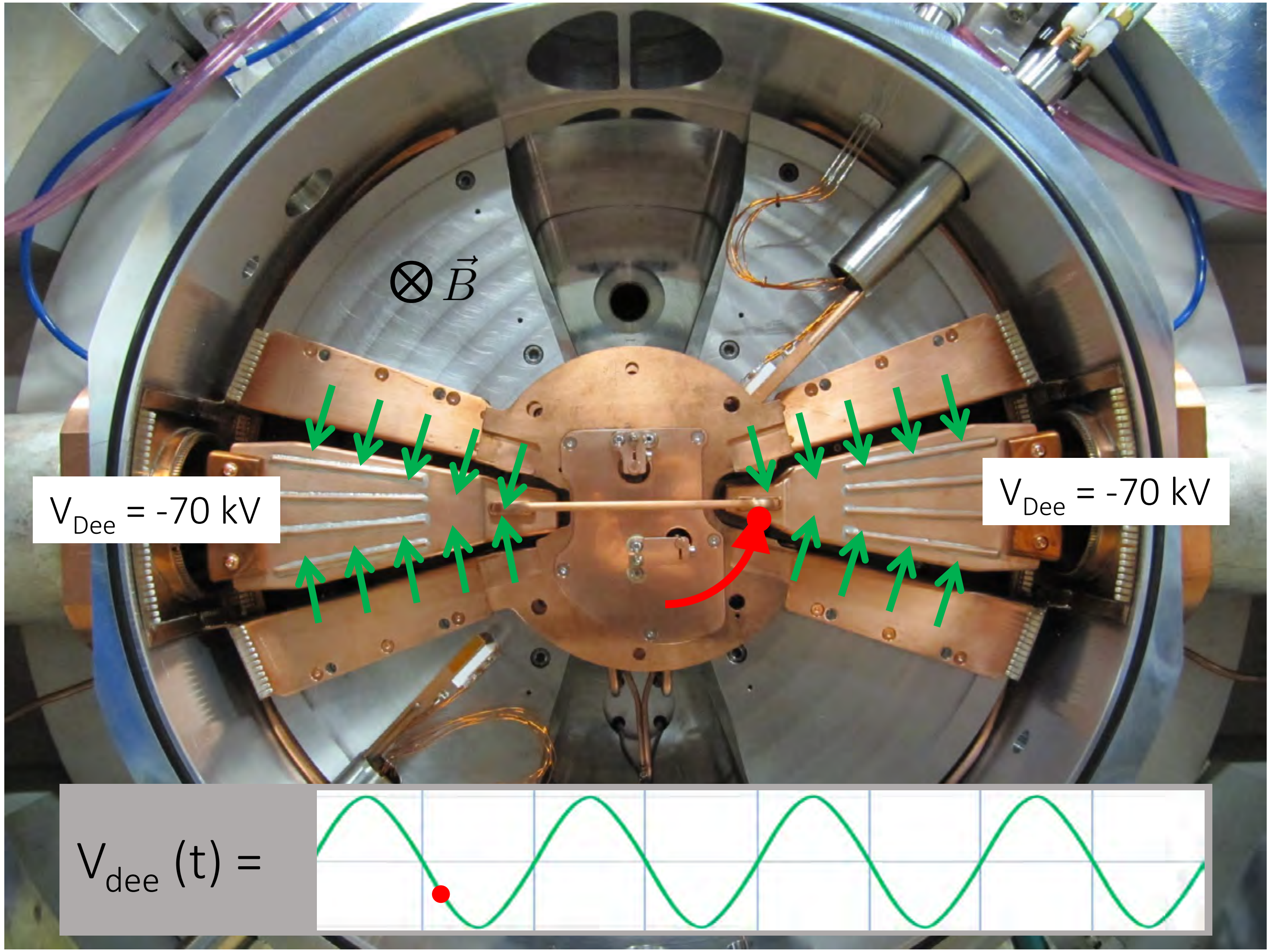
- Dee doesn’t have to be “D”-shaped:



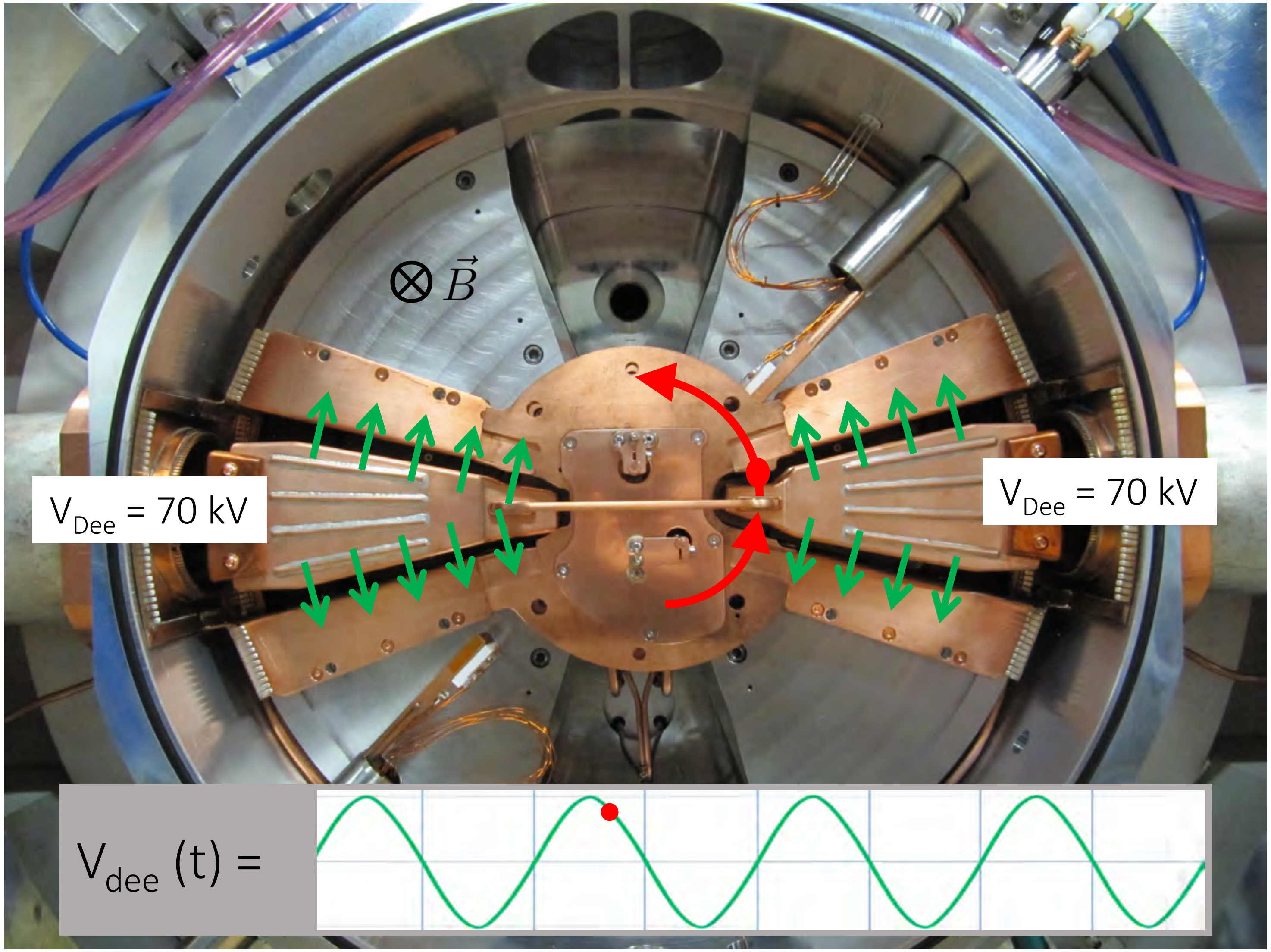
- In general: $\omega = h \cdot \frac{qB}{m}$, RF frequency can be any integer multiple of particle frequency.
- Dees can be made into double gap cavities with angle = 180/h

<u>Harmonic</u>
Integer multiple
of base frequency

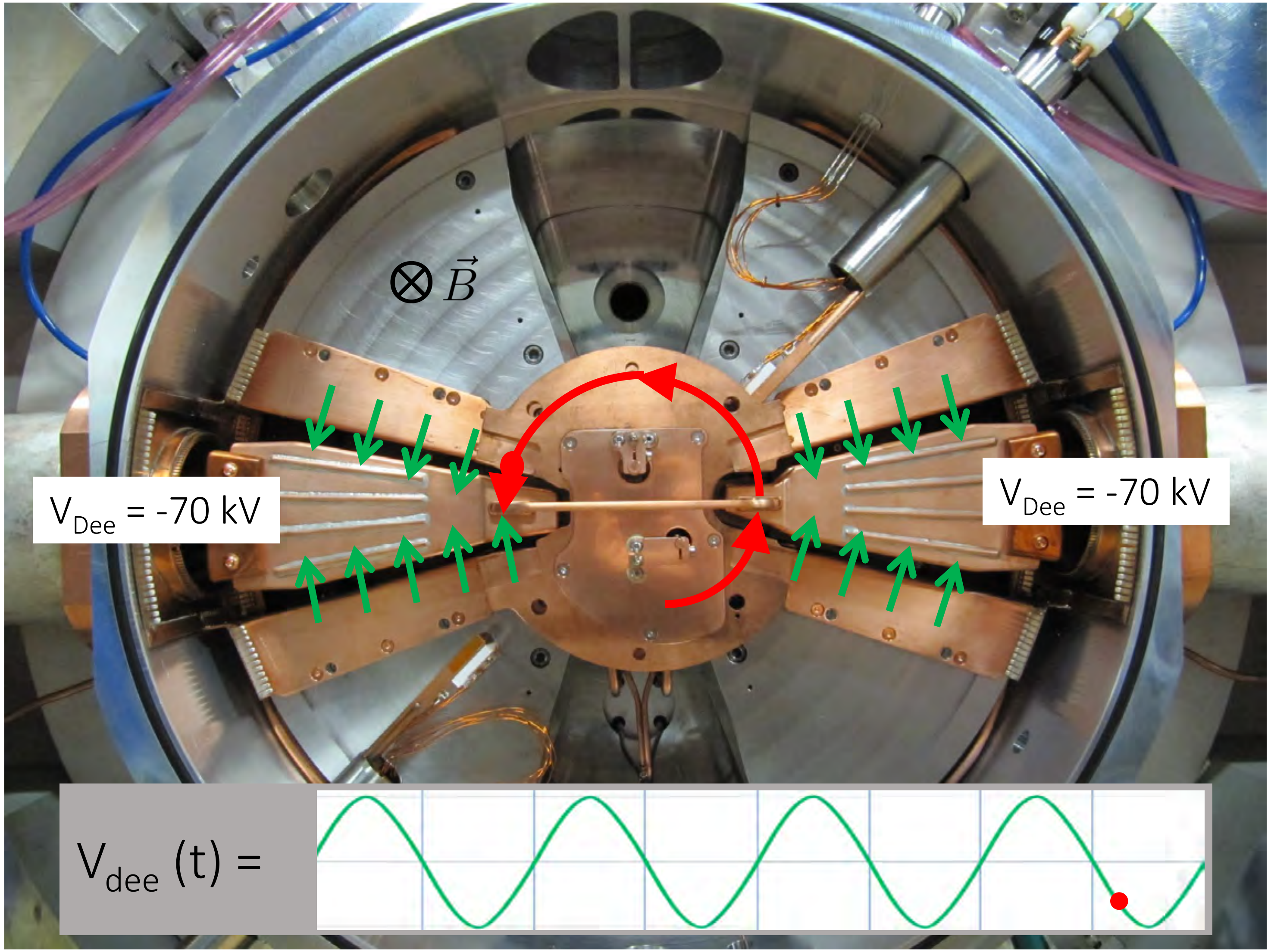
Acceleration (harmonic 6)



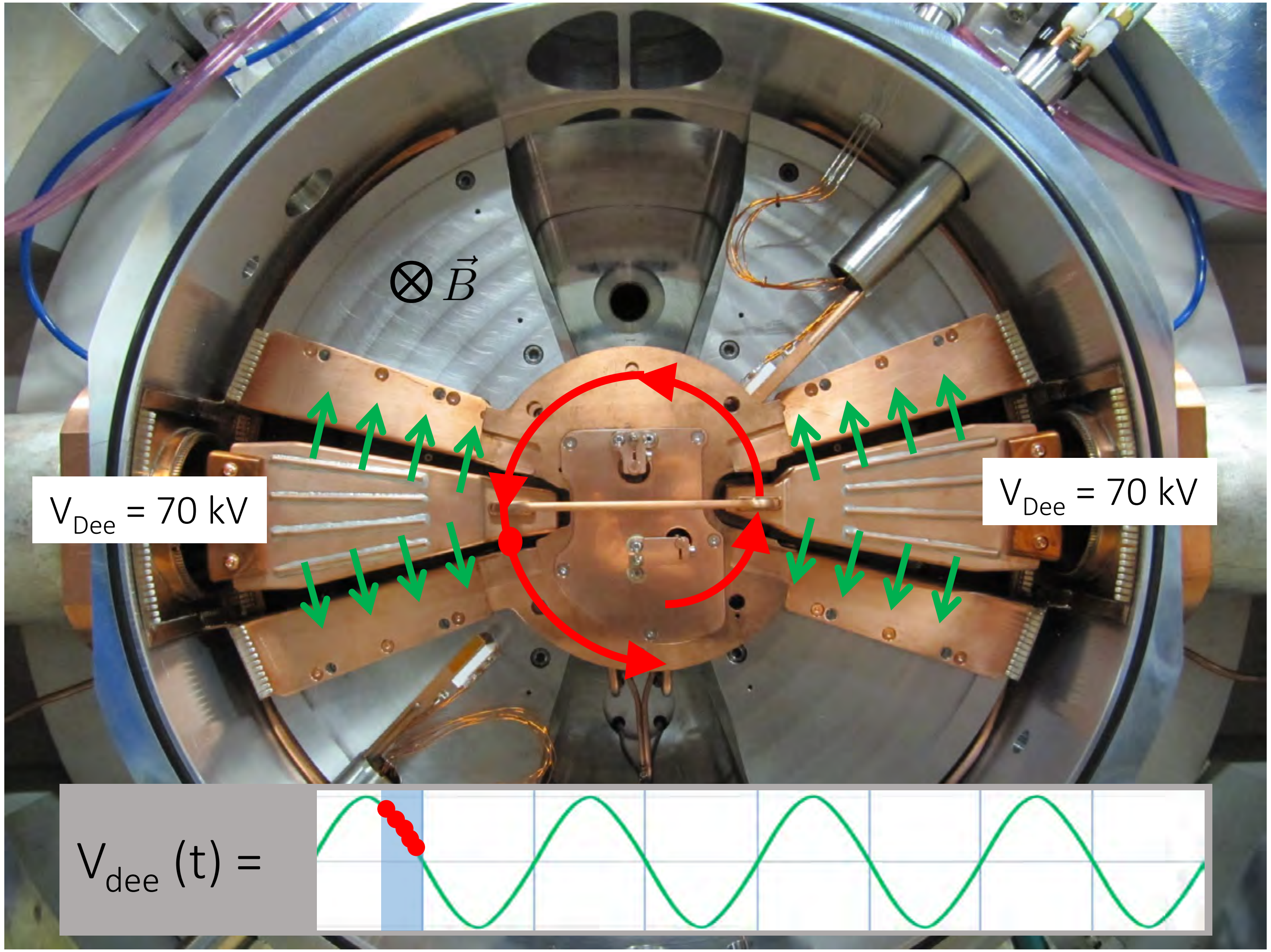
Acceleration (harmonic 6)



Acceleration (harmonic 6)



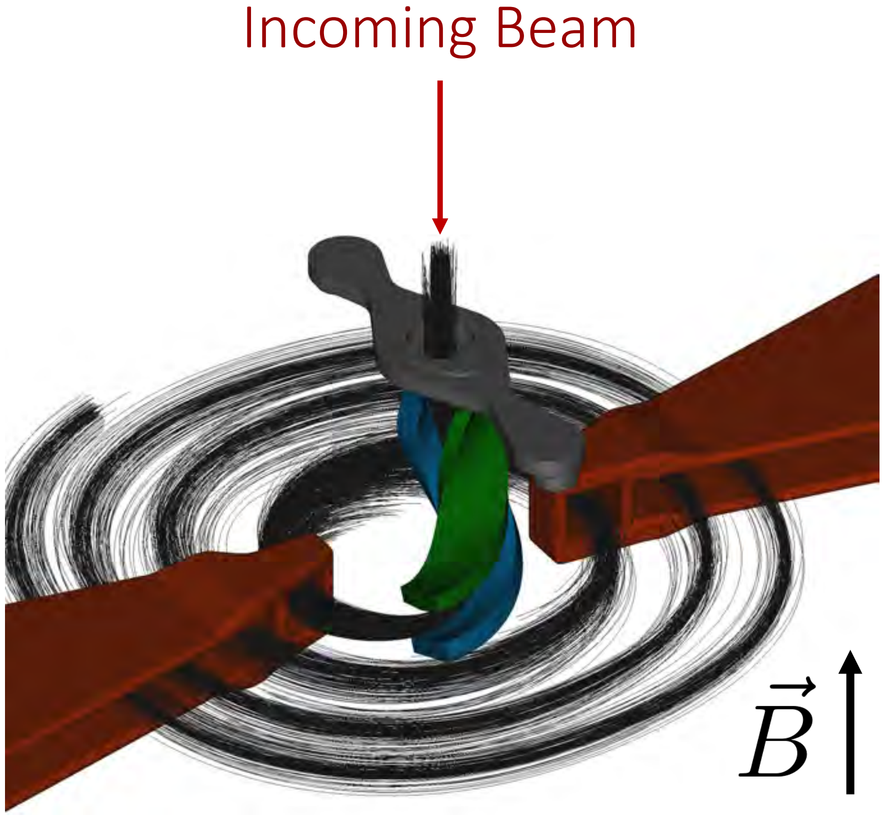
Only a narrow phase window can be populated



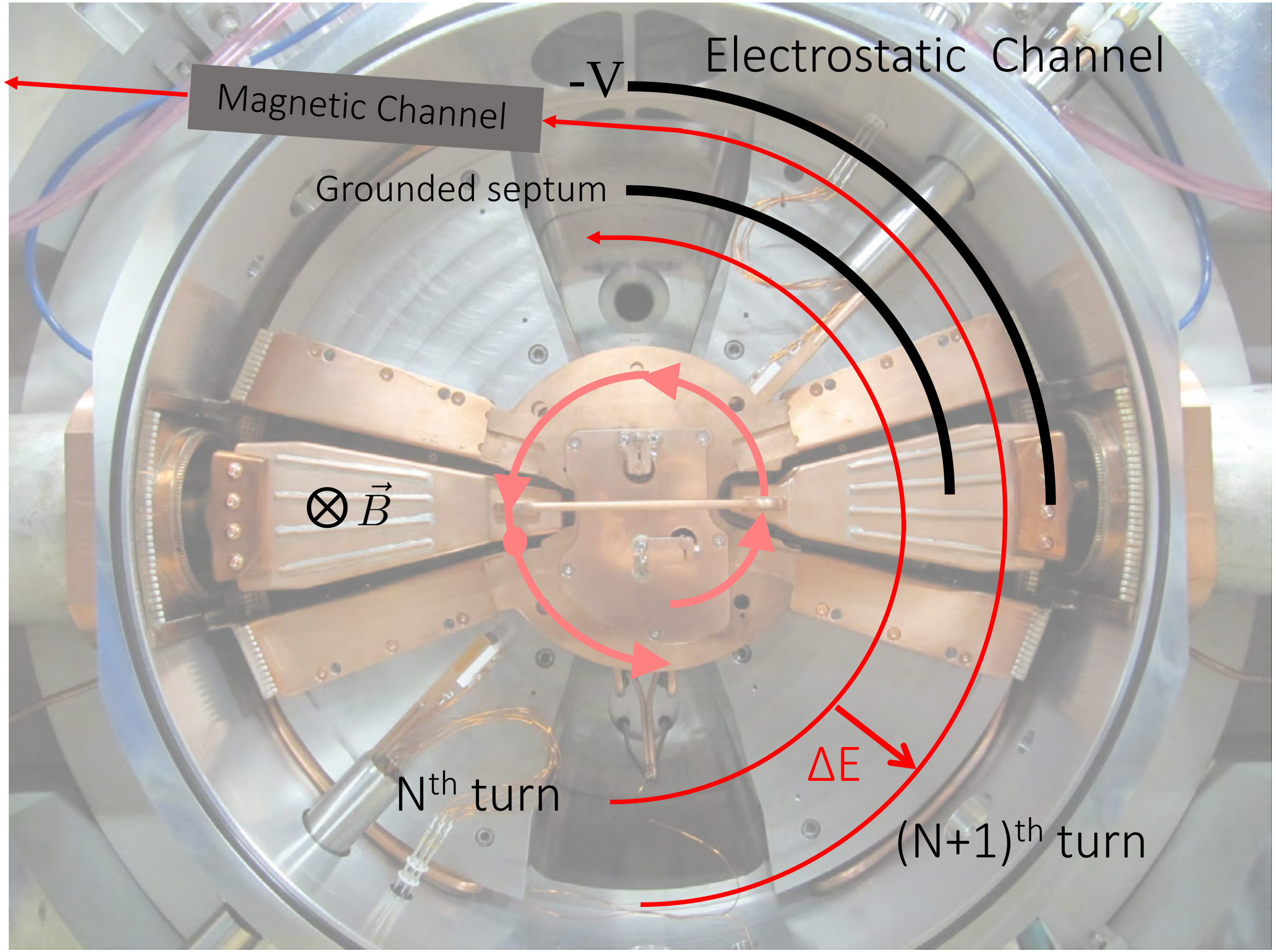
Phase Acceptance
Window in RF phase space that can safely be populated

Injection through a spiral inflector

- Cyclotron Main B-Field
- Electrostatic Field from Spiral Electrodes
- Combination guides particles
- Difficult to simulate precisely

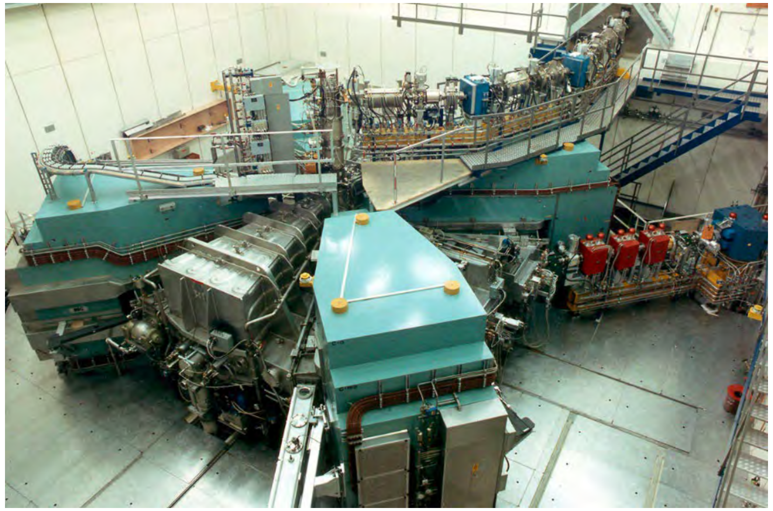


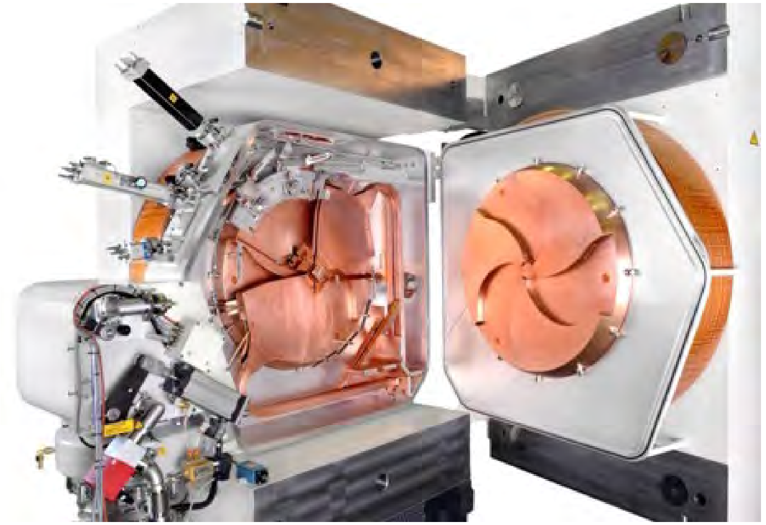
Extraction from a compact cyclotron



State of the art in high intensity cyclotrons

- PSI Injector II:
  - 2.7 mA of protons
  - 72 MeV
  - Separated Sector Cyclotron
  - Very large! Radius= 5 m
- Commercial Cyclotrons:
  - Isotope Production
  - ~1 mA of H-
  - Compact! Radius < 1 m
- We need:
  - Compact, and
  - with more beam (10 mA!)





Outline

- Original Motivation: IsoDAR neutrino physics
  - → In a few years this will yield very exciting particle physics

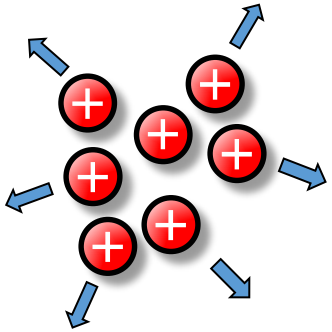
- Cyclotrons "101"
- The physics challenges of high intensity beams
  - → How we are changing the game

- More Applications:
  - Medical Isotopes, Materials, …
  - Multi-Megawatt beams for Particle Physics and ADS

What is the basic limitation?

- “Space charge” and the associated problems

10 mA of protons do not want to be crowded together in a bunch!



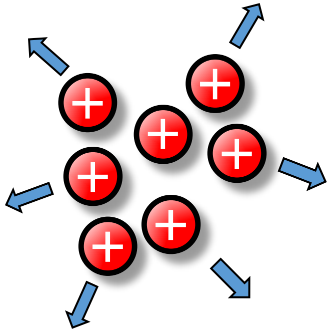
This is a dynamic problem,
the shape of the beam is constantly changing as you accelerate.

- But also *controlled* and *uncontrolled* beam loss!

What is the basic limitation?

- “Space charge” and the associated problems

10 mA of protons do not want to be crowded together in a bunch!



This is a dynamic problem,
the shape of the beam is constantly changing as you accelerate.

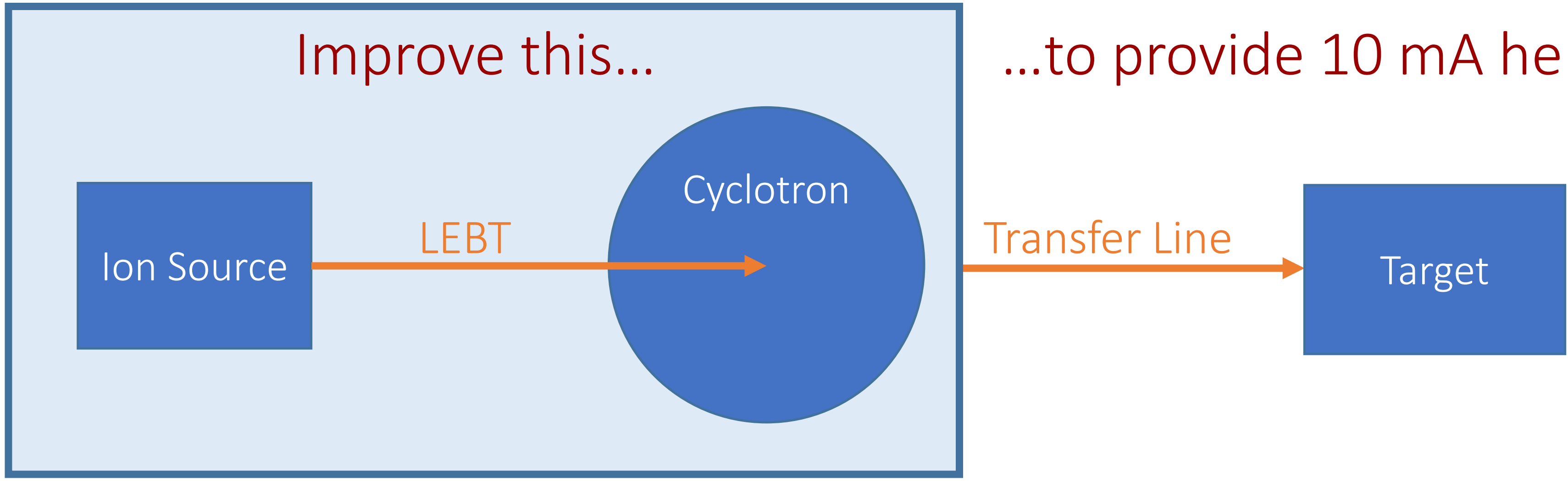
- But also *controlled* and *uncontrolled* beam loss!

What building blocks can we improve?

- Ion Source
- Low Energy Beam Transport (LEBT)
- Accelerator (Cyclotron)
  - Injection
  - Acceleration
  - Extraction

LEBT
Low Energy Beam Transport = Connection between ion source and accelerator

We must consider
space charge at every step!


Improve this…

…to provide 10 mA here

Trajectory equations with linear space-charge

M. Reiser, Wiley-VCH 2008

Trajectory Equations:

$$x'' + \kappa_{x0} x - \frac{2K}{x_m(x_m + y_m)} x = 0$$

$$y'' + \kappa_{y0} y - \frac{2K}{y_m(x_m + y_m)} y = 0$$

$$\kappa_{x0}, \kappa_{y0} \cdots \text{ focusing functions}$$

Envelope equations:

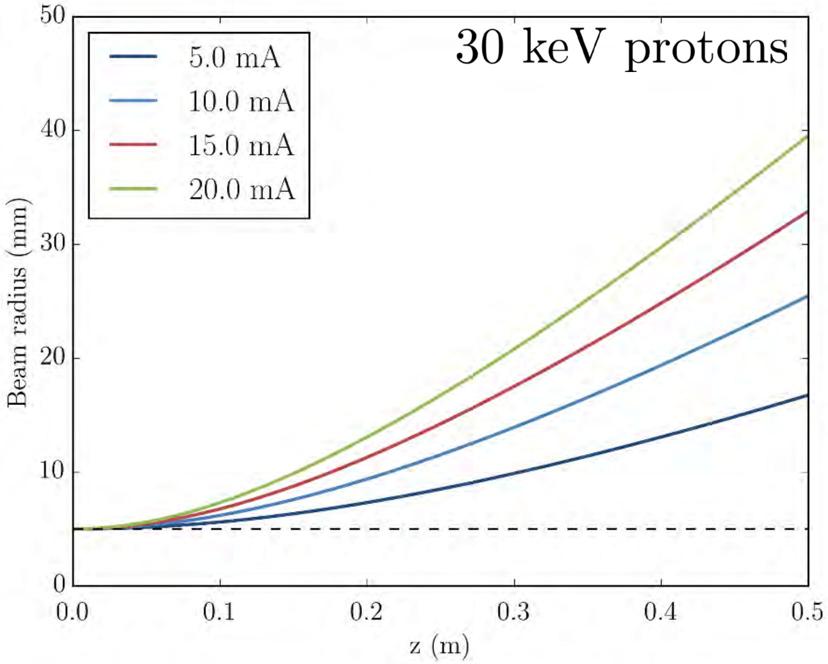
$$x_m'' + \kappa_{x0} x_m - \frac{2K}{x_m + y_m} - \frac{\epsilon_x^2}{x_m^3} = 0$$

$$y_m'' + \kappa_{y0} y_m - \frac{2K}{x_m + y_m} - \frac{\epsilon_y^2}{y_m^3} = 0$$

$$x_m, y_m \cdots \text{ beam edge}$$

Generalized Perveance:

$$K = \frac{q\mathrm{I} \cdot (1 - \gamma^2 \mathrm{f_e})}{2\pi\epsilon_0 m_0 c^3 \gamma^3 \beta^3}$$



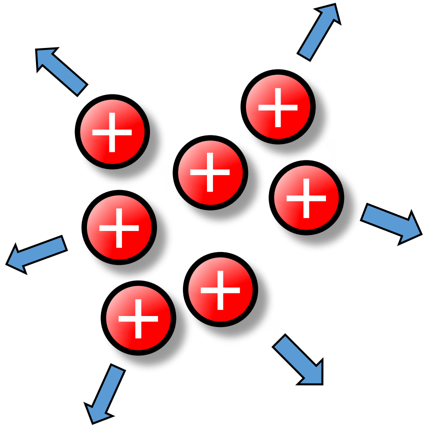
<u>Emittance</u>
Figure of merit for how quickly beam will spread out

There are “particle knobs” to turn

Generalized Perveance:

$$K = \frac{qI \cdot (1 - \gamma^2 f_e)}{2\pi\epsilon_0 m_0 c^3 \gamma^3 \beta^3}$$

a measure for space-charge

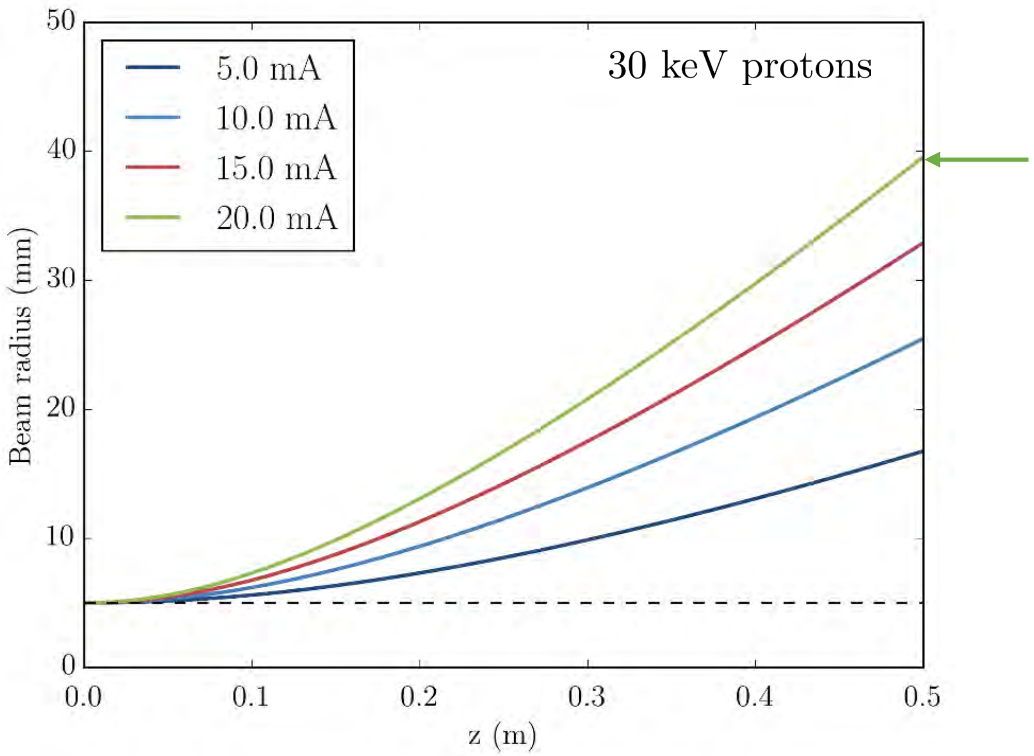


If we want to increase I, *we can change m and* E *to keep*

The perveance as low as possible

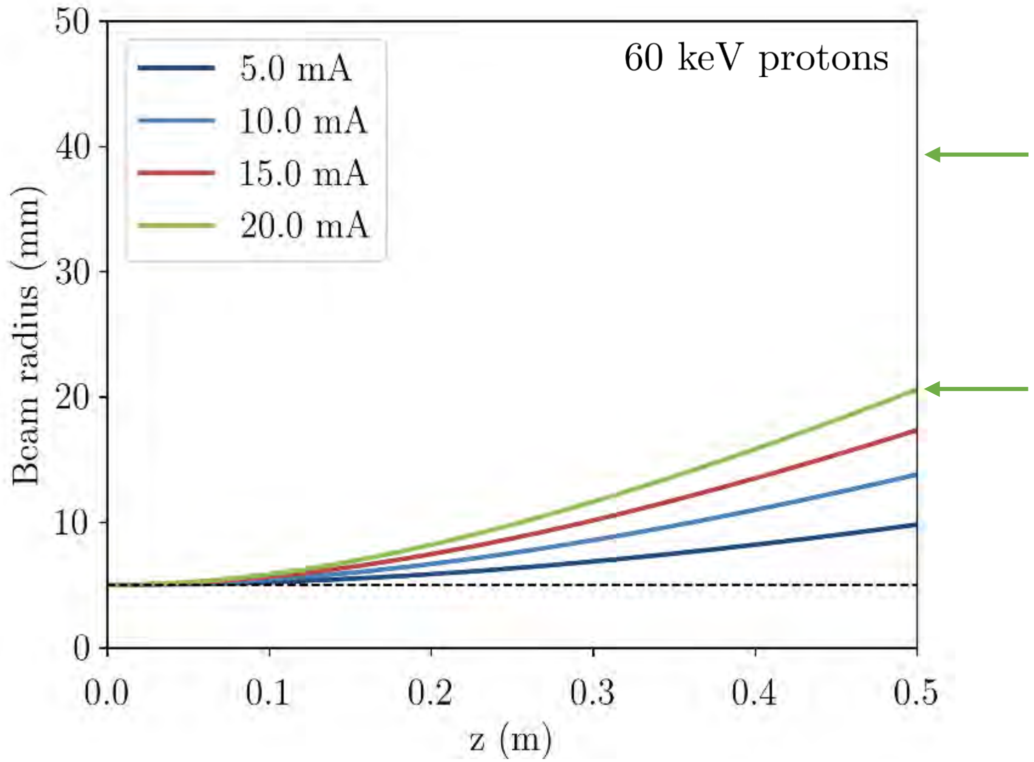
Space-charge makes injection difficult

- This becomes most problematic in the spiral inflector
- And Low Energy Beam Transport



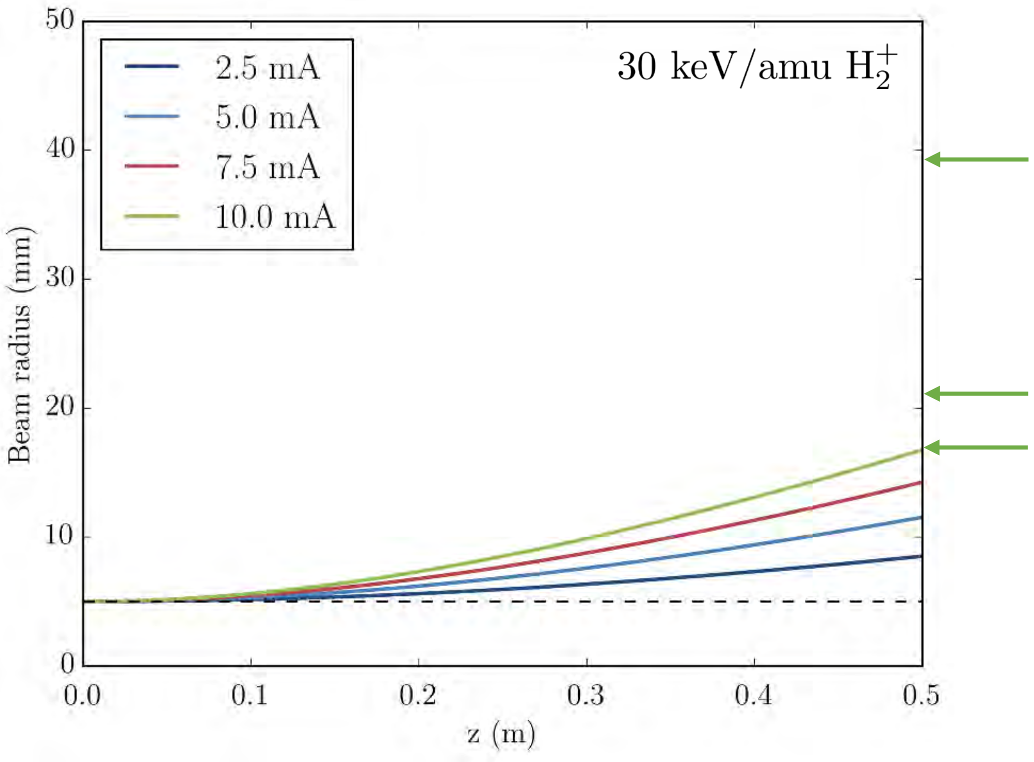
Space-charge makes injection difficult

- This becomes most problematic in the spiral inflector
- And Low Energy Beam Transport
- Let’s increase energy



Space-charge makes injection difficult

- This becomes most problematic in the spiral inflector
- And Low Energy Beam Transport
- Let’s increase energy … and change the ion?

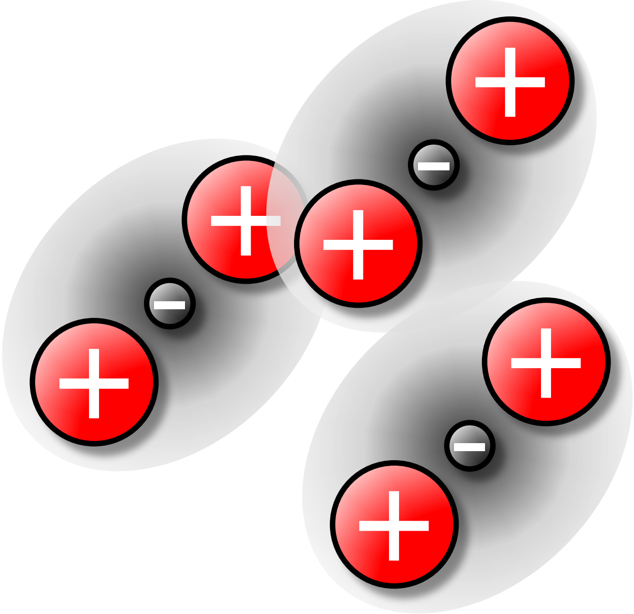


Note:

- 5 mA H_2^+ = 10 mA p^+

Innovation #1: H_2^+ instead of protons

- Two units of charge for one!
- Remove electron by stripping



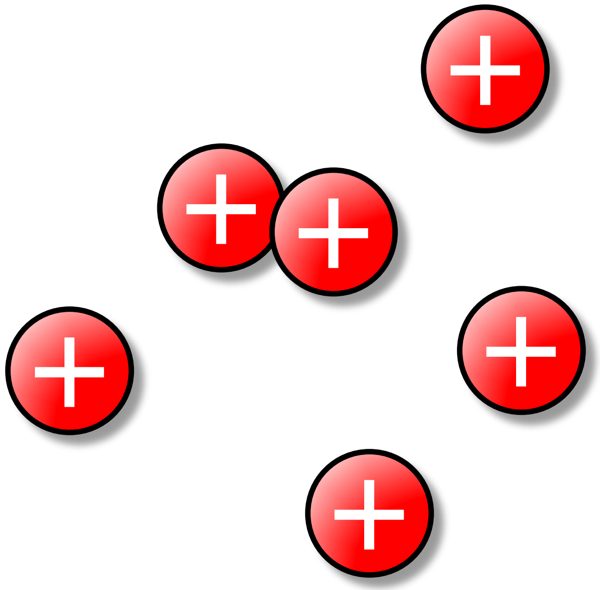
Note:

- 5 mA H_2^+ = 10 mA p^+

Innovation #1: H_2^+ instead of protons

- Two units of charge for one!

- Remove electron by stripping
  → get two protons per H_2^+



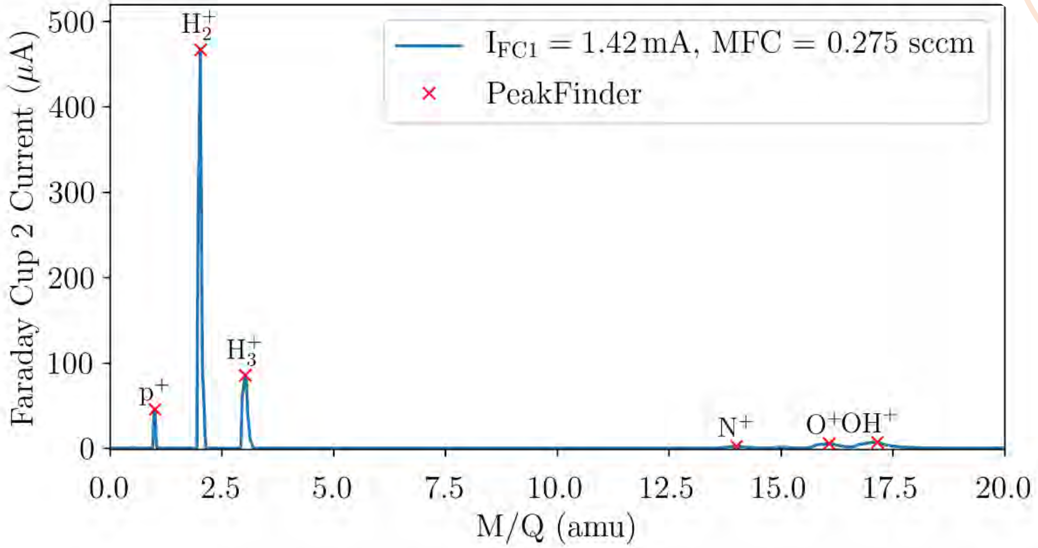
- Helps with Injection
- Helps with Low Energy Beam Transport

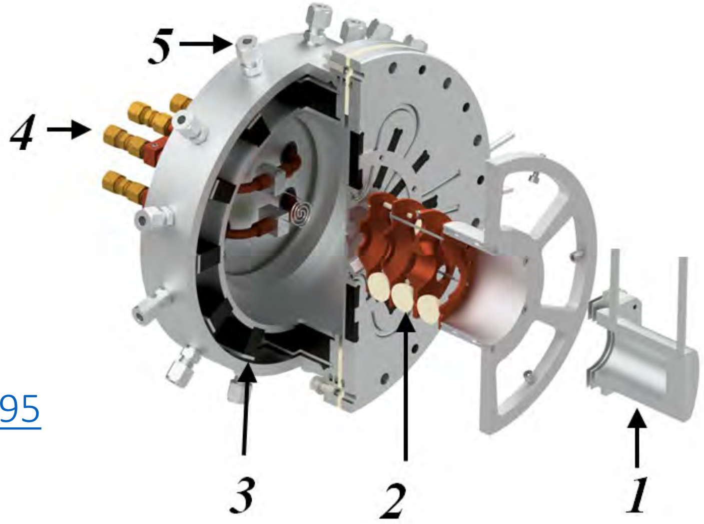
- And there are additional exciting ways to exploit this!

Note:
- 5 mA H_2^+ = 10 mA p^+

Innovation #2: H_2^+ ion source (MIST-1) → commissioned at 25% power at MIT (PSFC)

- Filament-driven multicusp ion source
- > 1 mA of H_2^+
- 80% purity
- High quality beam emittance: 0.05 π-mm-mrad (RMS, norm.)
- Now ramping up to 100% power



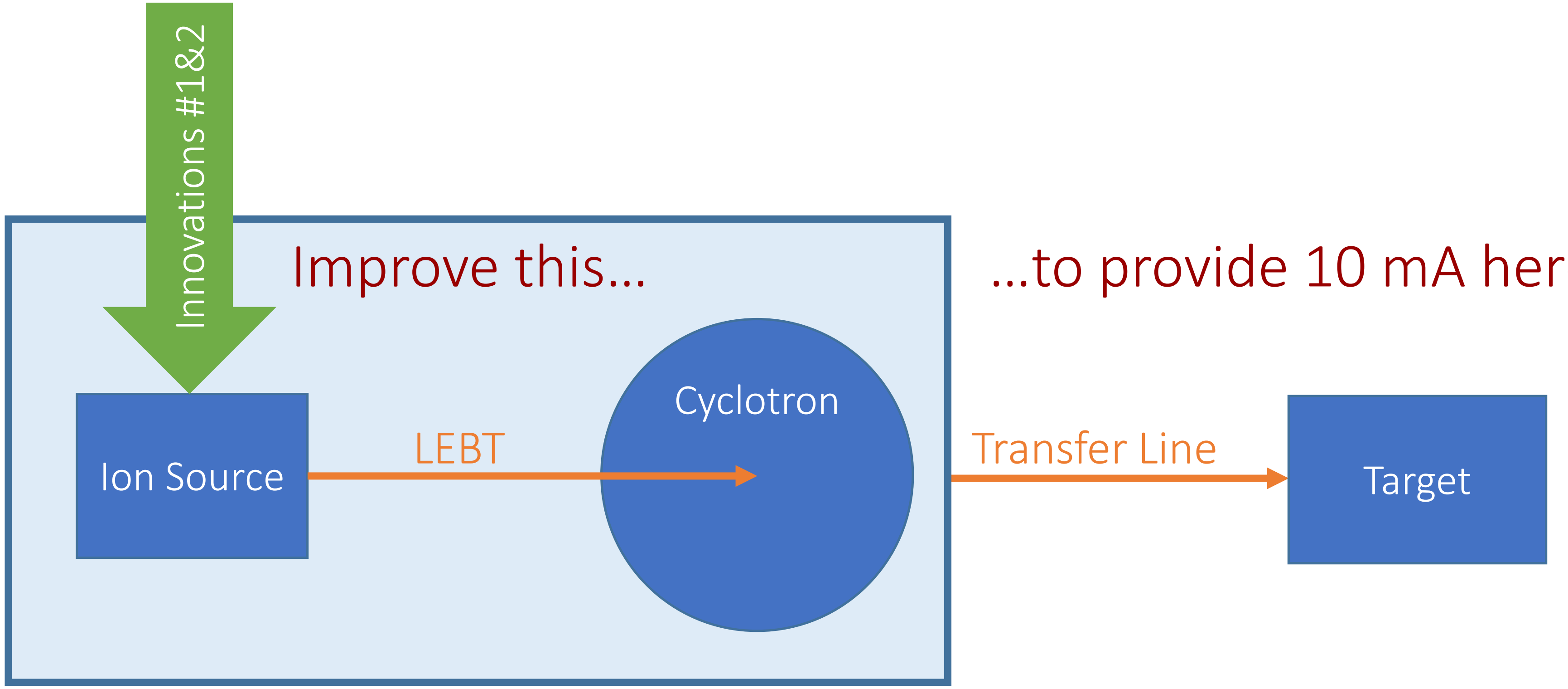


Emittance
Figure of merit for how quickly beam will spread out

Axani, DW et al. **RSI** (2016) https://aip.scitation.org/doi/10.1063/1.4932395
DW et al., **AIP Conf. Proc.** (2017) https://arxiv.org/abs/1811.01868
DW et al. **RSI** (2021) https://arxiv.org/abs/2008.12292

What building blocks can we improve?

MIST
Multicusp Ion Source Technology

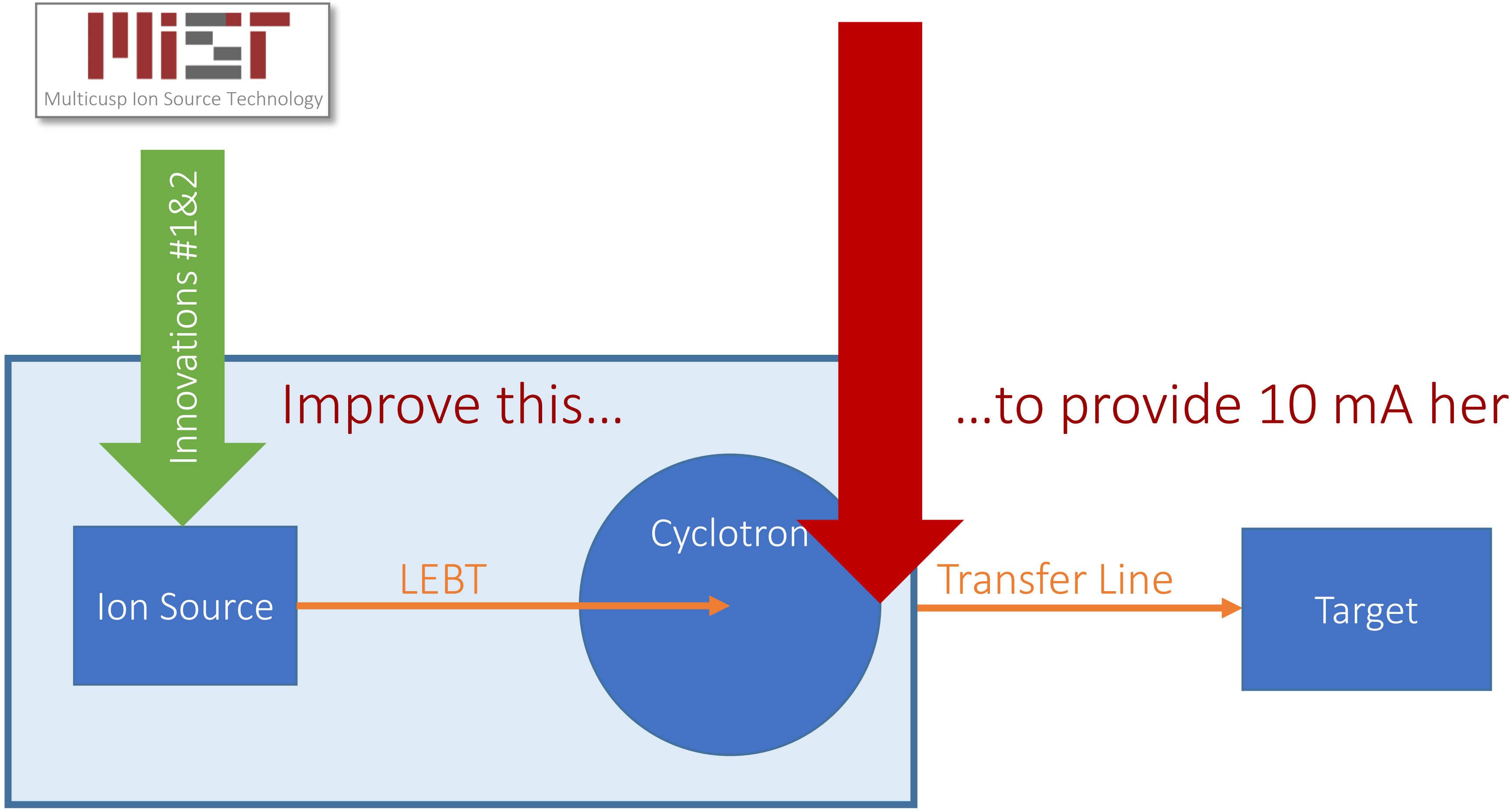


Improve this…

…to provide 10 mA here

What building blocks can we improve?

Now let’s jump to here:
Understanding Extraction



Multicusp Ion Source Technology

Innovations #1&2

Improve this…

…to provide 10 mA here

Ion Source

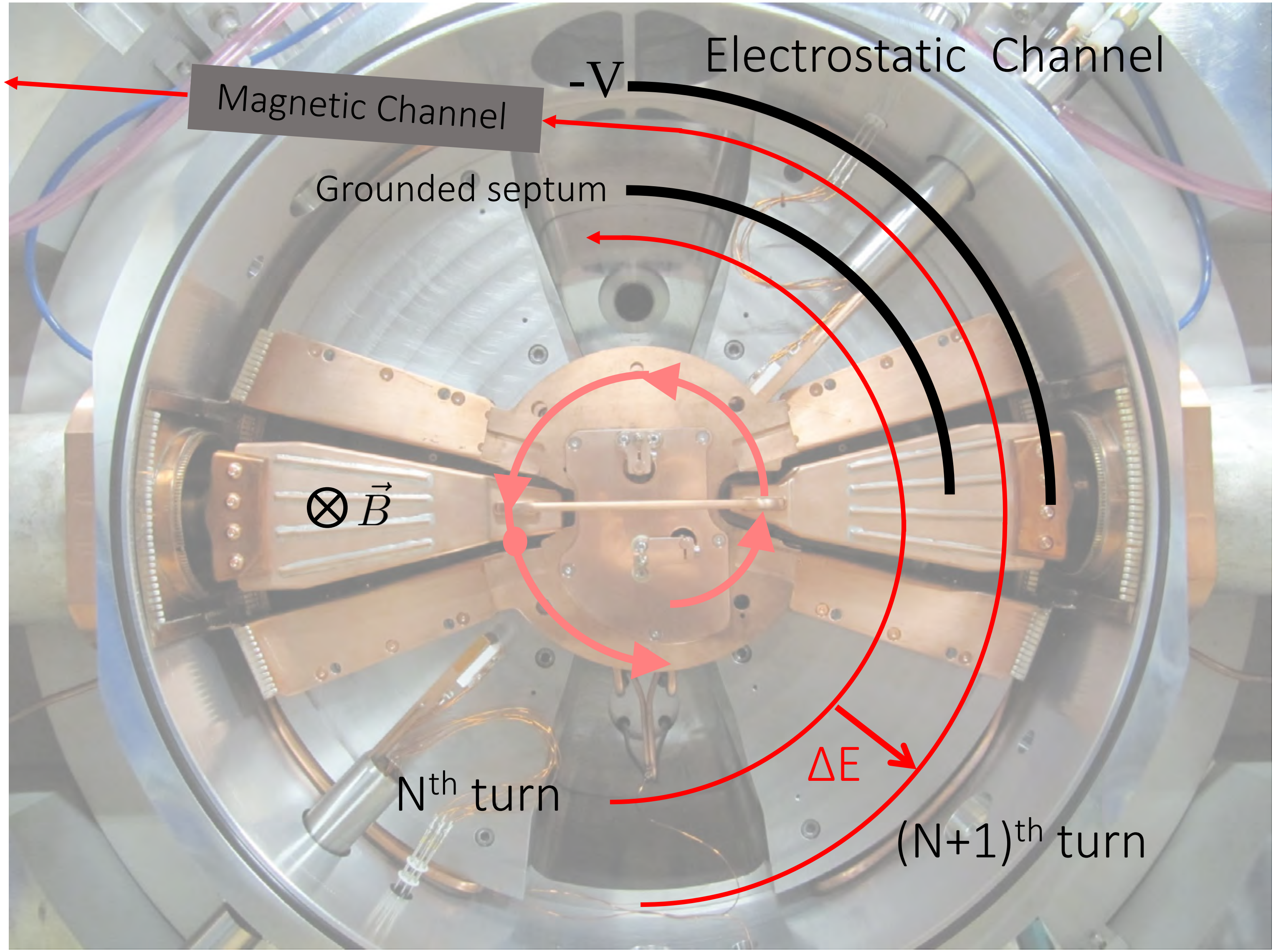
LEBT

Cyclotron

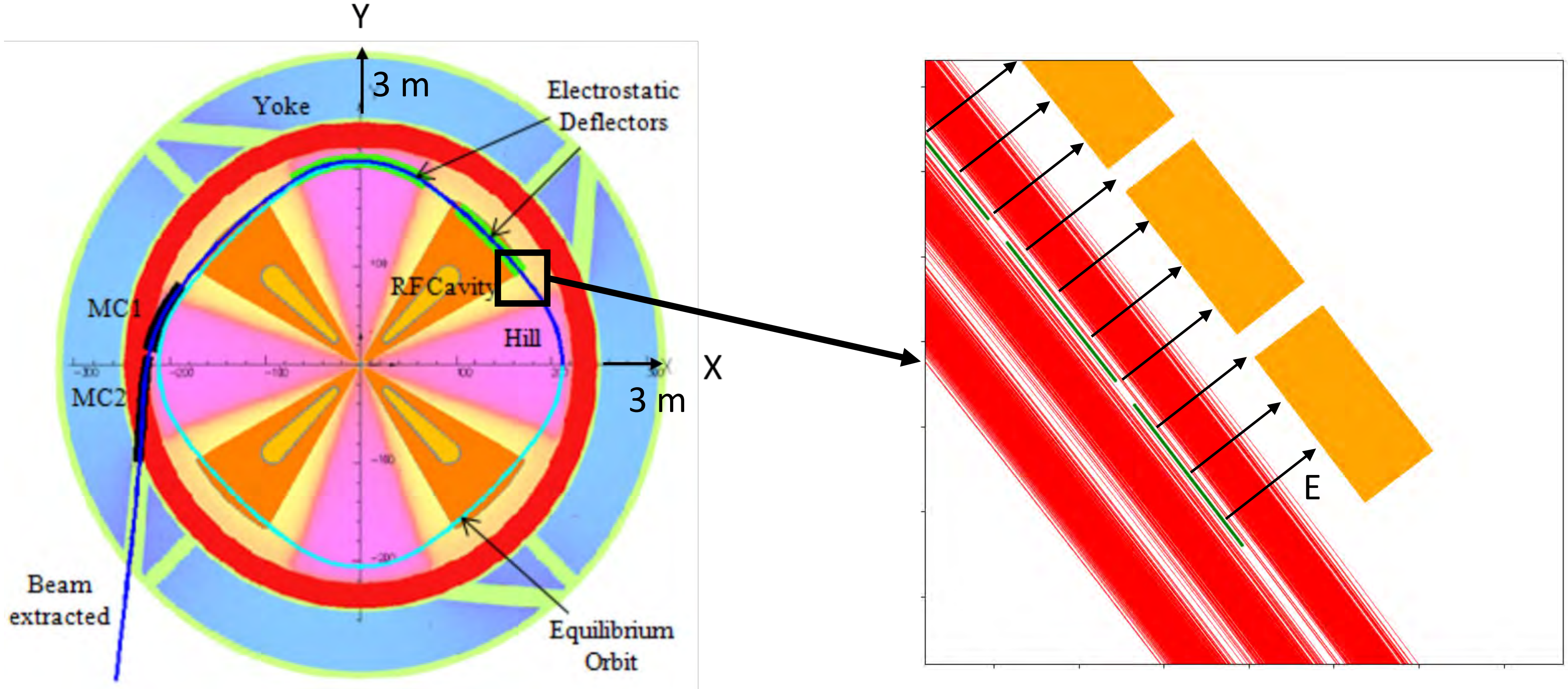
Transfer Line

Target

Extraction from a compact cyclotron

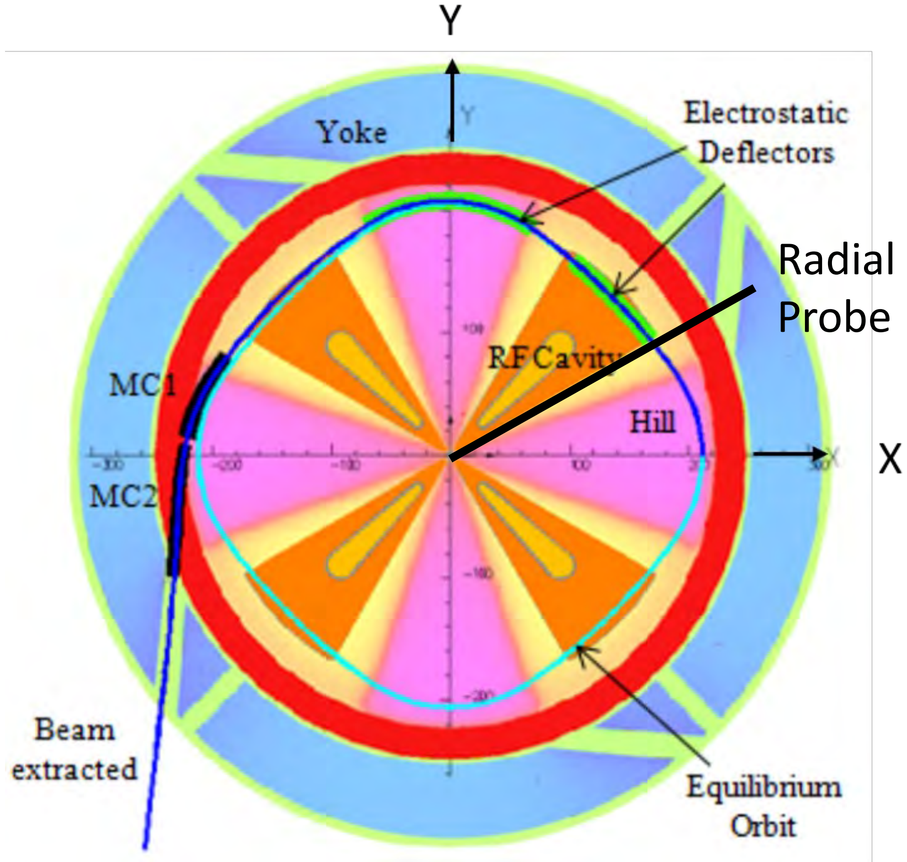


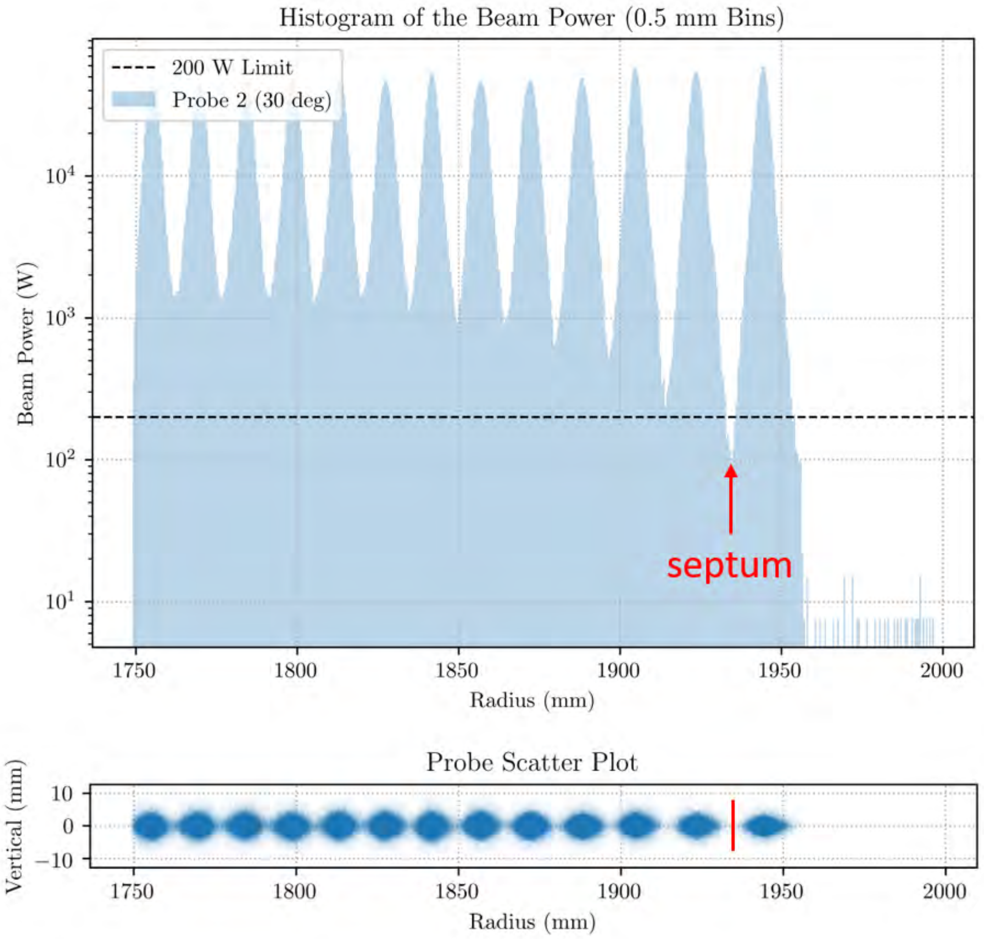
To run and perform routine maintenance, beam loss must be minimized (< 200 W)



To run and perform routine maintenance, beam loss must be minimized (< 200 W)

- Safety limit adopted from PSI:
  200 W or ~1 in 10k particles at 60 MeV/amu
- Otherwise there is too much activation



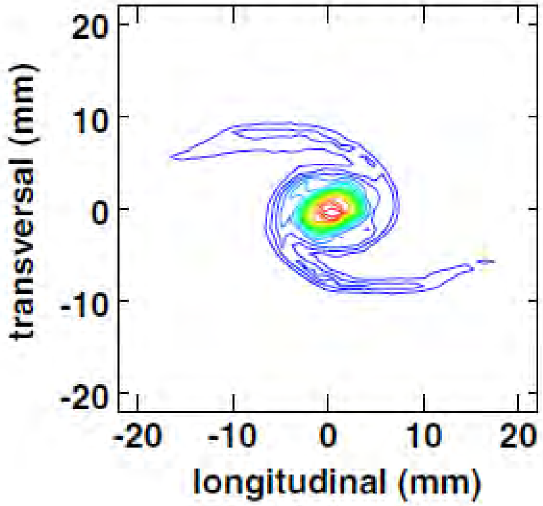


Three ways to maximize the turn separation and minimize losses

- Maximize Energy Gain/turn
  250 kV V_{dee}, 4 Dees (8 gaps)
  → almost 2 MeV/turn

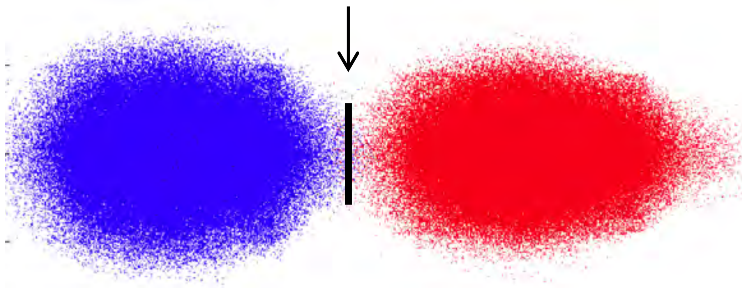
- Excite Precession through Resonance

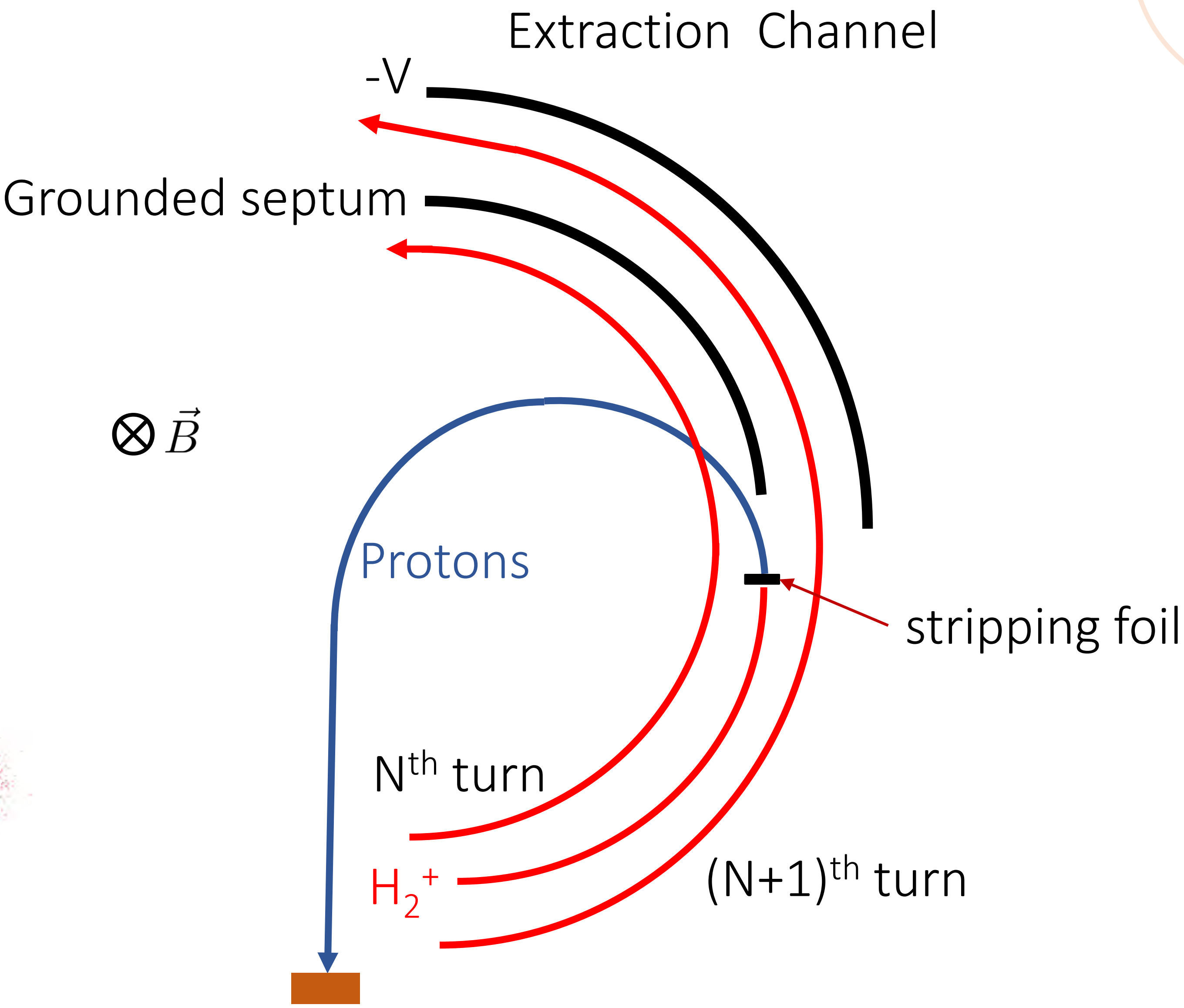
- Beam Dynamics: Vortex Motion
  - Vortex-like curling up of the beam into a circle in longitudinal-transverse space
  - Only happens in isochronous cyclotrons
  - Beam needs to be well matched



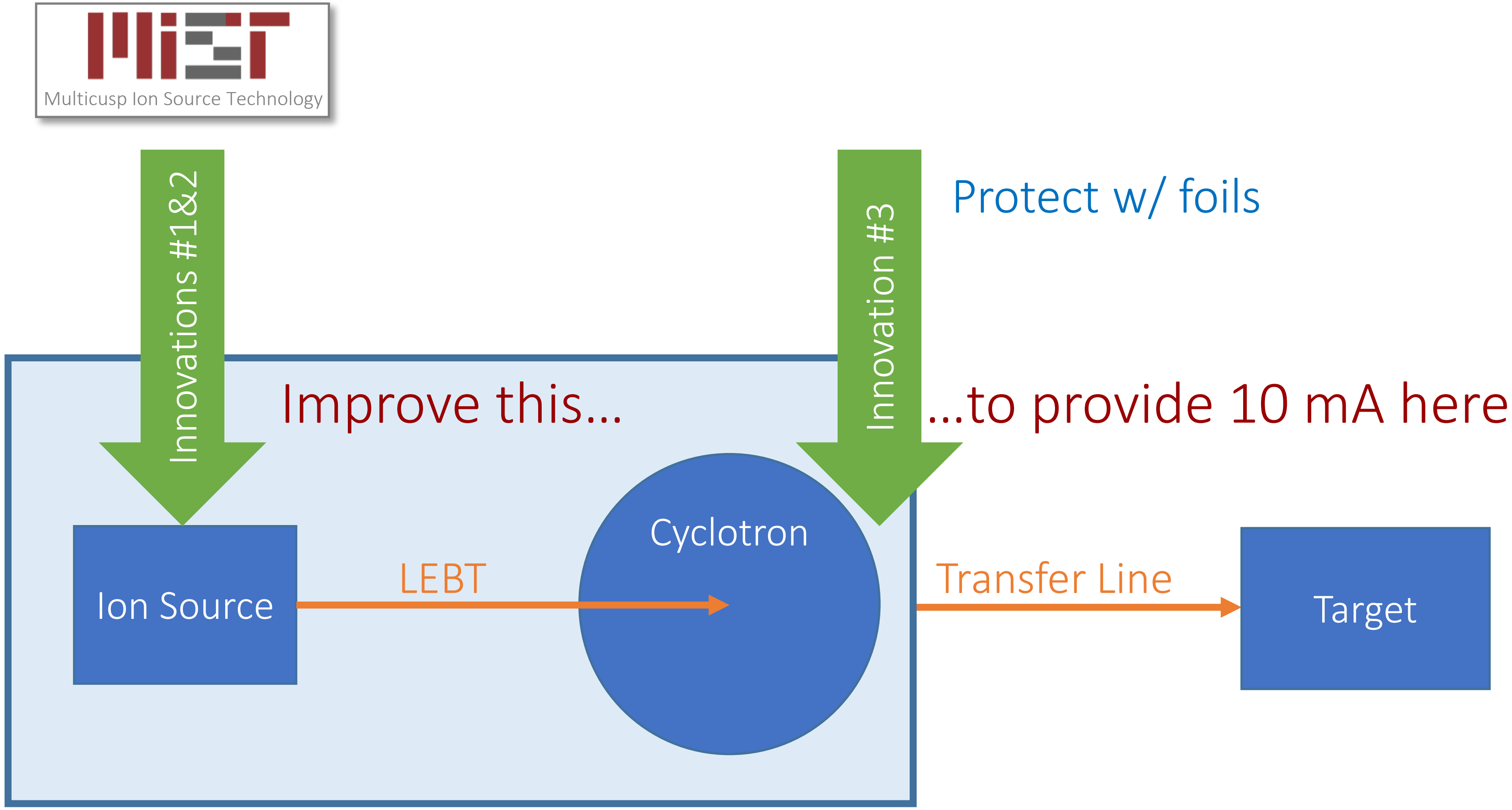
<u>Matched</u>
Initialize vortex motion as quickly as possible with minimal halo generation

A carbon stripping foil can protect the septum





What building blocks can we improve?



Multicusp Ion Source Technology

Innovations #1&2

Innovation #3

Protect w/ foils

Improve this…

…to provide 10 mA here

Ion Source

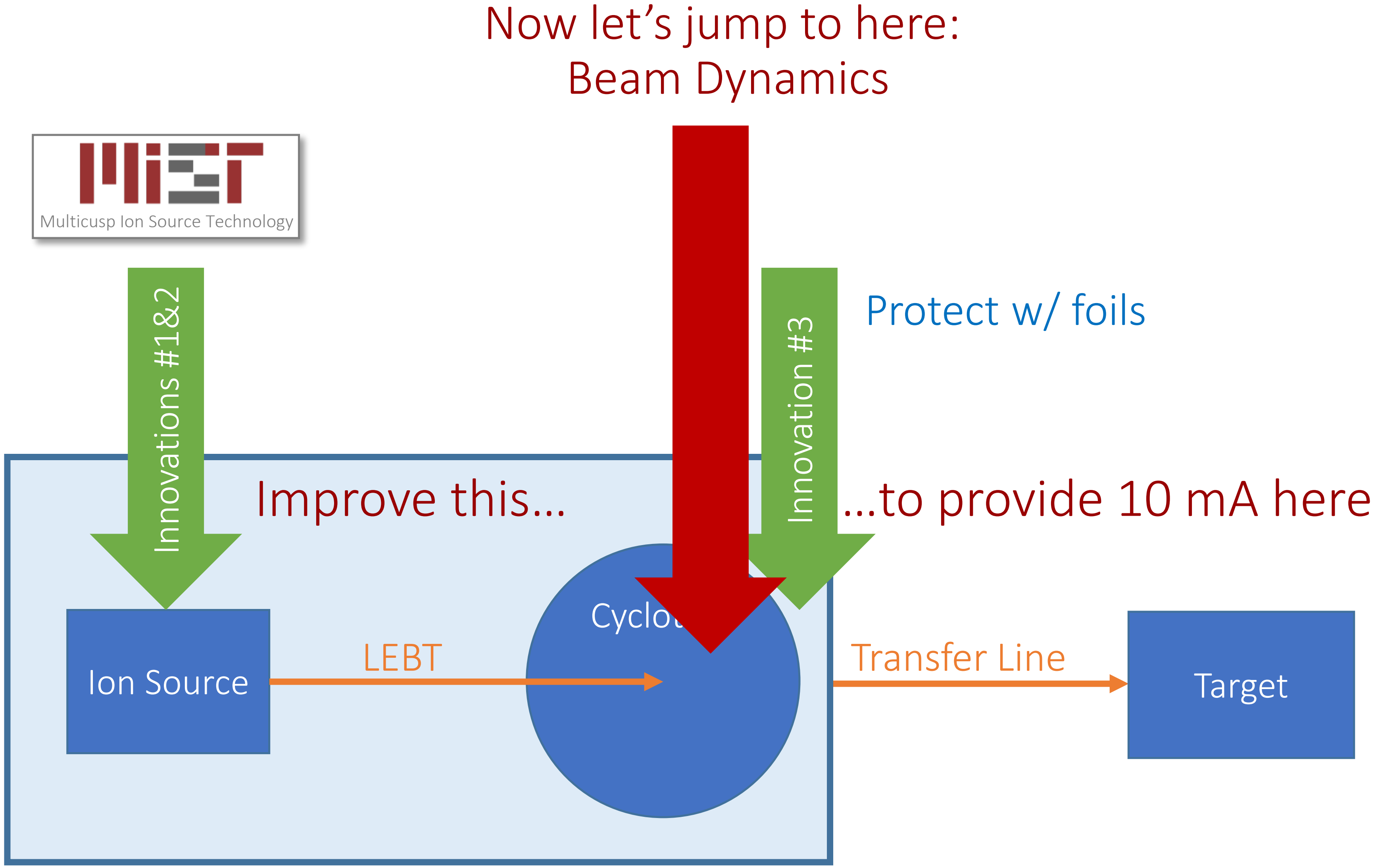
LEBT

Cyclotron

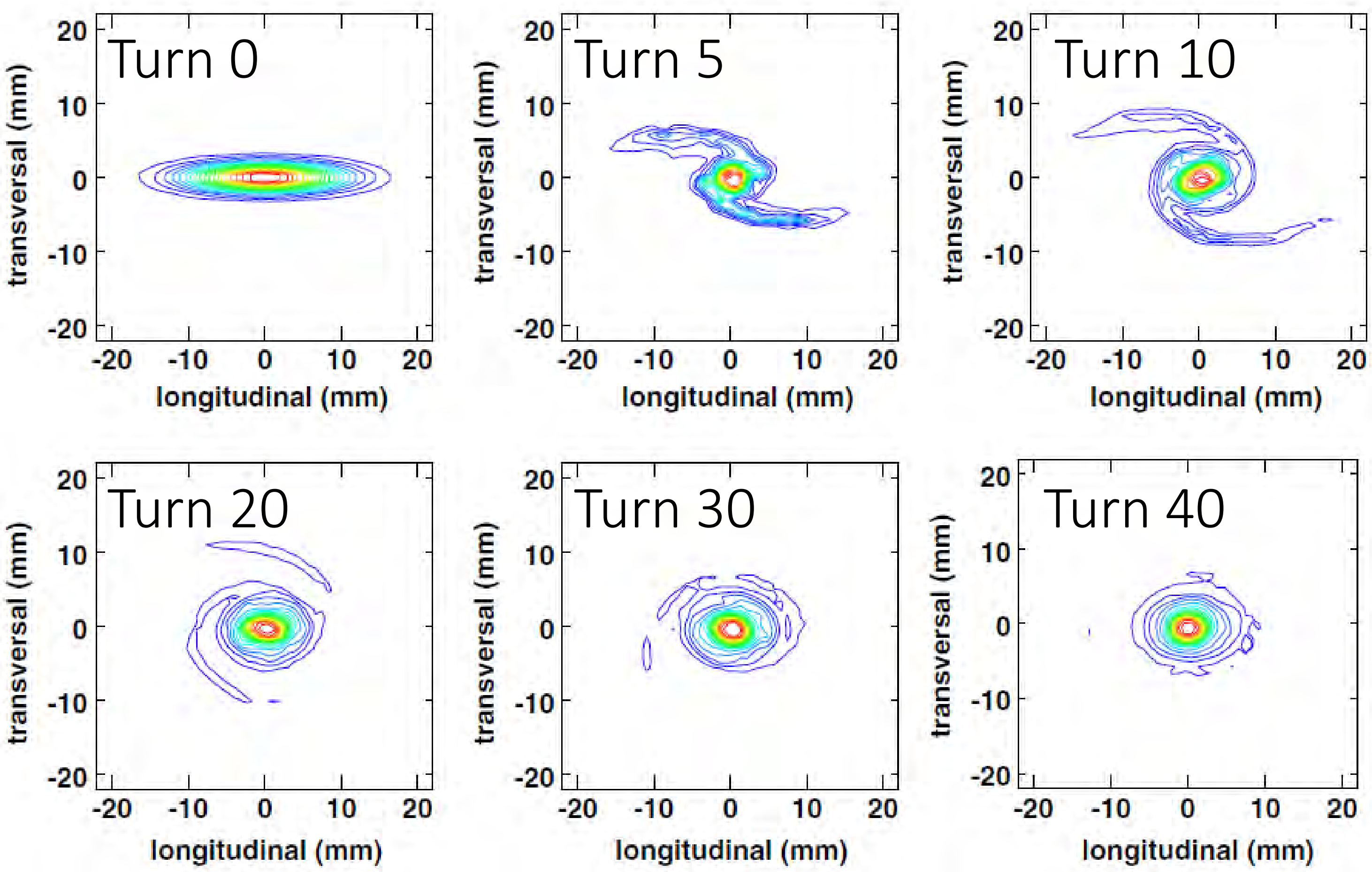
Transfer Line

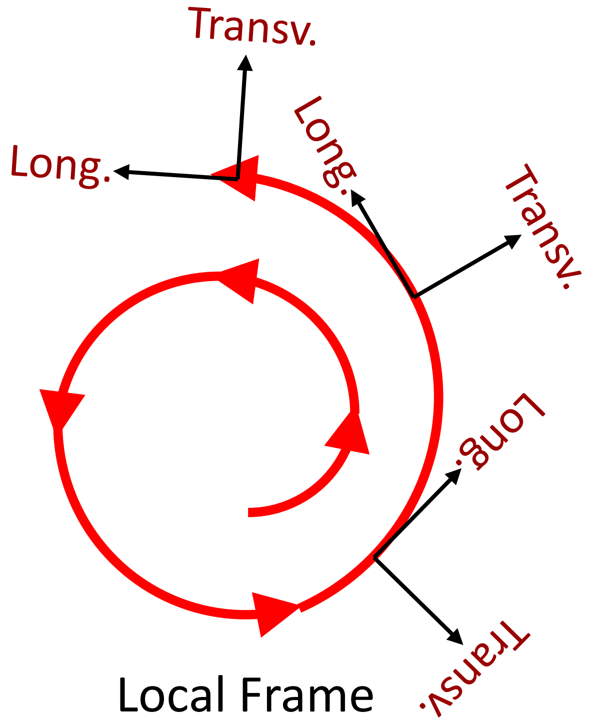
Target

What building blocks can we improve?



Vortex motion – OPAL Simulations for PSI Injector II




Transv.

Long.

Long.

Transv.

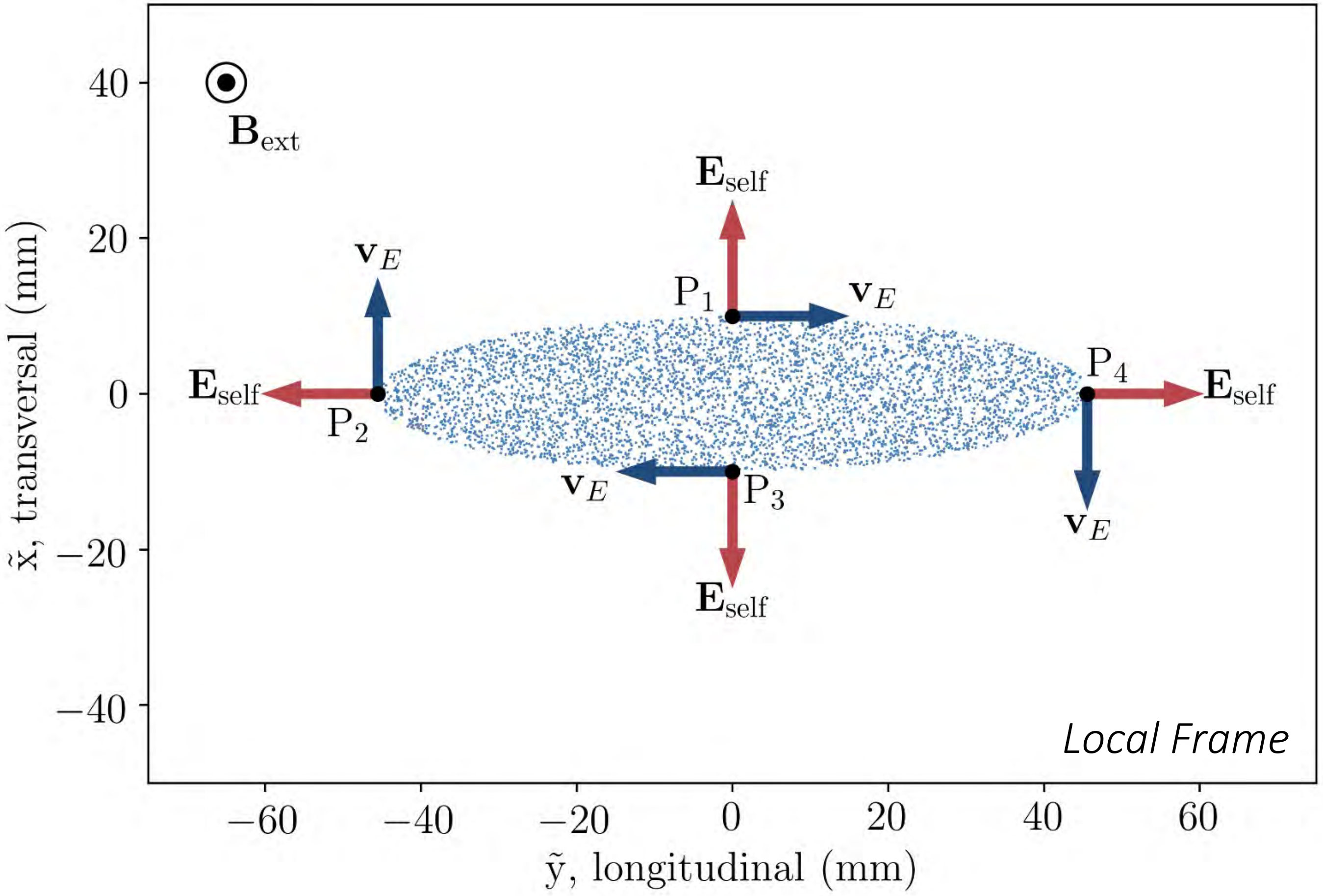
Long.

Transv.

Local Frame

Yang et al. **PRSTAB** (2010) https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.13.064201

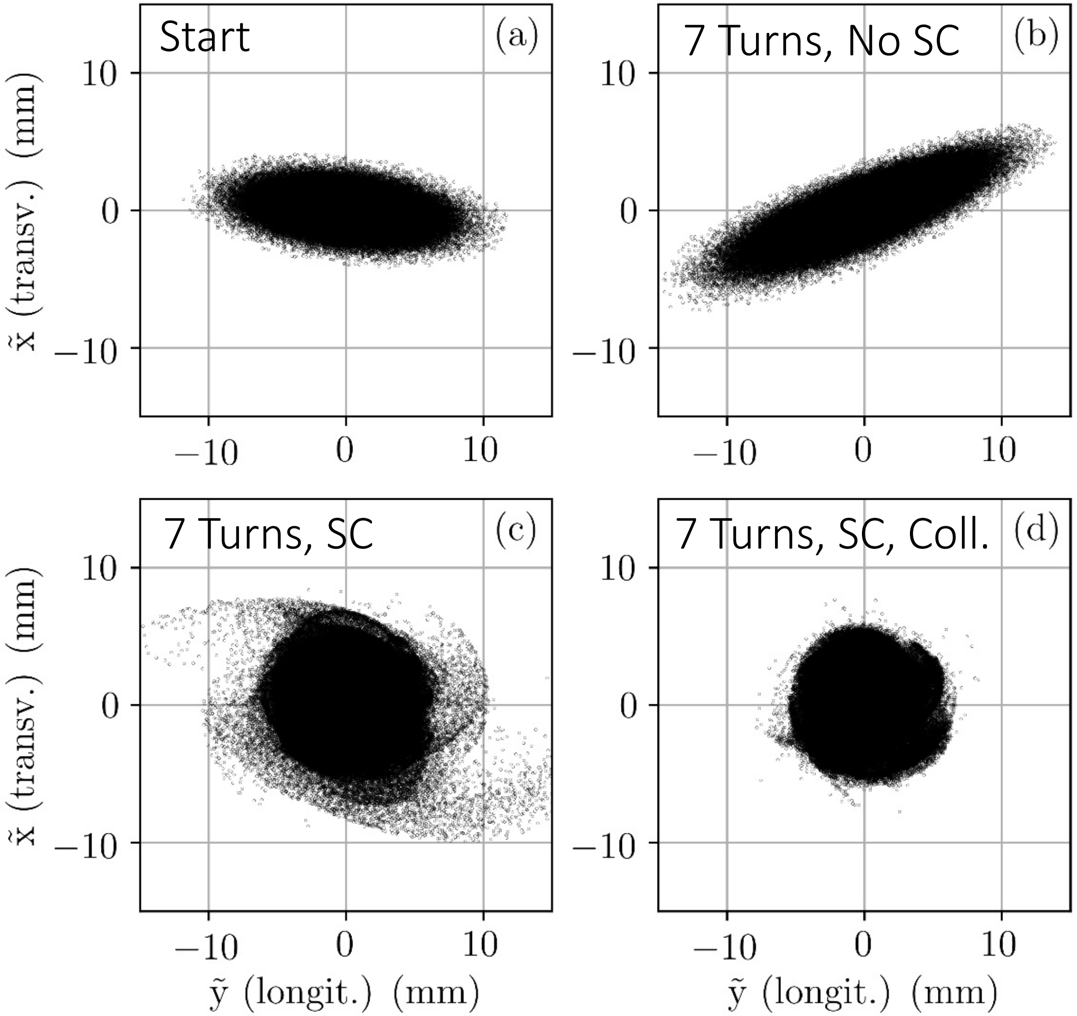
Vortex Motion - The “Intuitive” Picture



Lorentz force: $\mathbf{F} = q \cdot (\mathbf{v} \times \mathbf{B}_{\text{ext}}) + q \cdot \mathbf{E}_{\text{self}}$

E x B drift: $\mathbf{v}_E = \dfrac{\mathbf{E}_{\text{self}} \times \mathbf{B}_{\text{ext}}}{{\text{B}_{\text{ext}}}^2}$

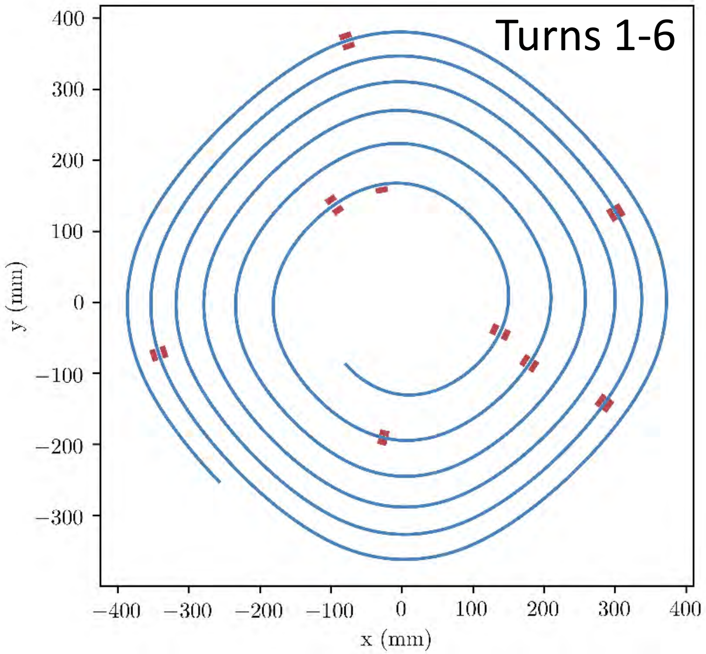
Vortex Motion in the IsoDAR 60 MeV/amu cyclotron

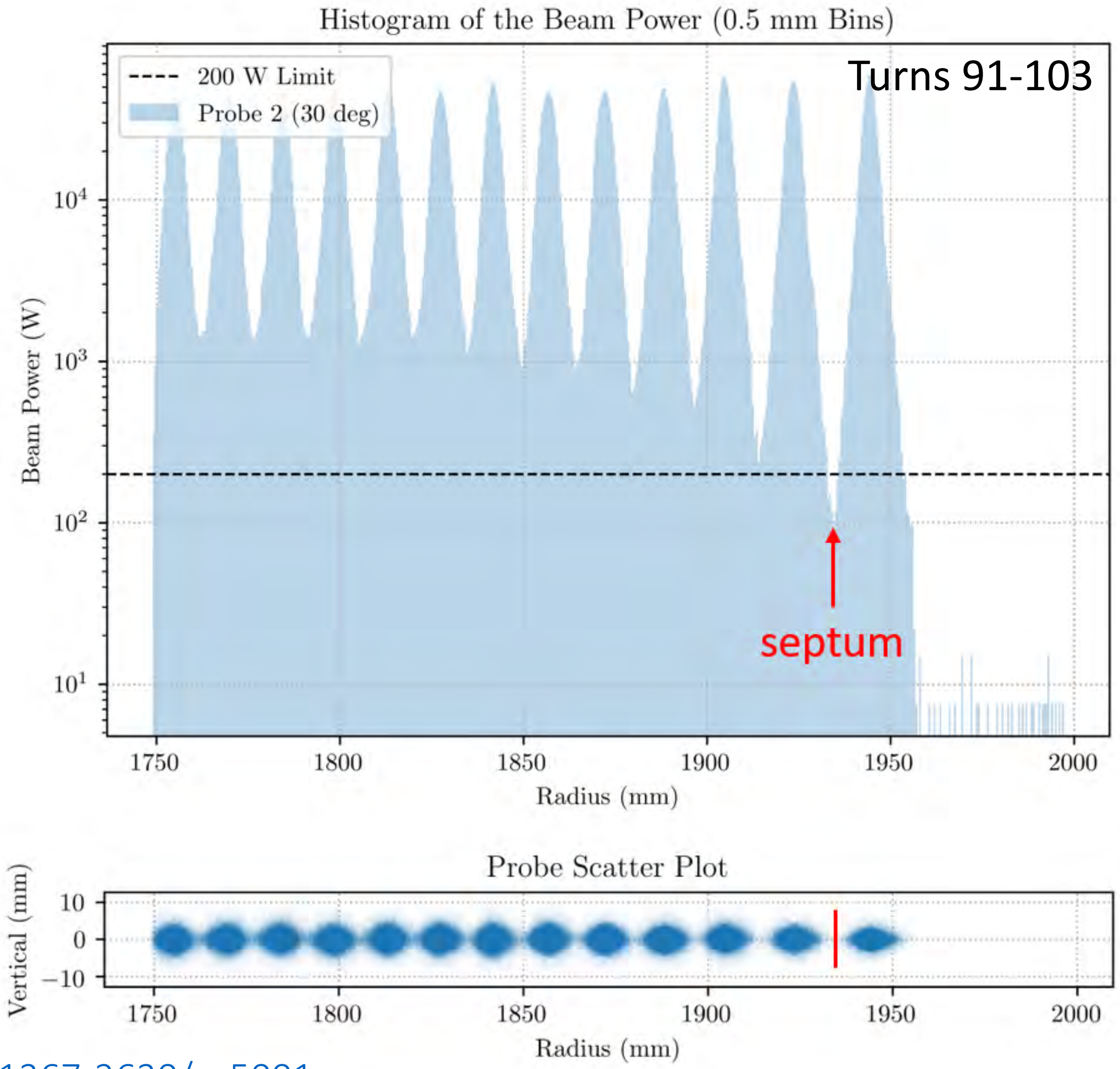


DW et al., **New J. Phys.** (2022) https://doi.org/10.1088/1367-2630/ac5001

Optimize phase, RF voltage, cavity shape, collimator placement

- Phase: -5°, V = 70-240kV
- Collimate Halo → ~30% loss
- 98 W on septum (~1e-4 rel.)

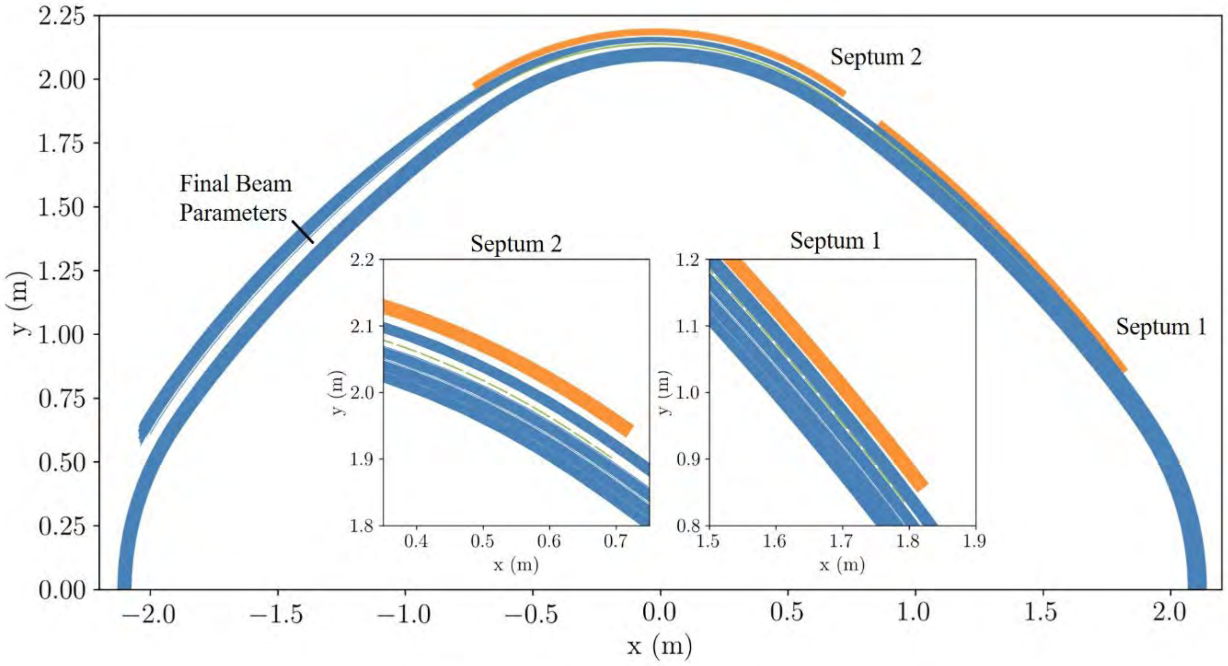




DW et al., **New J. Phys.** (2022) https://doi.org/10.1088/1367-2630/ac5001

Beam can be extracted with good quality

- Minimal losses at 60 MeV/amu: < 100 Watt!
- RMS Size:
  - Radial: 7.5 mm
  - Longitudinal: 11 mm
  - Vertical: 1.9 mm
- RMS, normalized emittance:
  - vertical: 0.44 mm-mrad
  - Radial: 3.8 mm-mrad
- Longitudinal emittance:
  - 0.1 MeV-deg

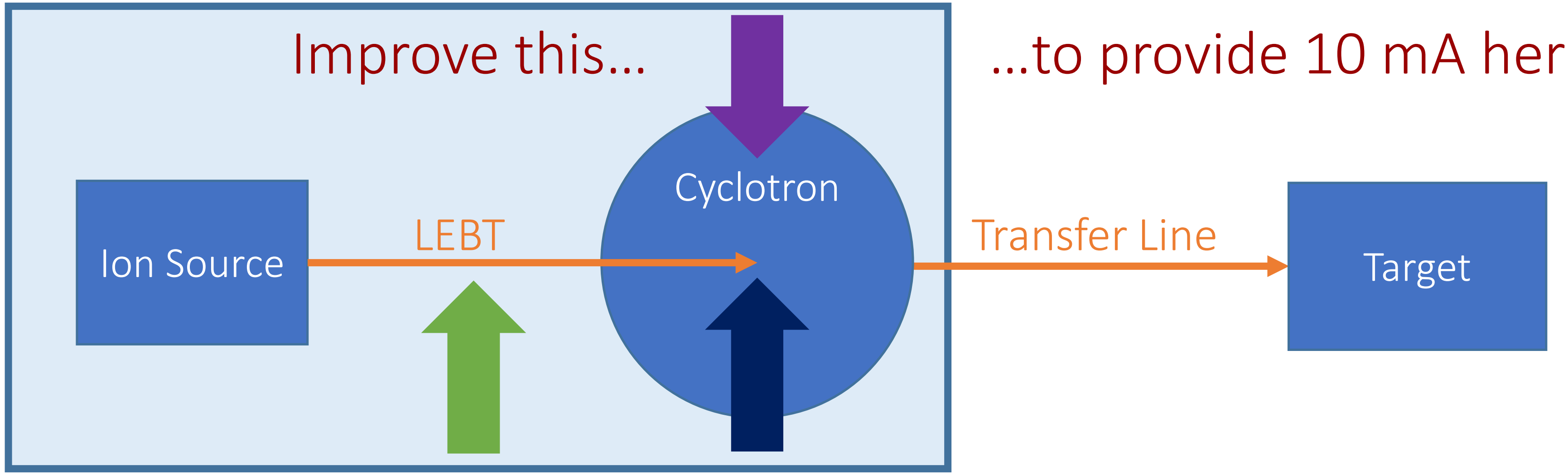


DW et al., **New J. Phys.** (2022) https://doi.org/10.1088/1367-2630/ac5001

But do we trust the simulations?

- Three important benchmark studies:
  - LEBT
  - Spiral Inflector
  - Cyclotron

In order to have the highest realism, PIC codes are necessary!
→ OPAL and WARP



PIC
"Particle-In-Cell"
A method to solve the collisionless Vlasov Equation.

But do we trust the simulations? Yes!

- Three important benchmark studies:
  - LEBT - WARP excellent agreement with measurements ✓

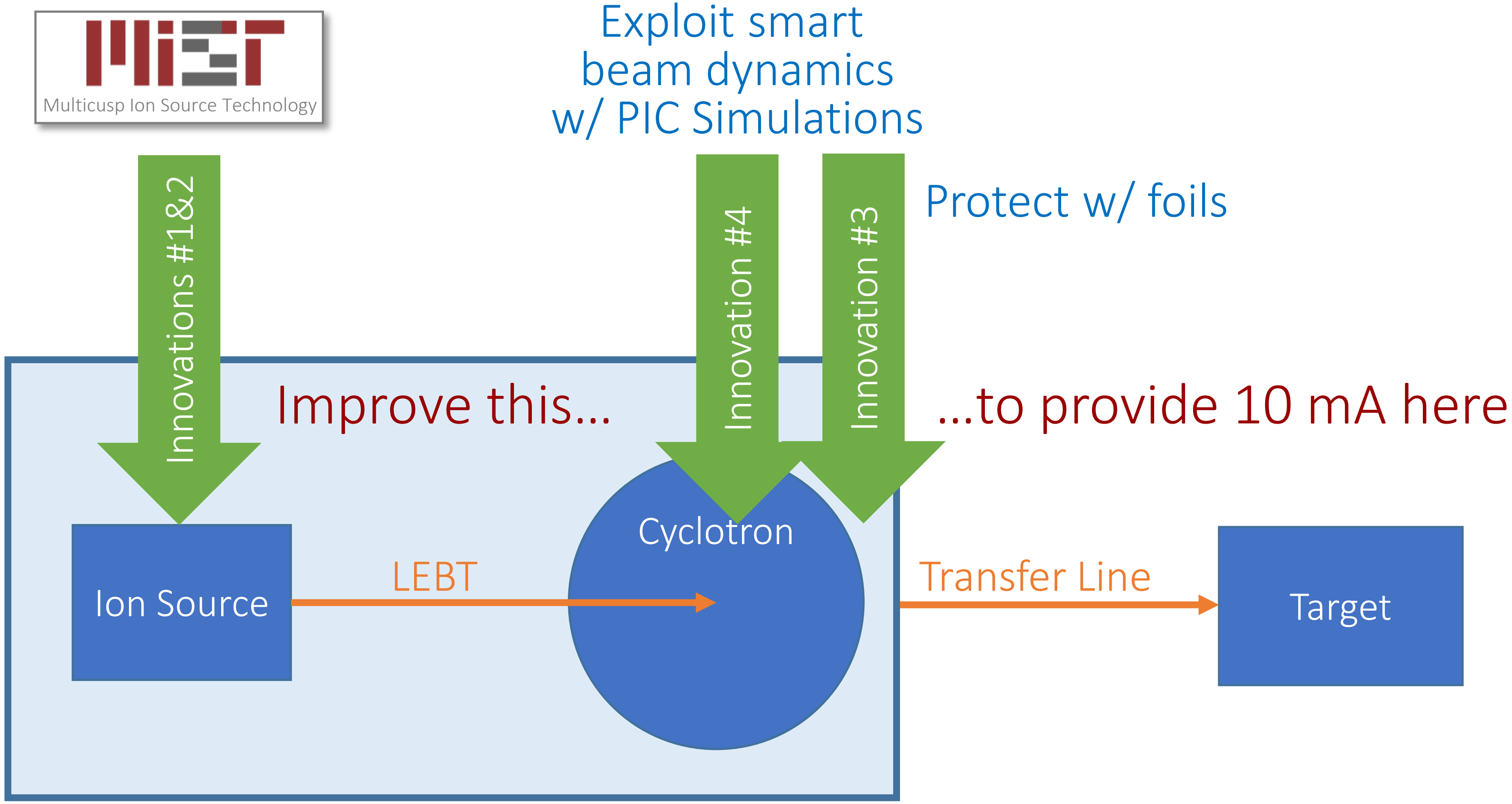
    DW et al. **JINST** (2015) arXiv:1508.03850
  - Spiral Inflector – New OPAL module, benchmarked against theory and experiment ✓

    DW et al. **Phys. Rev. AB** (2017) https://arxiv.org/abs/1612.09018
  - Cyclotron – OPAL has been heavily benchmarked against PSI and other experiments ✓

    Yang et al. **PRSTAB** (2010) PhysRevSTAB.13.064201

    Adelmann et al. *The OPAL Code* (2019) https://arxiv.org/abs/1905.06654

What building blocks can we improve?



Multicusp Ion Source Technology

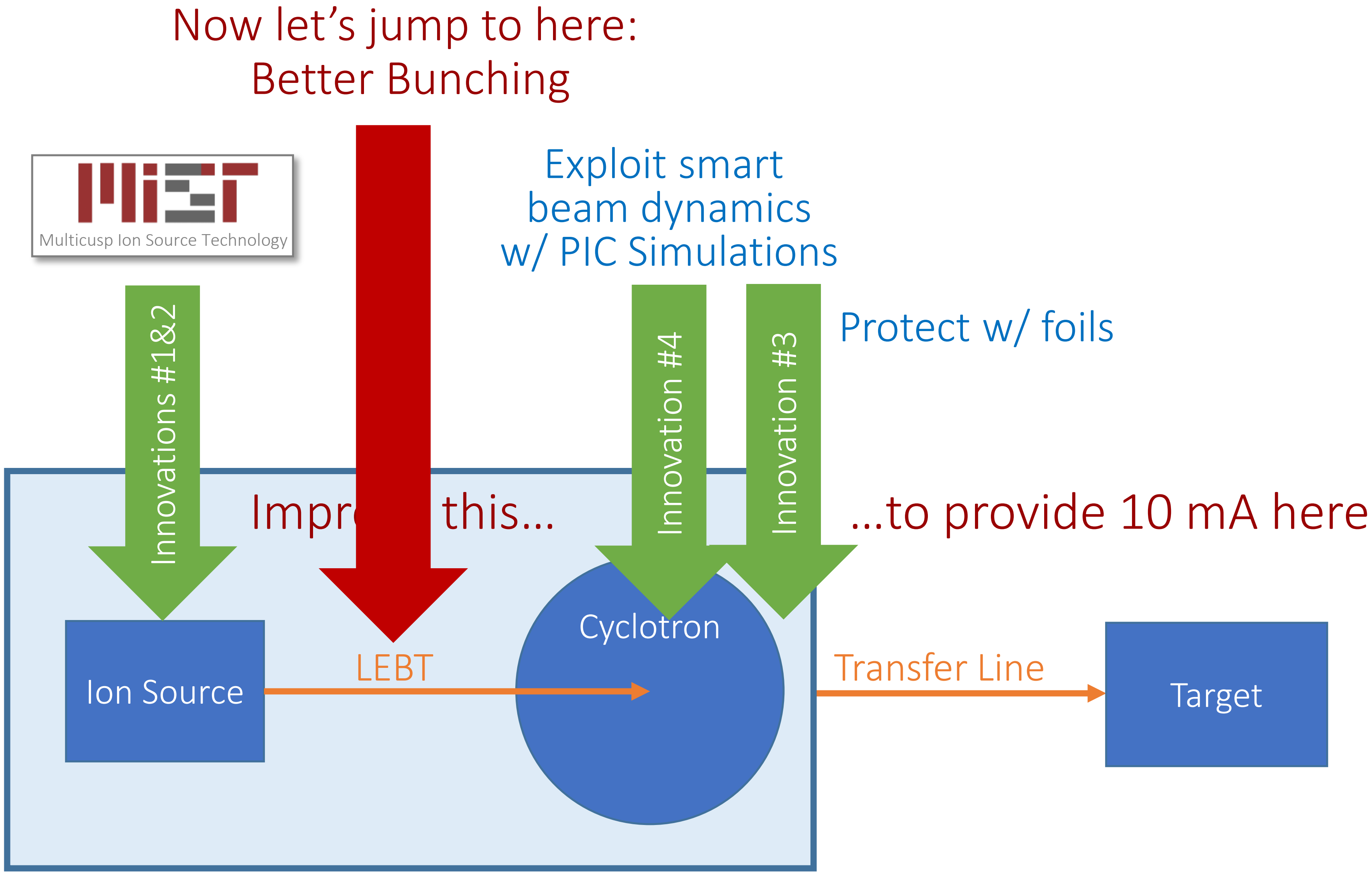
Exploit smart beam dynamics w/ PIC Simulations

Protect w/ foils

Improve this…

…to provide 10 mA here

What building blocks can we improve?



Now let's jump to here:
Better Bunching

Multicusp Ion Source Technology

Exploit smart
beam dynamics
w/ PIC Simulations

Protect w/ foils

Innovations #1&2

Innovation #4

Innovation #3

Impr this…

…to provide 10 mA here

Ion Source

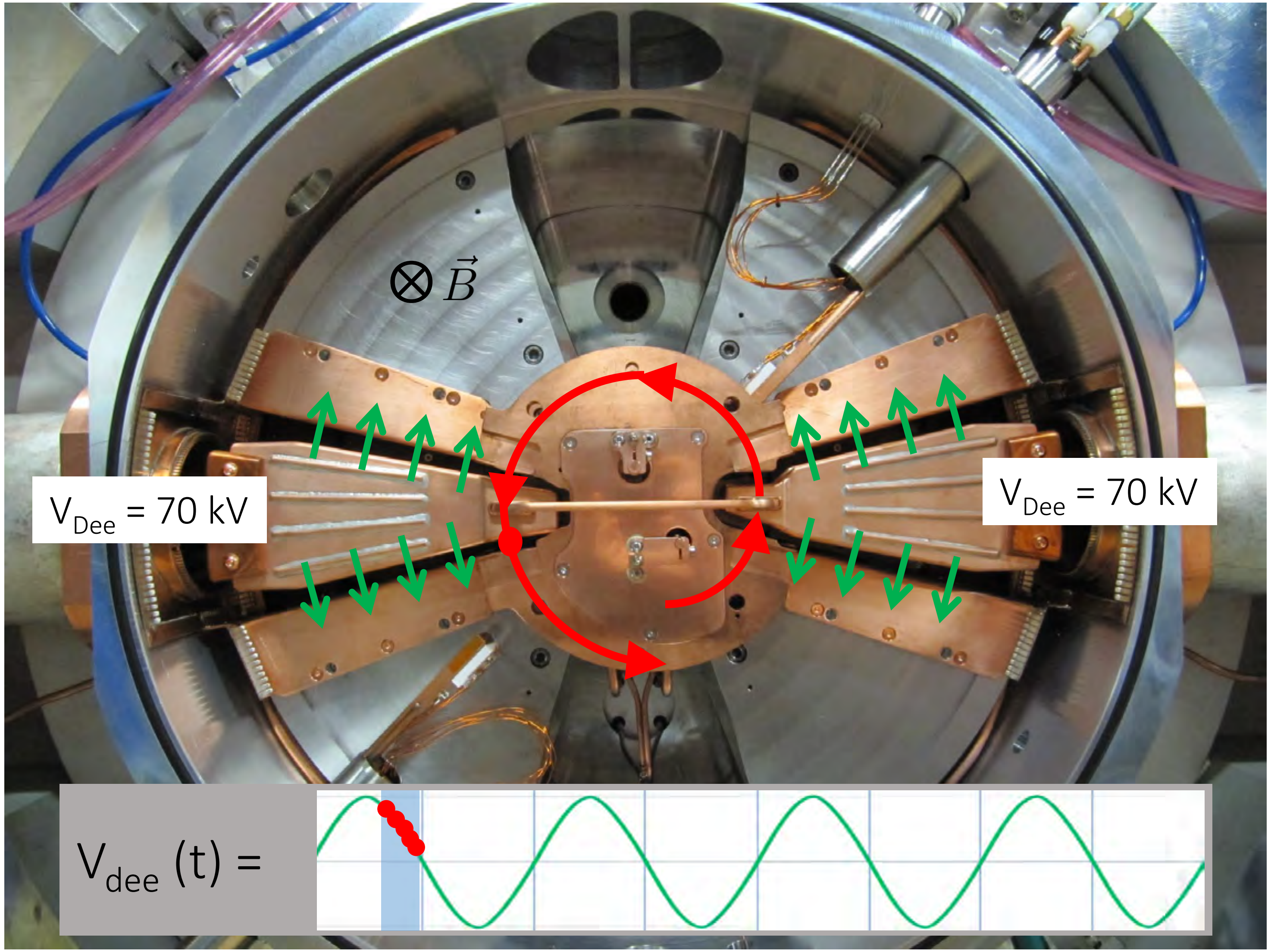
LEBT

Cyclotron

Transfer Line

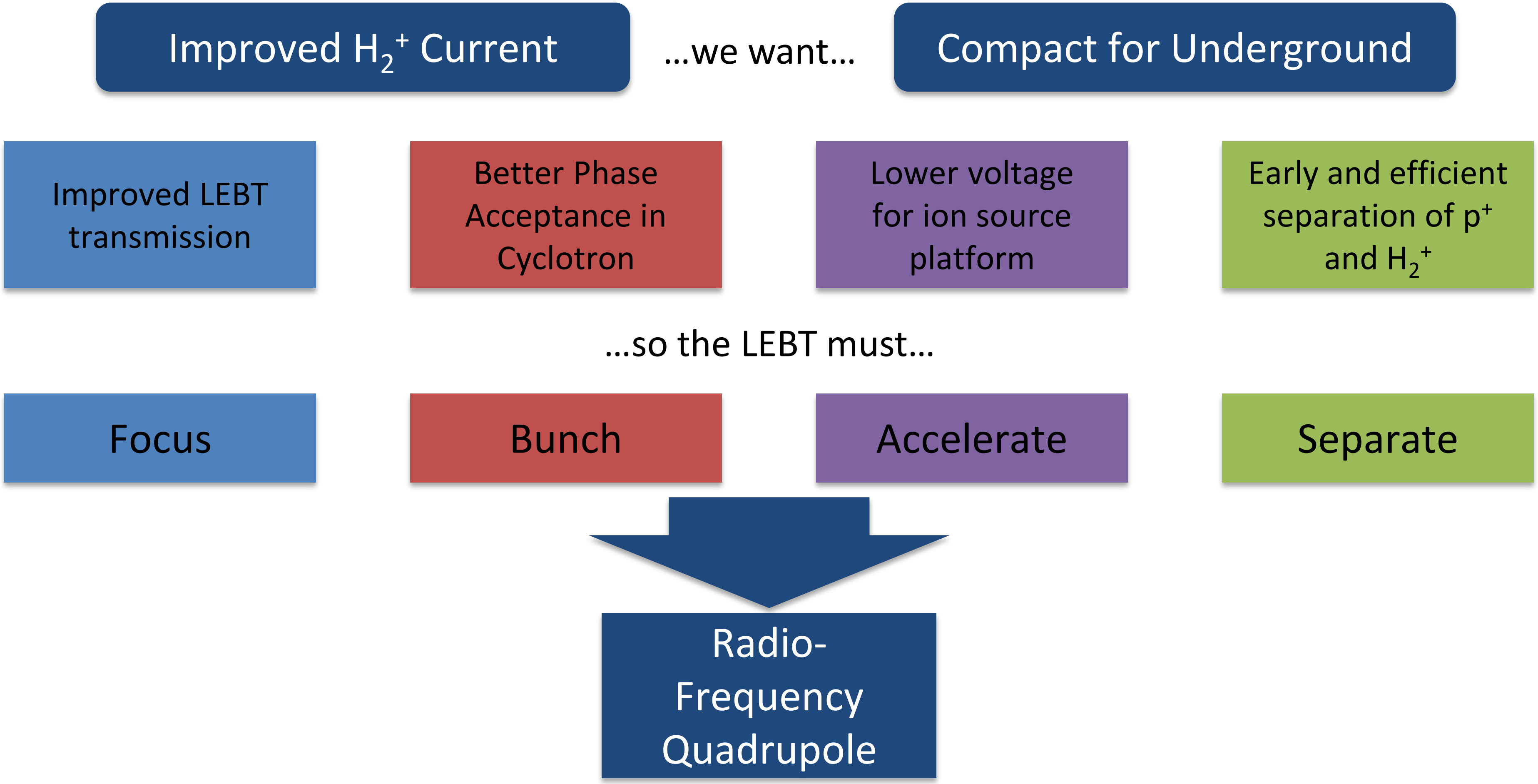
Target

Only a narrow phase window can be populated



Phase Acceptance
Window in RF wave space that can safely be populated

How can we improve phase acceptance and make our system more compact? → RFQ Bunching



Improved H_2^+ Current …we want… Compact for Underground

Improved LEBT transmission

Better Phase Acceptance in Cyclotron

Lower voltage for ion source platform

Early and efficient separation of p^+ and H_2^+

…so the LEBT must…

Focus

Bunch

Accelerate

Separate

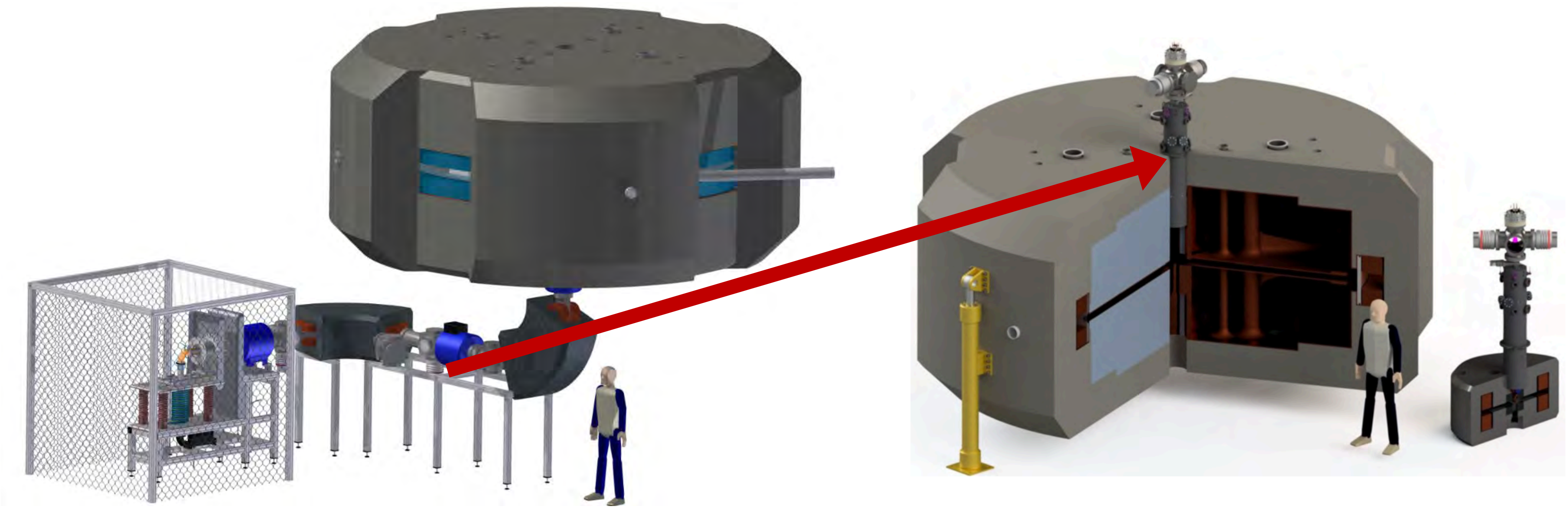
Radio-Frequency Quadrupole

Caveat: Because of the strong bunching and tight focusing, the bunches begin to spread quickly after the RFQ

→ Direct Injection

Innovation #5: RFQ-DIP

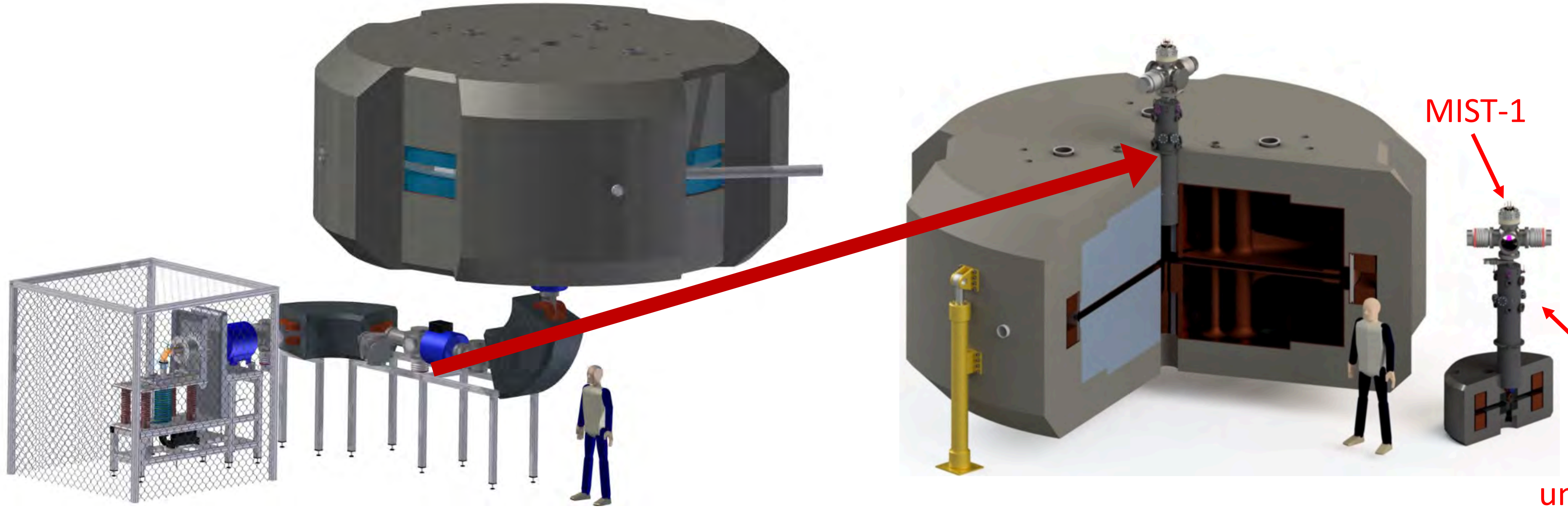
- Radio Frequency Quadrupole – Direct Injection Project



DW et al. **RSI** (2016) https://aip.scitation.org/doi/abs/10.1063/1.4935753
DW et al. **NIMA** (2018) https://arxiv.org/abs/1807.03759
DW et al. **JACoW** IPAC2021-TUXB07 (2021) https://inspirehep.net/literature/1962316

Innovation #5: RFQ-DIP

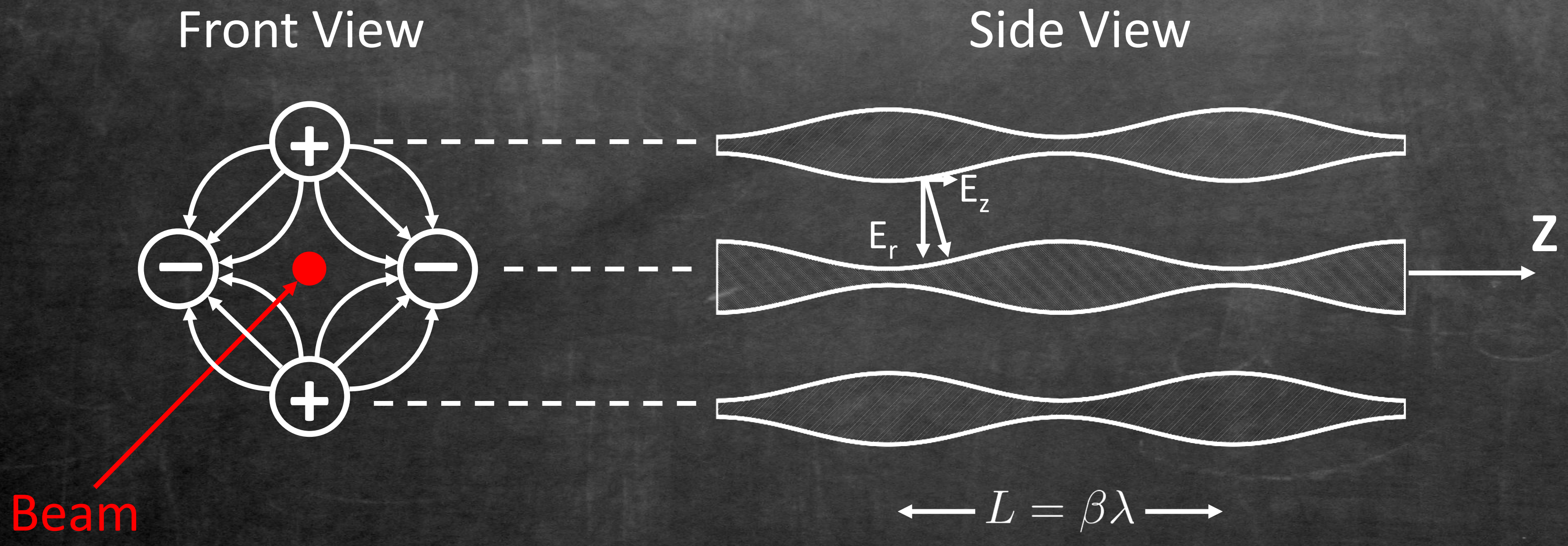
- Radio Frequency Quadrupole – Direct Injection Project


MIST-1

NSF-Funded
RFQ Prototype
under construction

DW et al. **RSI** (2016) https://aip.scitation.org/doi/abs/10.1063/1.4935753
DW et al. **NIMA** (2018) https://arxiv.org/abs/1807.03759
DW et al. **JACoW** IPAC2021-TUXB07 (2021) https://inspirehep.net/literature/1962316

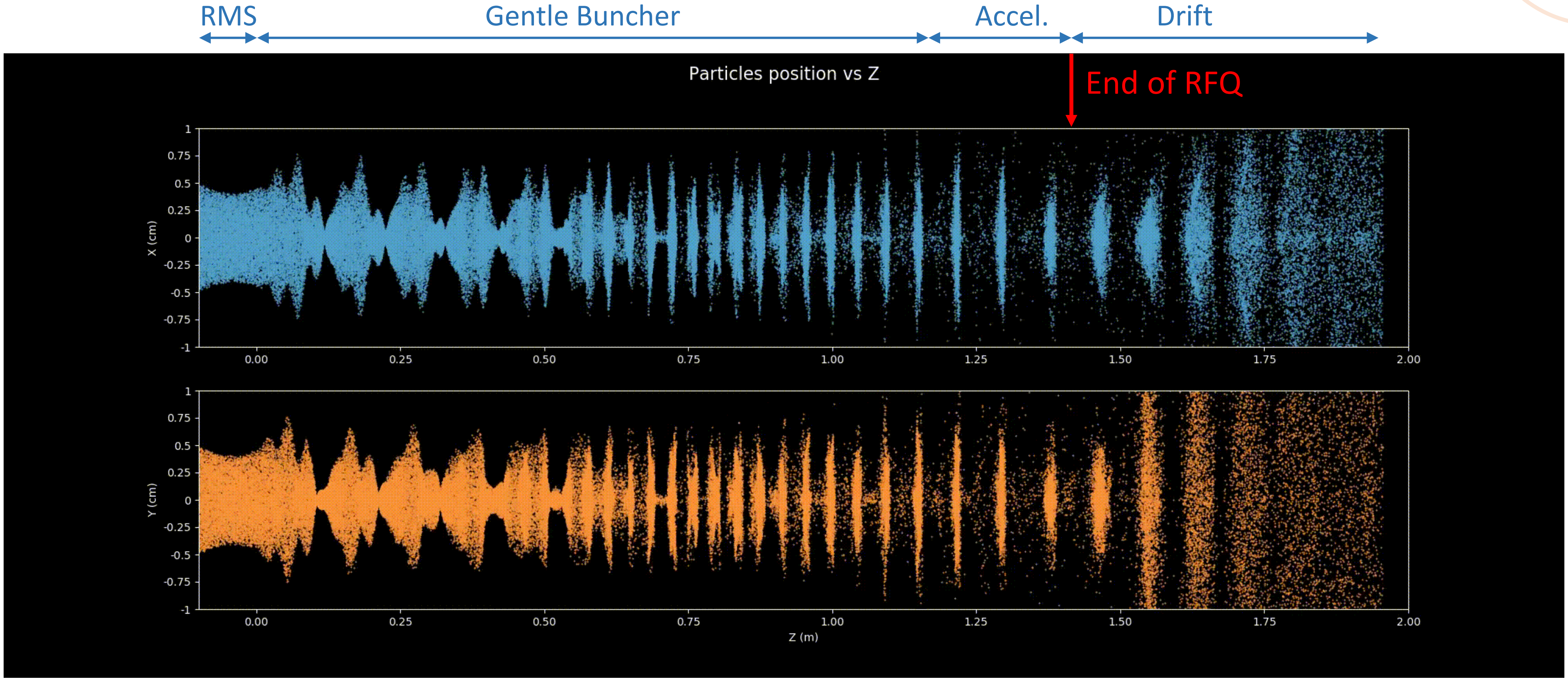
RFQ General Principle



$$\mathrm{V}(t) = \mathrm{V}_{\mathrm{max}} \cdot \cos(\omega_{\mathrm{RF}} \cdot t - \Phi_S)$$

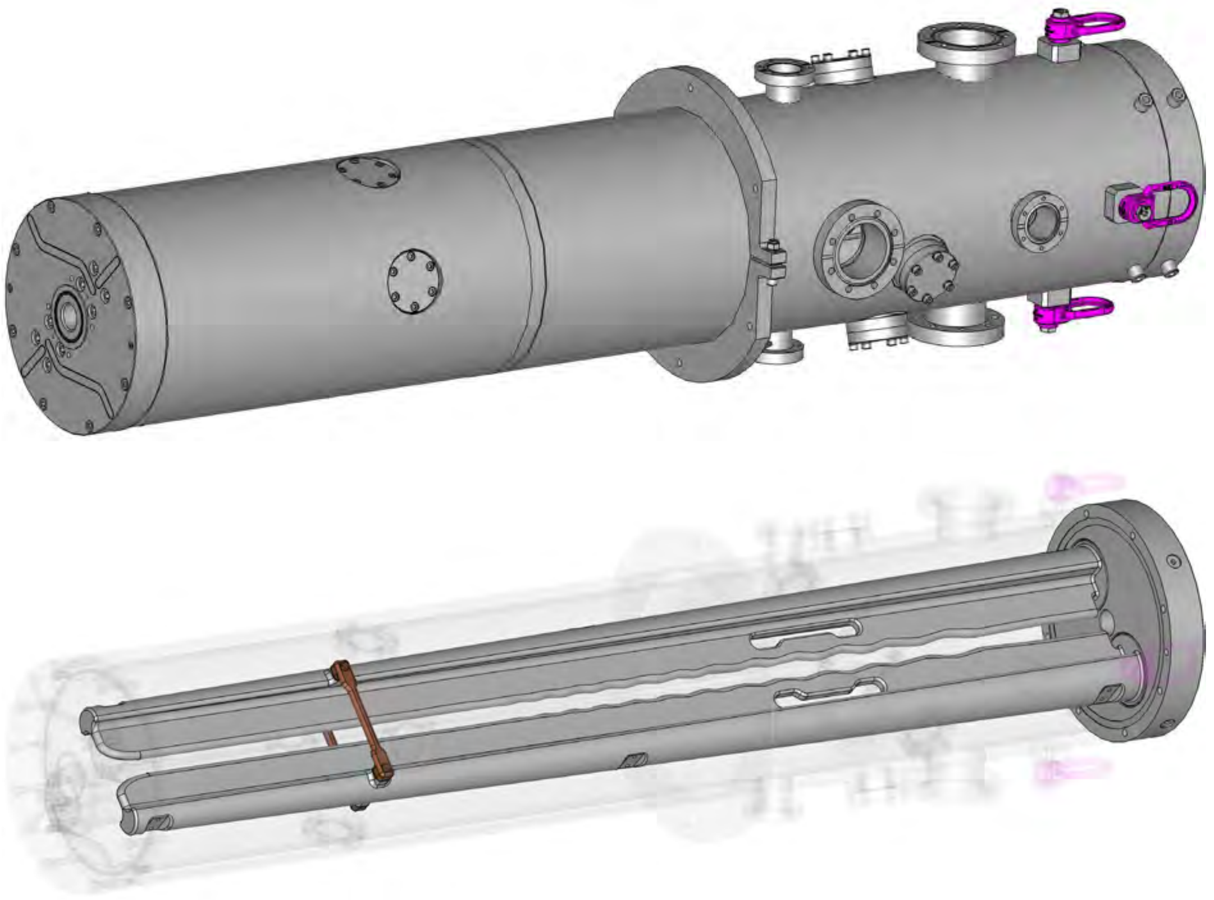
- Continuous focusing like in a series of alternating F/D Electrostatic quadrupoles
- Wiggles lead to acceleration and bunching (RF bunching similar to cyclotron)
- Same frequency as cyclotron (32.8 MHz)

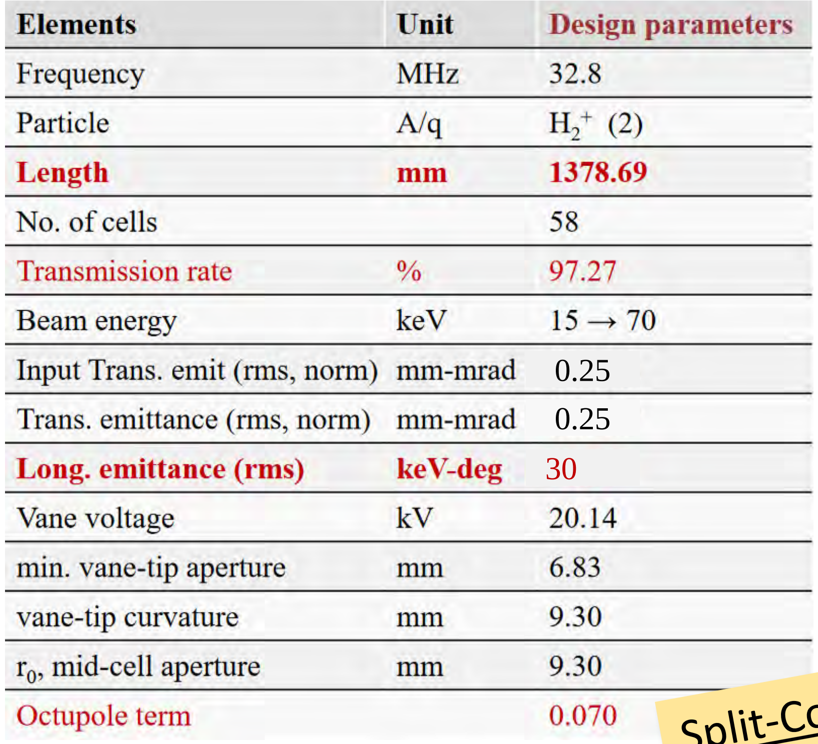
Particles are continuously focused transversally, while being bunched longitudinally



Highly accurate particle in cell (PIC) simulations using well-established WARP code
Cave: Older simulation, not a well-matched beam!

Split-coaxial RFQ bunches the beam at 32.8 MHz





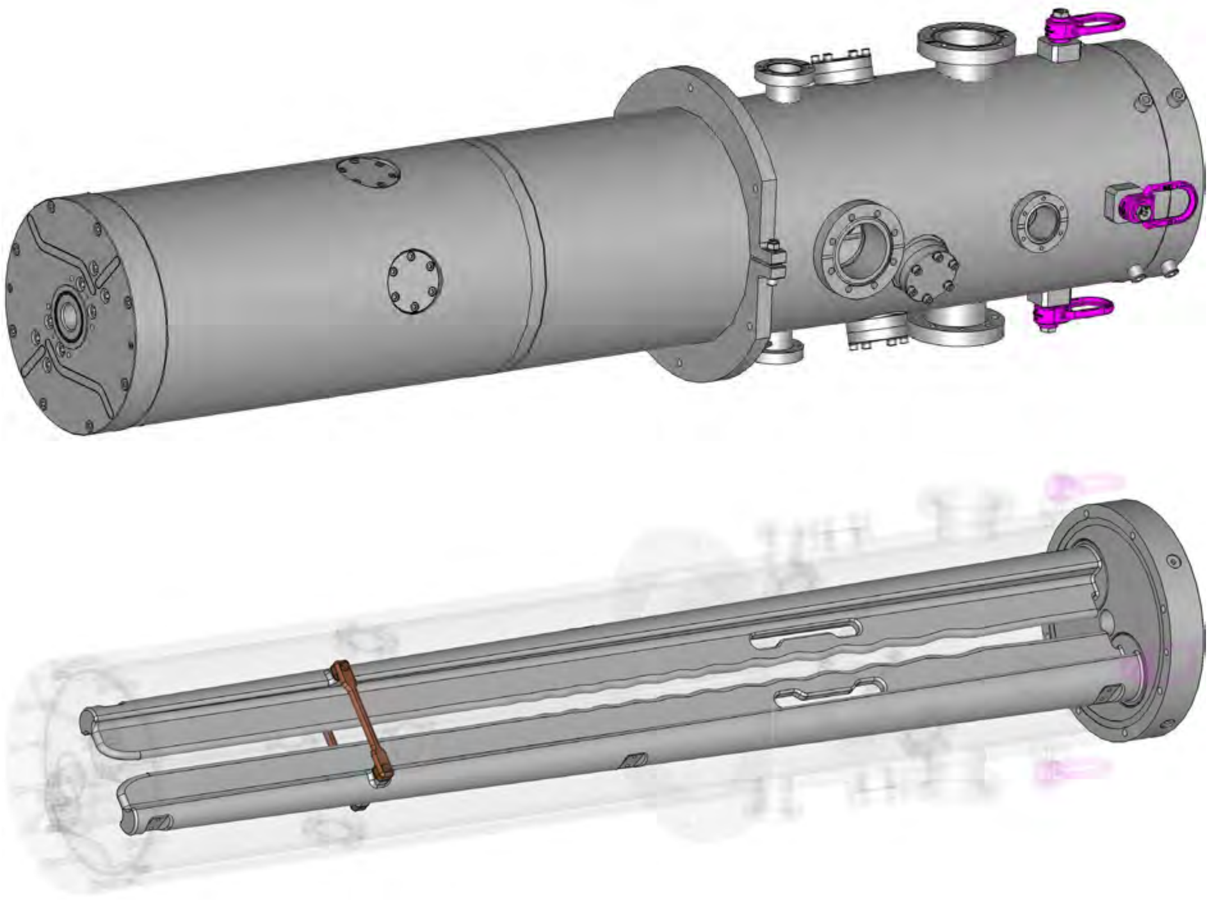
Elements	Unit	Design parameters
Frequency	MHz	32.8
Particle	A/q	H_2^+ (2)
Length	**mm**	**1378.69**
No. of cells		58
Transmission rate	%	97.27
Beam energy	keV	15 → 70
Input Trans. emit (rms, norm)	mm-mrad	0.25
Trans. emittance (rms, norm)	mm-mrad	0.25
Long. emittance (rms)	**keV-deg**	30
Vane voltage	kV	20.14
min. vane-tip aperture	mm	6.83
vane-tip curvature	mm	9.30
r_0, mid-cell aperture	mm	9.30
Octupole term		0.070
Power:	kW	< 6

Split-Coaxial RFQ
Eigenmode of tank allows low frequency with small diameter

Technical Design by Bevatech, GmbH, Germany

7 Papers at the IPAC'21 Conference

Split-coaxial RFQ bunches the beam at 32.8 MHz



Elements	Unit	Design parameters
Frequency	MHz	32.8
Particle	A/q	H_2^+ (2)
Length	**mm**	**1378.69**
No. of cells		58
Transmission rate	%	97.27
Beam energy	keV	15 → 70
Input Trans. emit (rms, norm)	mm-mrad	0.25
Trans. emittance (rms, norm)	mm-mrad	0.25
Long. emittance (rms)	**keV-deg**	30
Vane voltage	kV	20.14
min. vane-tip aperture	mm	6.83
vane-tip curvature	mm	9.30
r_0, mid-cell aperture	mm	9.30
Octupole term		0.070
Power:	kW	< 6

Split-Coaxial RFQ
Eigenmode of tank allows low frequency with small diameter

Technical Design by Bevatech, GmbH, Germany

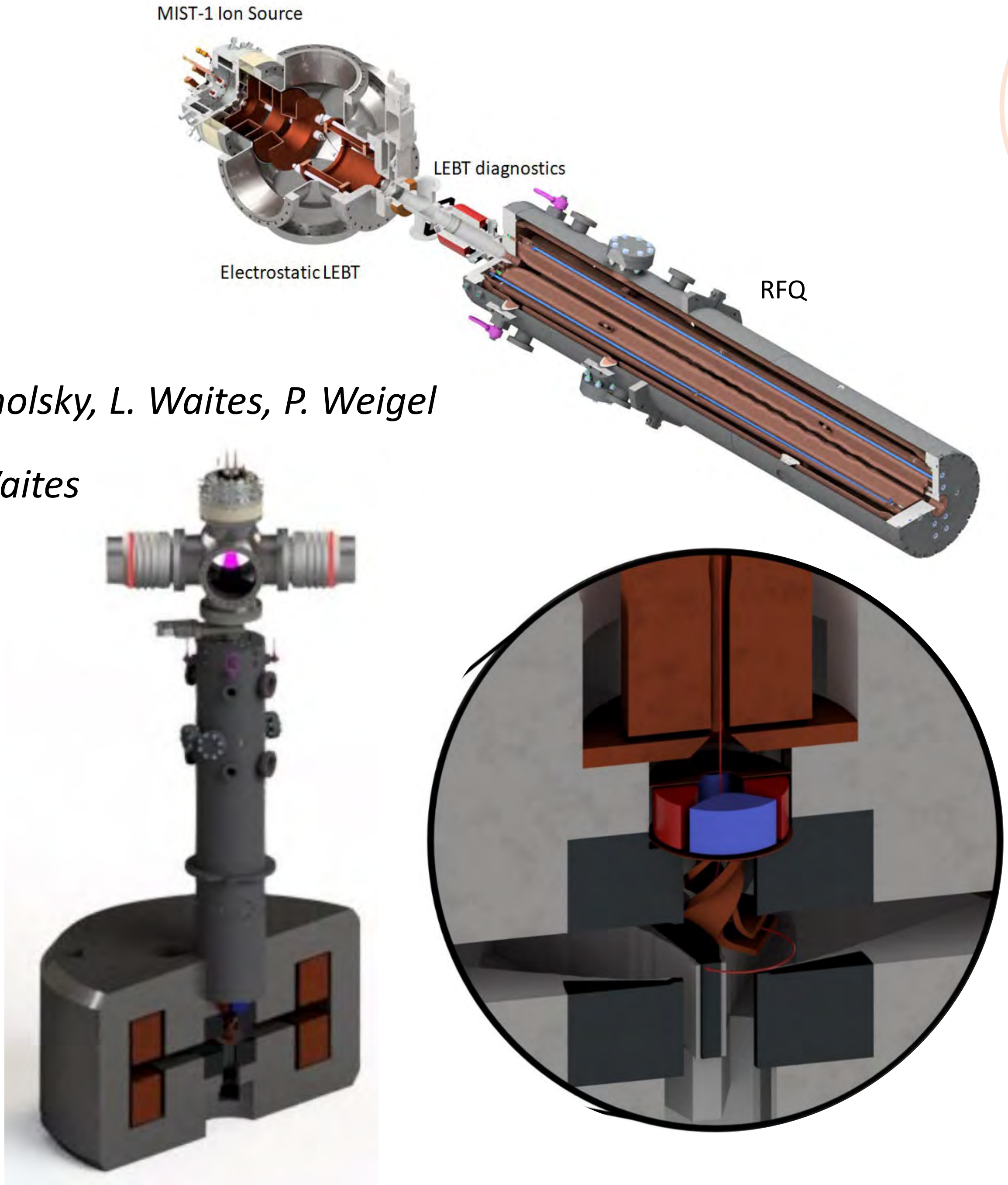
7 Papers at the IPAC’21 Conference

RFQ-DIP Prototype

Radiofrequency Quadrupole –
Direct Injection Project

- Ion Source (MIST-1) *S. Axani, J. Smolsky, L. Waites, P. Weigel*
- Mini-ES-LEBT (Chop/Steer) *L. Waites*
- RFQ *JB. Bahng, D. Koser, M. Sangroula*
- Injection (re-focusing) *P. Weigel*
- 1 MeV/amu test cyclotron
- Diagnostics

- This is the needed experimental verification of RFQ-DIP & vortex motion



MachineLearning() – Why “Surrogate Models”

- Particle accelerator simulations can be complex with large sets of input parameters
- Optimization requires repeated evaluation of points in parameter-hyperspace.
- Surrogate model: train neural net on sparse set of points in this hyperspace
- Evaluation of surrogate model is orders of magnitude faster than original simulation
  - Optimization
  - Real-Time Feedback

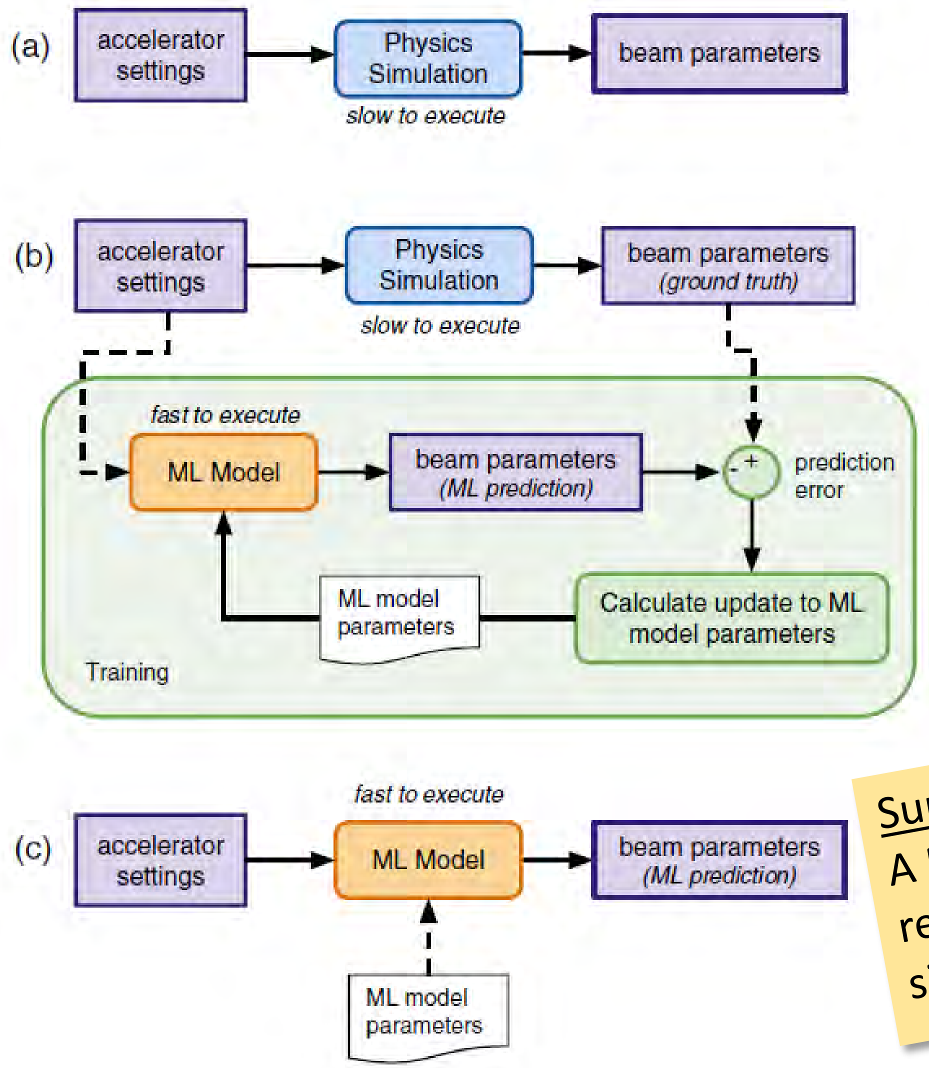
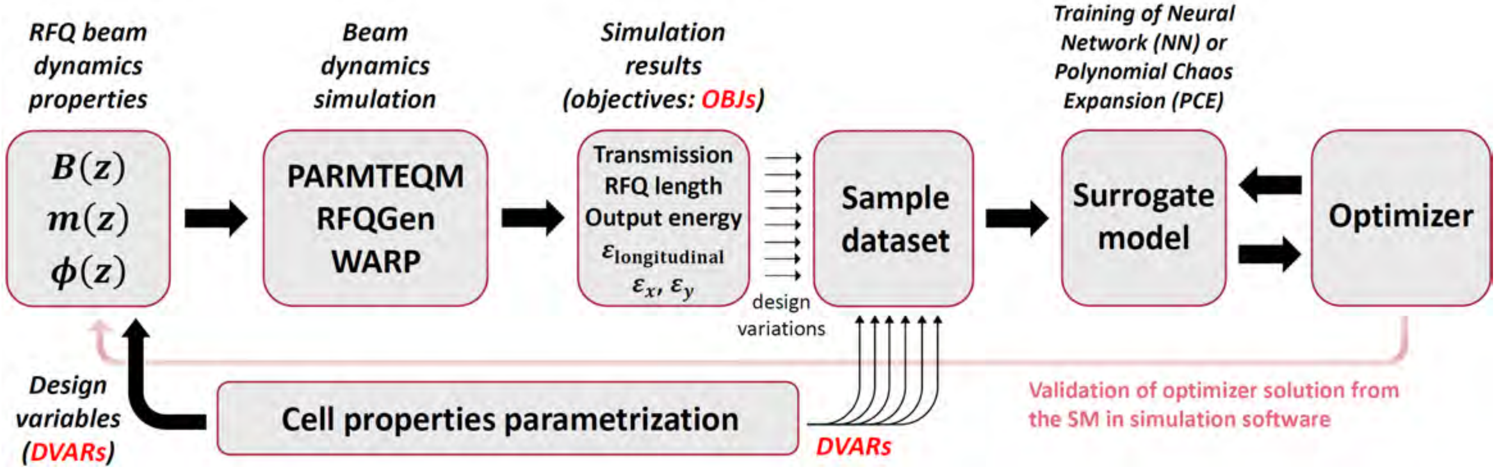


Image: A. Edelen et al. **PRAB** 23, 044601 (2020)

__Surrogate Model__
A ML-trained NN to replace costly PIC simulations.

MachineLearning() - RFQ



RFQ beam dynamics properties

$B(z)$
$m(z)$
$\phi(z)$

Beam dynamics simulation

PARMTEQM
RFQGen
WARP

Simulation results (objectives: OBJs)

Transmission
RFQ length
Output energy
$\varepsilon_{\text{longitudinal}}$
$\varepsilon_x, \varepsilon_y$

design variations

Sample dataset

Training of Neural Network (NN) or Polynomial Chaos Expansion (PCE)

Surrogate model

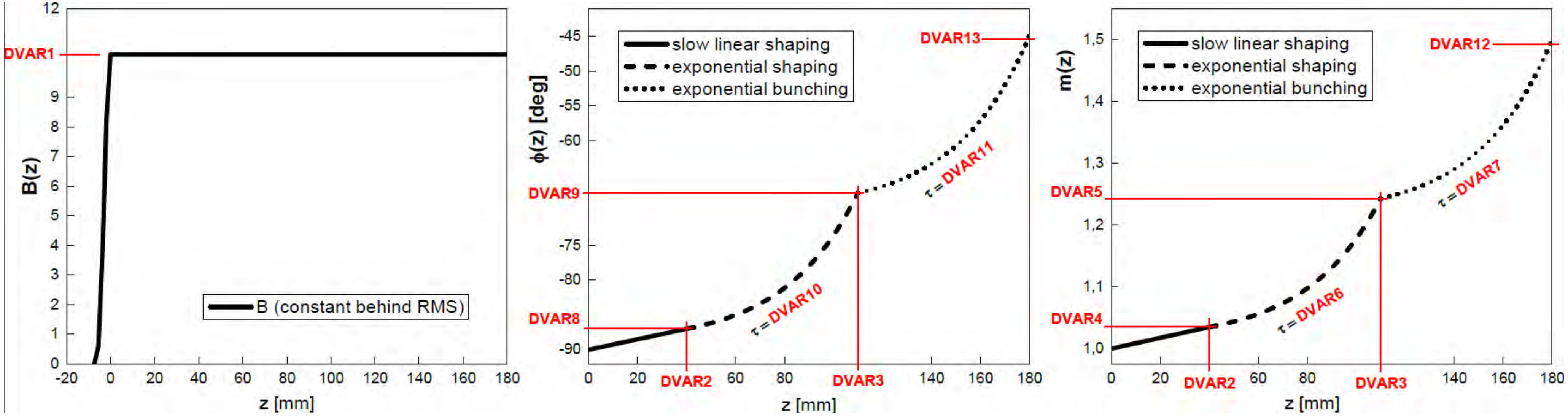
Optimizer

Design variables (DVARs)

Cell properties parametrization

DVARs

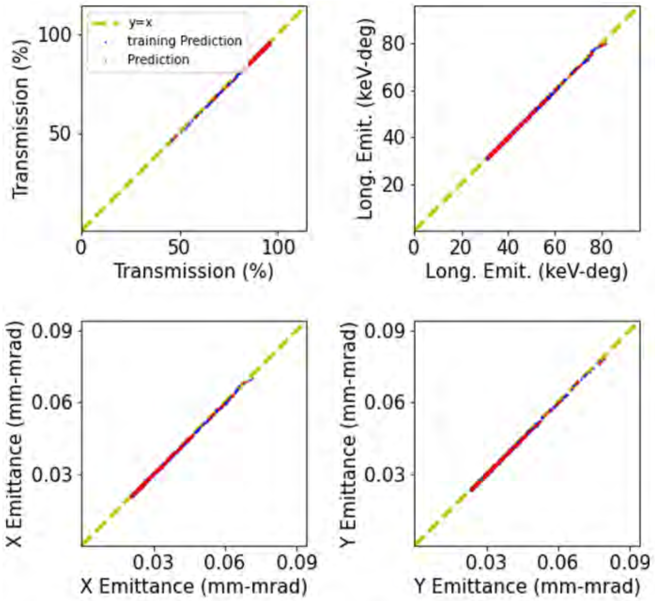
Validation of optimizer solution from the SM in simulation software



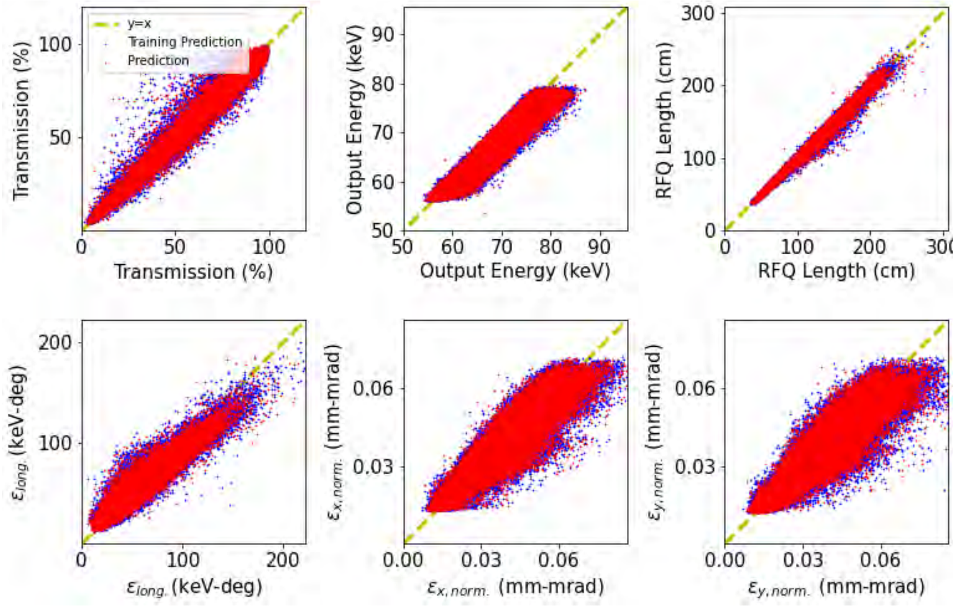
Koser et al. **Front. Phys.** (2022) https://arxiv.org/abs/2112.02579

MachineLearning() - RFQ

- Excellent results for Twiss parameters
- Bodes well for tuning assistant



- Challenges with RFQ mechanical design prediction
- Interesting avenue of research!
- Can already be used to restrict parameter space for optimization



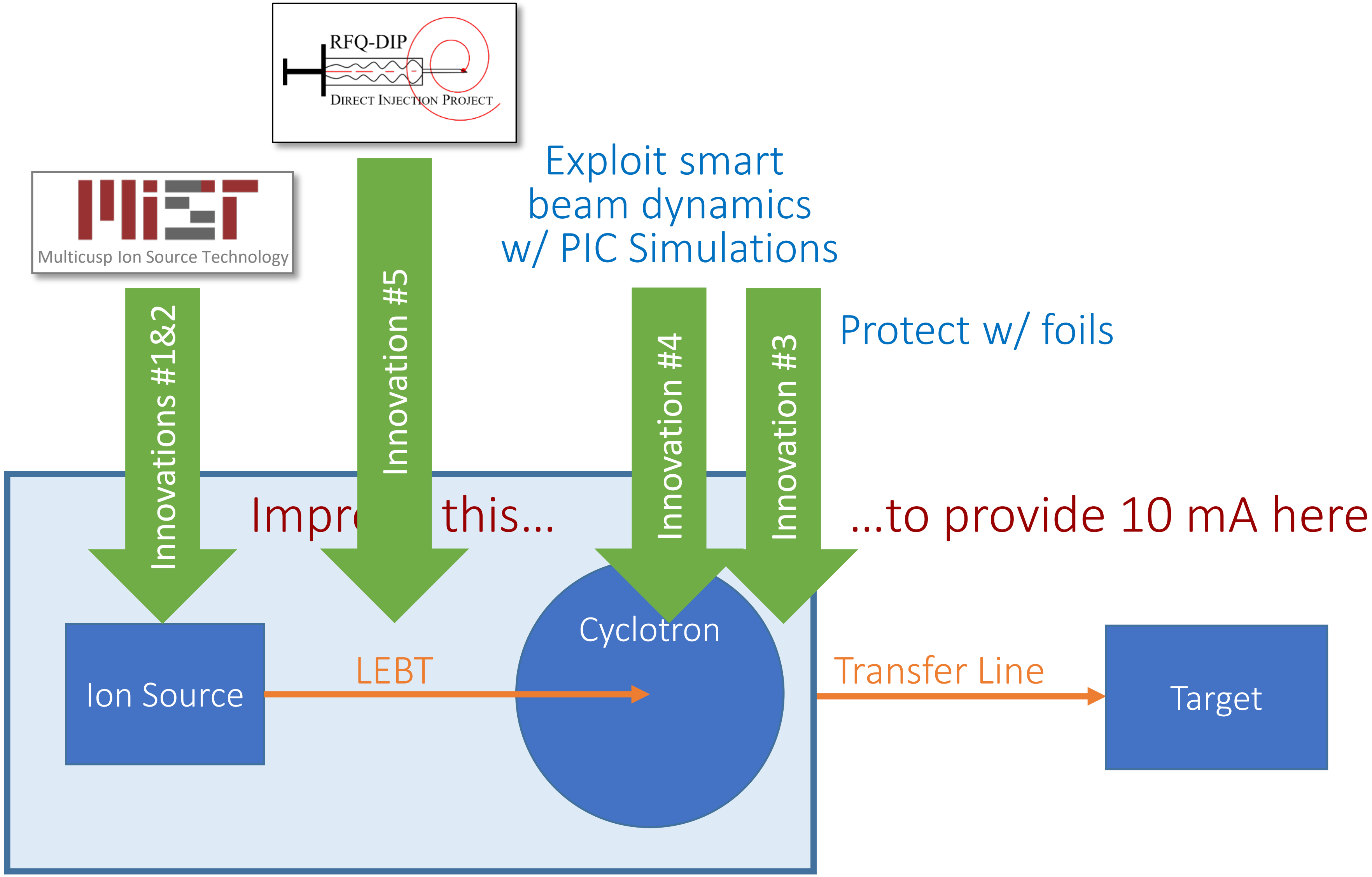
Koser et al. **Front. Phys.** (2022) https://arxiv.org/abs/2112.02579

Wishlist for IsoDAR – Use Surrogate Models for

- Optimizing the LEBT and matching of the beam to the RFQ
  - Test-problem
  - Have decent solution for comparison, few parameters clear goal.
- RFQ Optimization and beam prediction ✓ https://arxiv.org/abs/2112.02579
- Optimizing spiral inflector and central region
  - Larger set of parameters (SI voltage, tilt, gap, focusing, RF phases, angles…)
  - Somewhat involved process (generate CAD model, FEM for fields, run in OPAL…)
- Full cyclotron optimization and uncertainty quantification ✓

  https://arxiv.org/abs/2103.09352
- Add together into start-to-end model for "Virtual Accelerator" for assistance during commissioning and tuning at run-time.

What building blocks can we improve?



RFQ-DIP

Direct Injection Project

Multicusp Ion Source Technology

Innovations #1&2

Innovation #5

Exploit smart beam dynamics w/ PIC Simulations

Innovation #4

Innovation #3

Protect w/ foils

Impr this…

…to provide 10 mA here

Ion Source

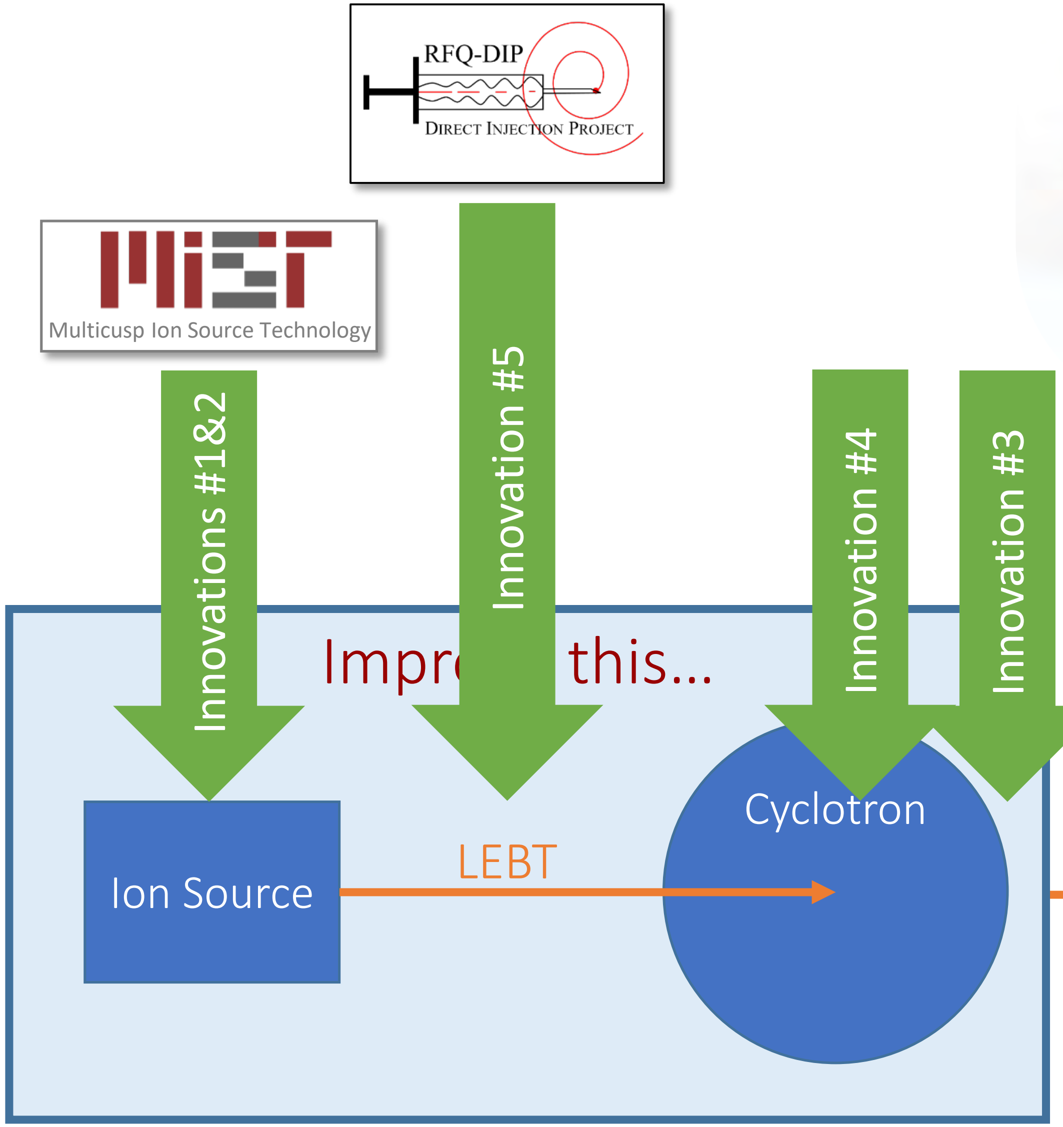
LEBT

Cyclotron

Transfer Line

Target

What building blocks can we improve?



Multicusp Ion Source Technology

RFQ-DIP

Direct Injection Project

Innovations #1&2

Innovation #5

Innovation #4

Innovation #3

Impr this…

…to provide 10 mA here

Ion Source

LEBT

Cyclotron

Transfer Line

Target

We have designed the IsoDAR Cyclotron!

Coming soon to a cavern ~~near you~~!

In South Korea

Outline

- Original Motivation: IsoDAR neutrino physics
  → In a few years this will yield very exciting particle physics

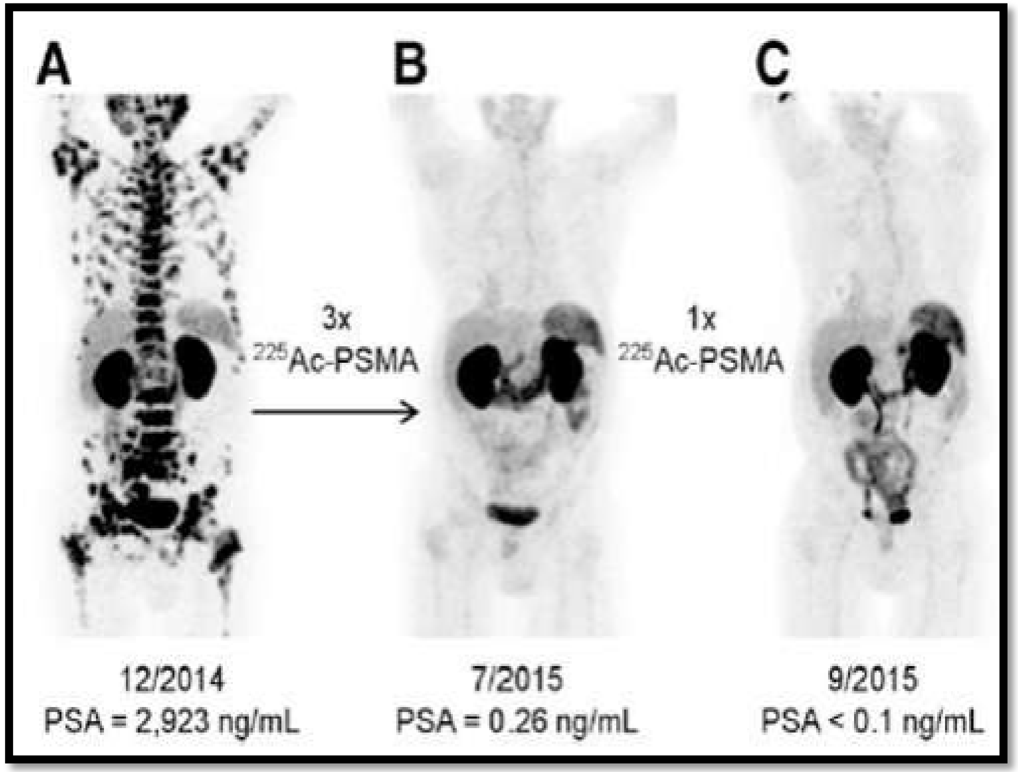
- Cyclotrons "101"
- The physics challenges of high intensity beams
  → How we are changing the game

- More Applications:
  - Medical Isotopes, Materials, … I will cover this now
  - Multi-Megawatt beams for Particle Physics and ADS … ask me later

IsoDAR can produce relatively rare medical isotopes

- Few 60 MeV/amu accelerators,
  - On market machines < 1 mA
  - Lab-based accelerators are not at dedicated facilities
  - Our cyclotons can be built by consortia of hospitals

- There is real need for...
  - ^{68}Ge/^{68}Ga: PET isotope
  - ^{225}Ac: Alpha emitter

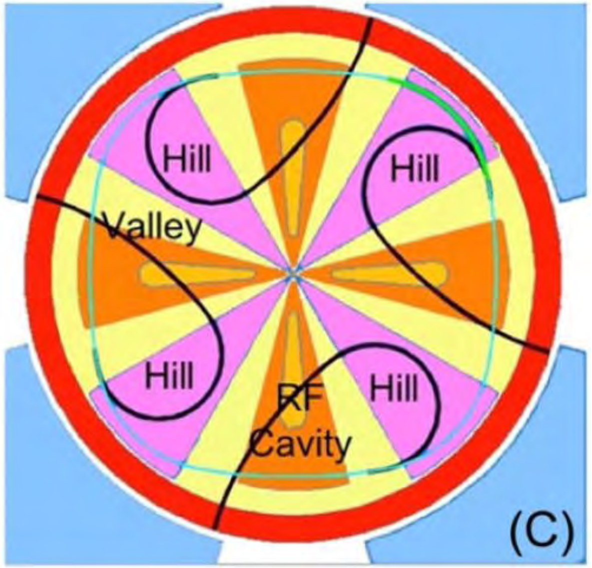


J. Alonso et al. **Nature** (2019) https://www.nature.com/articles/s42254-019-0095-6
L. Waites et al. **EJNMMI** (2020) https://doi.org/10.1186/s41181-020-0090-3

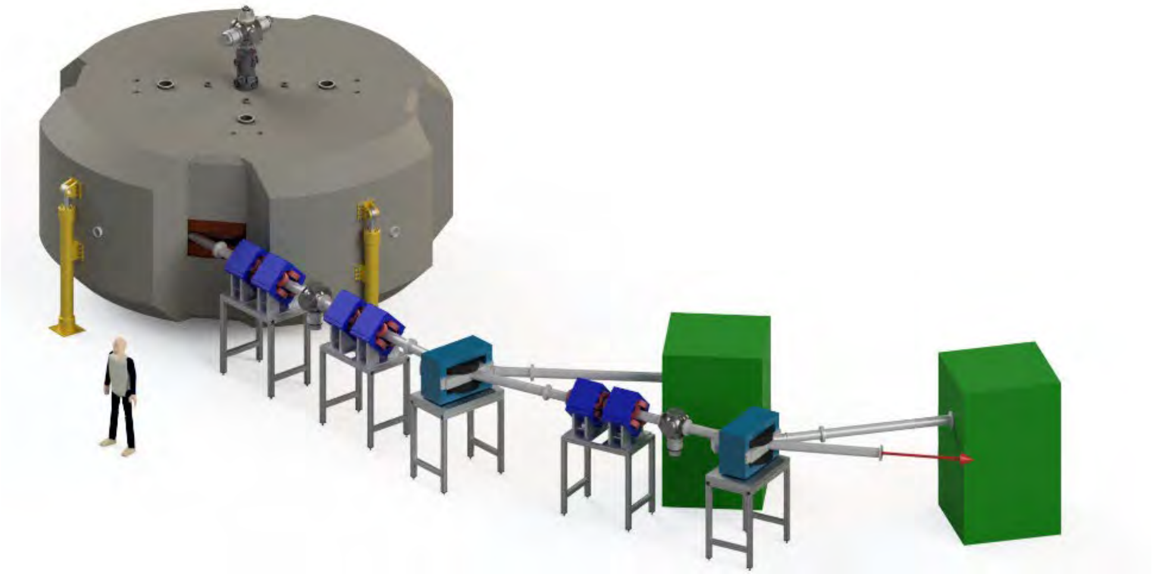
IsoDAR will produce 10 mA @ 60 MeV... Can isotope targets handle that?

- No, at least not at the moment
- But H_2^+ gives another option... Split the beam between many targets

split internally...

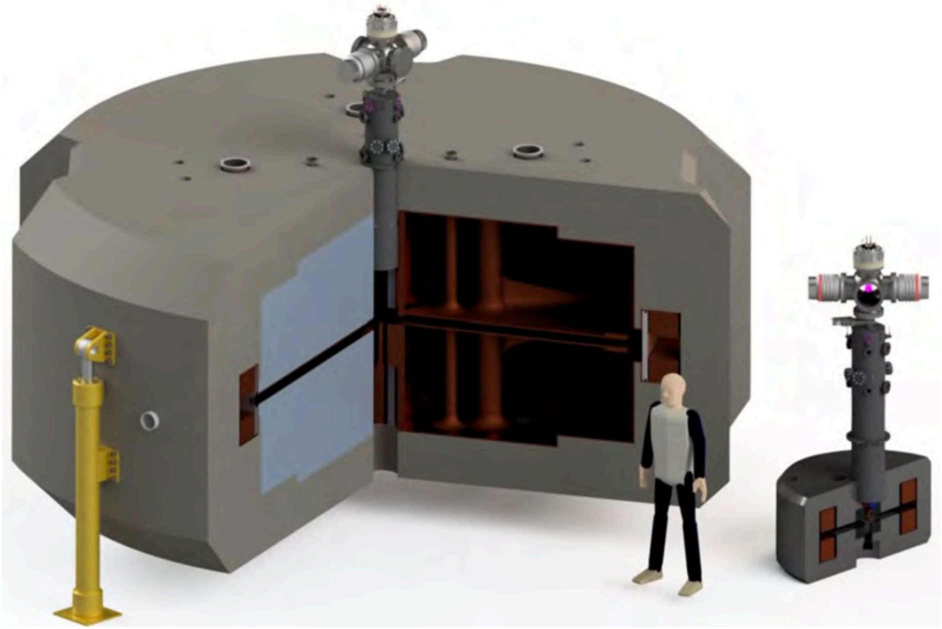


Or split externally



But wait, there's more!

- Exploring medical isotope production with other ions with m/q = 2
- Innovations are upstream of ~1.5 MeV/amu
- Same design works from 1 to 60 MeV/amu ... A family of cyclotrons!
  → A wide range of isotopes...



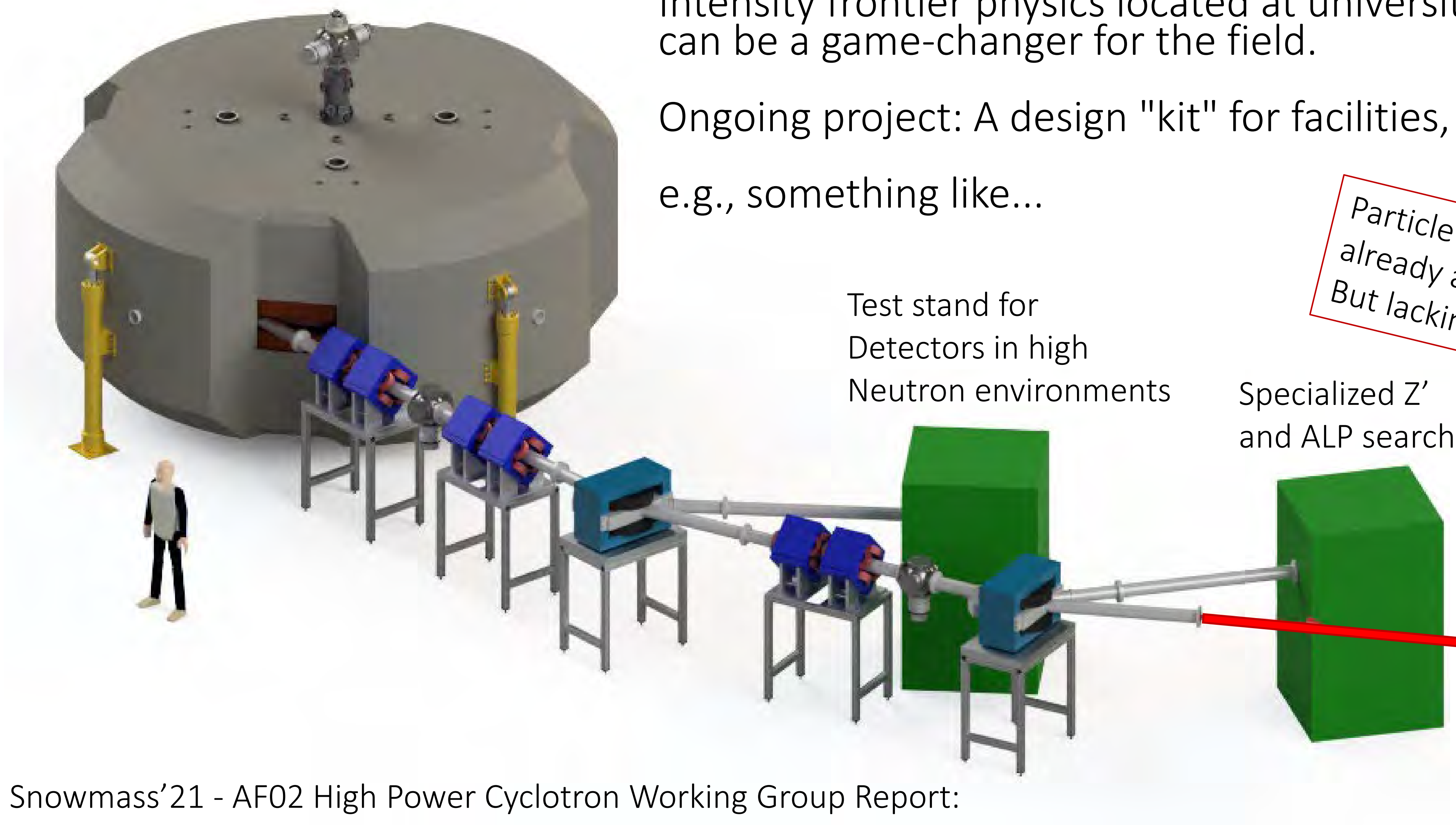
Also → Local facilities for particle physics!

Intensity frontier physics located at universities can be a game-changer for the field.

Ongoing project: A design "kit" for facilities,

e.g., something like...

Particle physics needs/concepts already appearing on arXiv, But lacking a source to run!



Test stand for Detectors in high Neutron environments

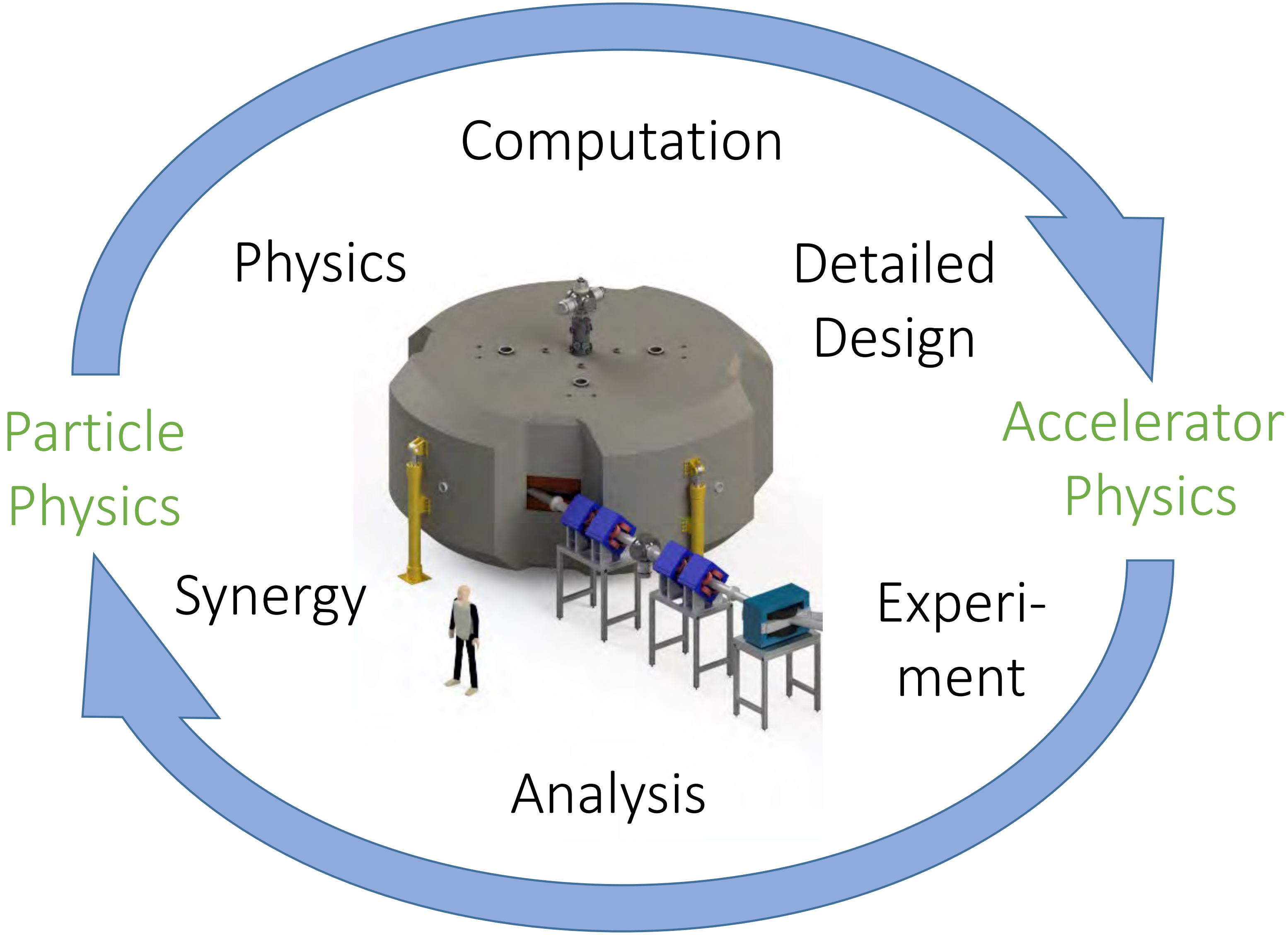
Specialized Z’ and ALP searches

DAR flux for Coherent Scattering...

...Other examples

Snowmass’21 - AF02 High Power Cyclotron Working Group Report: https://arxiv.org/abs/2203.07919 (lots of PSI input!)

In Summary...



Computation

Physics

Detailed Design

Particle Physics

Accelerator Physics

Synergy

Experiment

Analysis

Planned milestones in next 10 years

- Machine Learning:
  - Surrogate Model for ion source/LEBT tuning - 2022
  - First demonstration of ML-assisted RFQ design – 2023
  - Followed by new ML developments and proofs of principle.
- Machines:
  - 3.5 MeV machine – first-of-its-kind complete prototype – 2025 (Above-ground test machine for IsoDAR running, isotopes)
  - "Kit" for design for any energy from 1 to 60 MeV – 2025
  - IsoDAR 60 MeV Cyclotron – completed by 2027
- Particle Physics:
  - IsoDAR, definitive experiment in exotic neutrino sector - 2032
- Many more applications to follow!
  - CP-violation, ADS, materials, isotopes…

References

- IsoDAR@Yemilab – CDR: IsoDAR Collaboration **arXiv** (2021) arxiv:2110.10635
- IsoDAR@Yemilab – Physics: J. Spitz et al. **PRD** (2022) arxiv:2111.09480
- Ion Source: Winklehner et al. **RSI** (2021) https://arxiv.org/abs/2008.12292
- RFQ-DIP: D. Winklehner et al. **RSI** (2016) https://aip.scitation.org/doi/abs/10.1063/1.4935753
- RFQ-DIP: D. Winklehner et al. **NIMA** (2018) https://arxiv.org/abs/1807.03759
- ML for RFQ: D. Koser et al. (submitted to Frontiers, 2022) https://arxiv.org/abs/2112.02579
- Spiral Inflector: D. Winklehner et al. **PRAB** (2017) https://arxiv.org/abs/1612.09018
- Cyclotron: Winklehner et al. **New Journ. Phys.** (2022) https://doi.org/10.1088/1367-2630/ac5001
- Isotopes: J. Alonso et al. **Nature** (2019) https://www.nature.com/articles/s42254-019-0095-6
- Isotopes: L. Waites et al. **EJNMMI** (2020) https://doi.org/10.1186/s41181-020-0090-3
- Target, ^{8}Li yield: A. Bungau et al. **arXiv** (2018) https://arxiv.org/abs/1805.00410
- Target, shielding: A. Bungau et al. **arXiv** (2019) https://arxiv.org/abs/1909.08009
- First experimental tests: Winklehner et al. **JINST** (2015) arXiv:1508.03850
- Yang et al. **PRSTAB** (2010) PhysRevSTAB.13.064201
- The OPAL Code: Adelmann et al. **arXiv** (2019) https://arxiv.org/abs/1905.06654
- High-Power Cyclotron Report: Winklehner et al. **arXiv** (2022) https://arxiv.org/abs/2203.07919