Prototypes of an ion trap for the Barium tagging of nEXO

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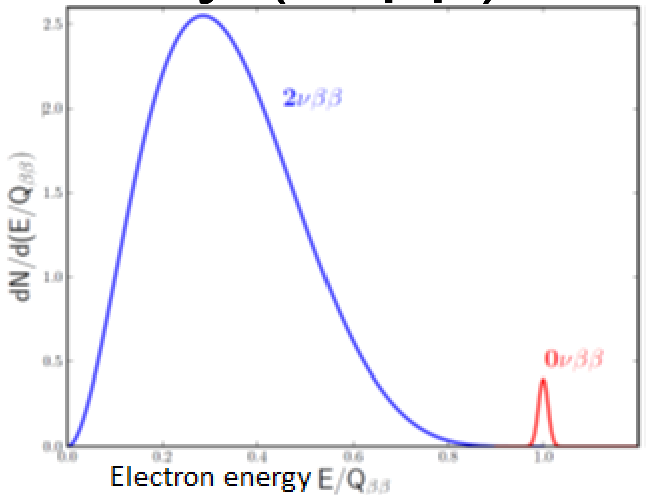
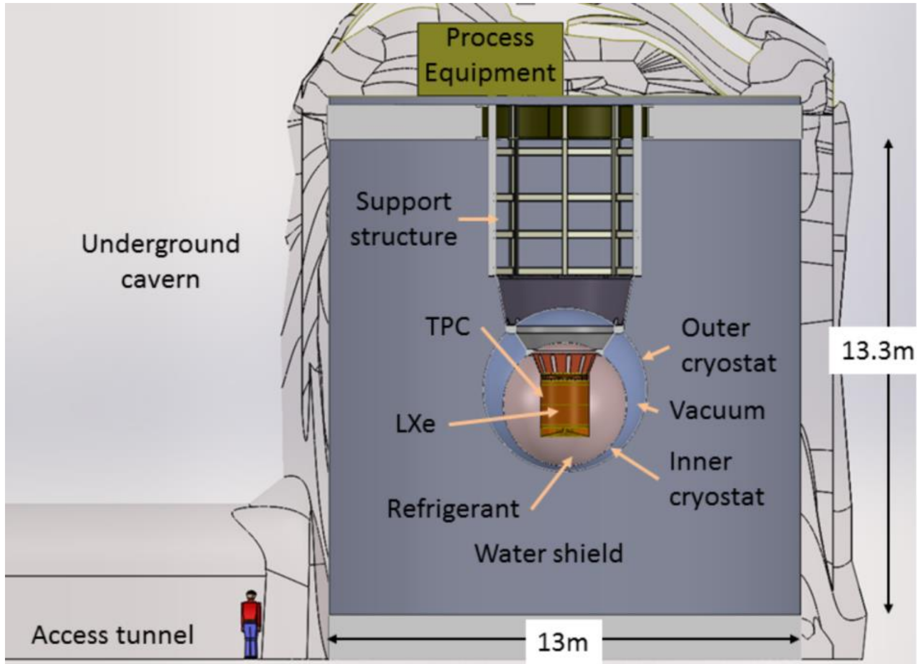
nEXO: next Enriched Xenon Observatory

- Search for neutrinoless double beta decay (0νββ)
- 2νββ: $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$

  0νββ: $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$



  - If 0νββ detected,
    - Validate neutrinos to be their own anti-particles (Majorana)
    - **Lepton numbers** do not conserve
    - **Neutrinos' absolute mass scale?**
  - Challenge: 0νββ half-life > 10^{25} yrs
    - Requires **low background**
      - Underground detector
      - Radiation shielding
    - **Barium tagging**



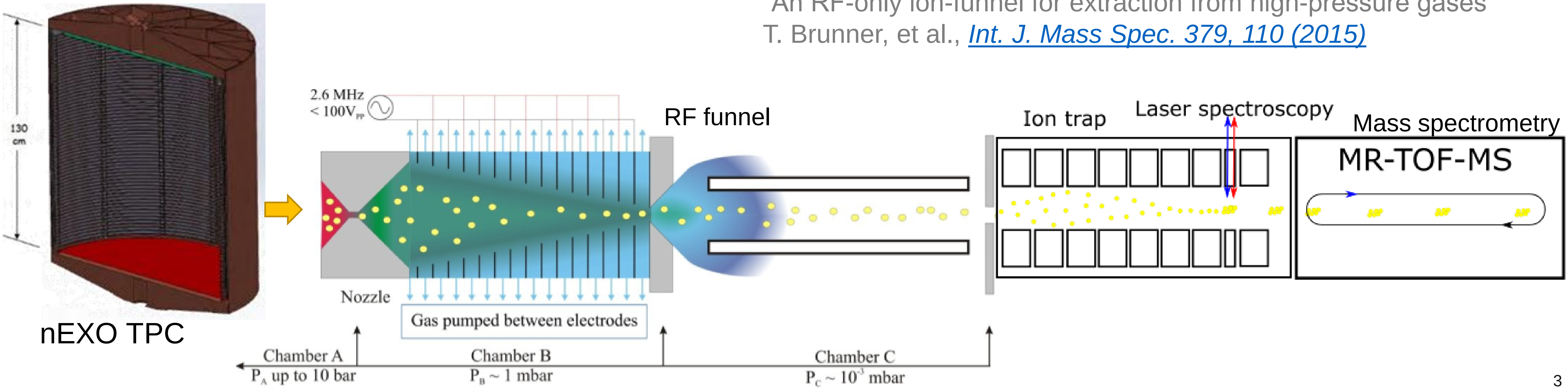
Barium tagging: the ultimate method for background rejection

- A potential upgrade for nEXO
- Multiple approaches
  - Stanford U: laser resonance ionization, mass spectrometry

    "An apparatus to manipulate and identify individual Ba ions from bulk liquid Xe"
    K. Twelker et al., *Rev. Sci. Instrum. 85, 095114 (2014)*
  - Colorado State U: cold probe, laser spectroscopy

    "Imaging individual Ba atoms in solid xenon for barium tagging in nEXO"
    C. Chambers, et al., *Nature 569, 203-207 (2019)*
  - McGill, Carleton, TRIUMF: RF funnel, **ion trap**, laser spectroscopy, mass spectrometry

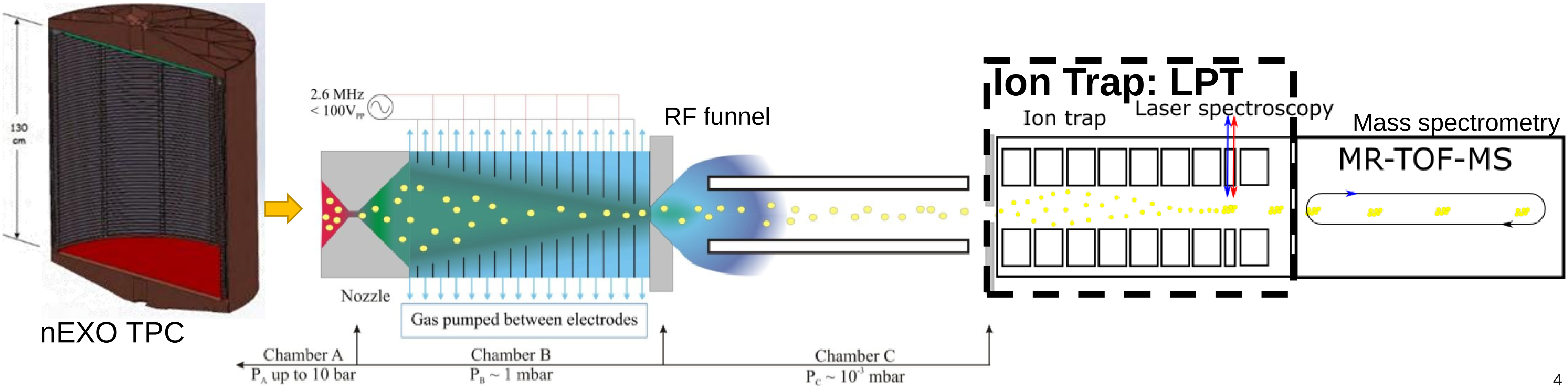
    "An RF-only ion-funnel for extraction from high-pressure gases"
    T. Brunner, et al., *Int. J. Mass Spec. 379, 110 (2015)*



Ion trap requirements

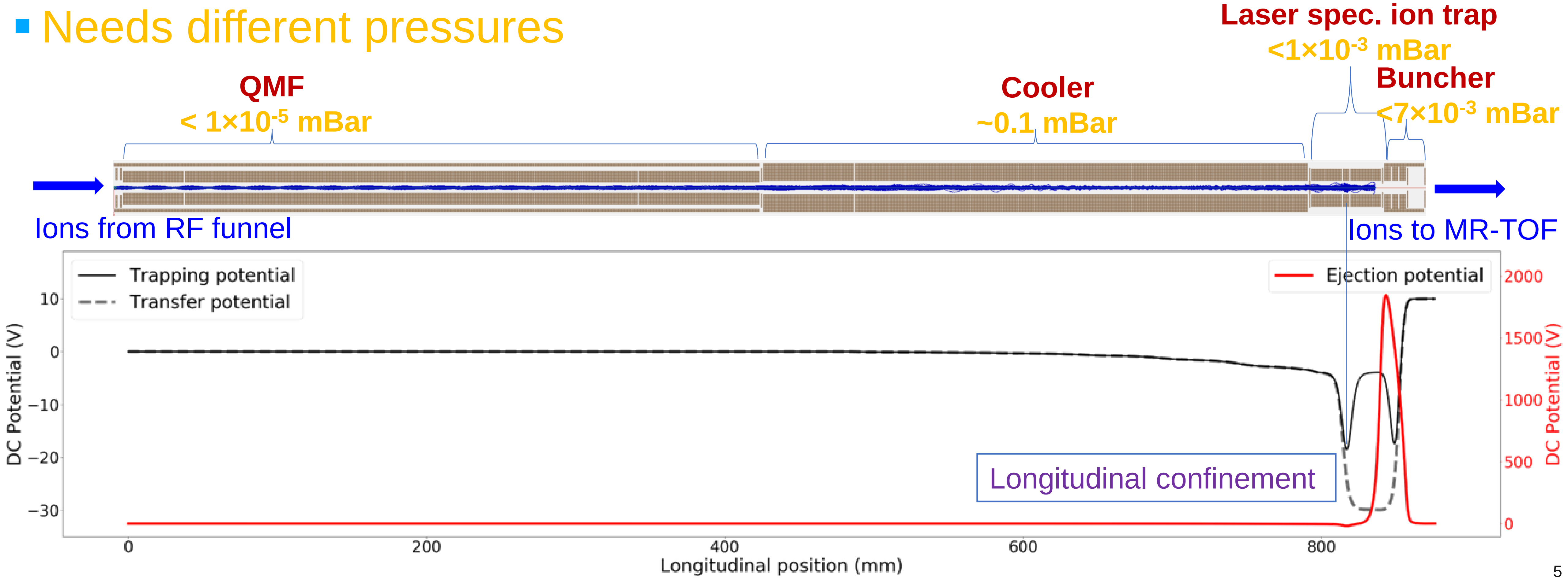
- Continuously capture all the extracted ions
- Cool ions and store them for laser spectroscopy identification
  - Low temperature to avoid Doppler broadening
- Found contaminant ions in offline experiments, purify ions with $m/\Delta m$>80
- Eject ions as fine bunches to a Multi-Reflection Time-of-Flight (MR-TOF) mass spectrometer
  - Small energy spread and time spread

Needs to develop a special linear Paul trap (LPT)

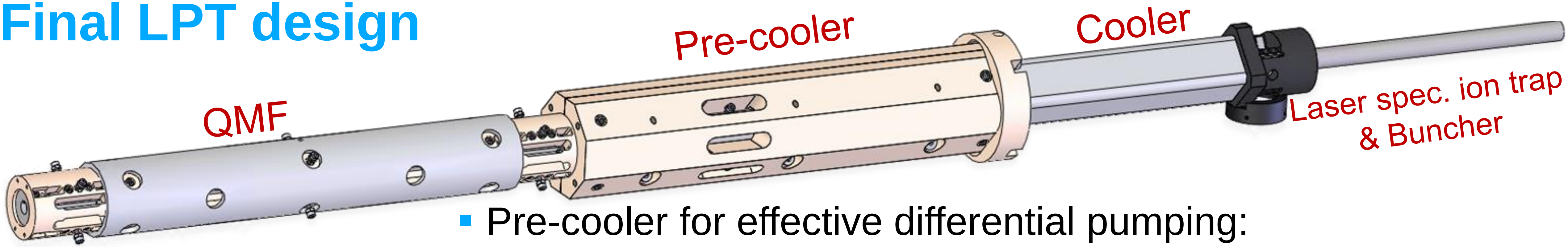


Linear Paul Trap (LPT)

- Major components
  - Quadrupole mass filter (QMF): ion purification according to ion mass-to-charge ratio
  - Cooler: ion cooling with helium buffer gas
  - Laser spectroscopy ion trap (LSIT): barium ion identification
  - Buncher: ion ejection for the MR-TOF mass spectrometer
- Needs different pressures

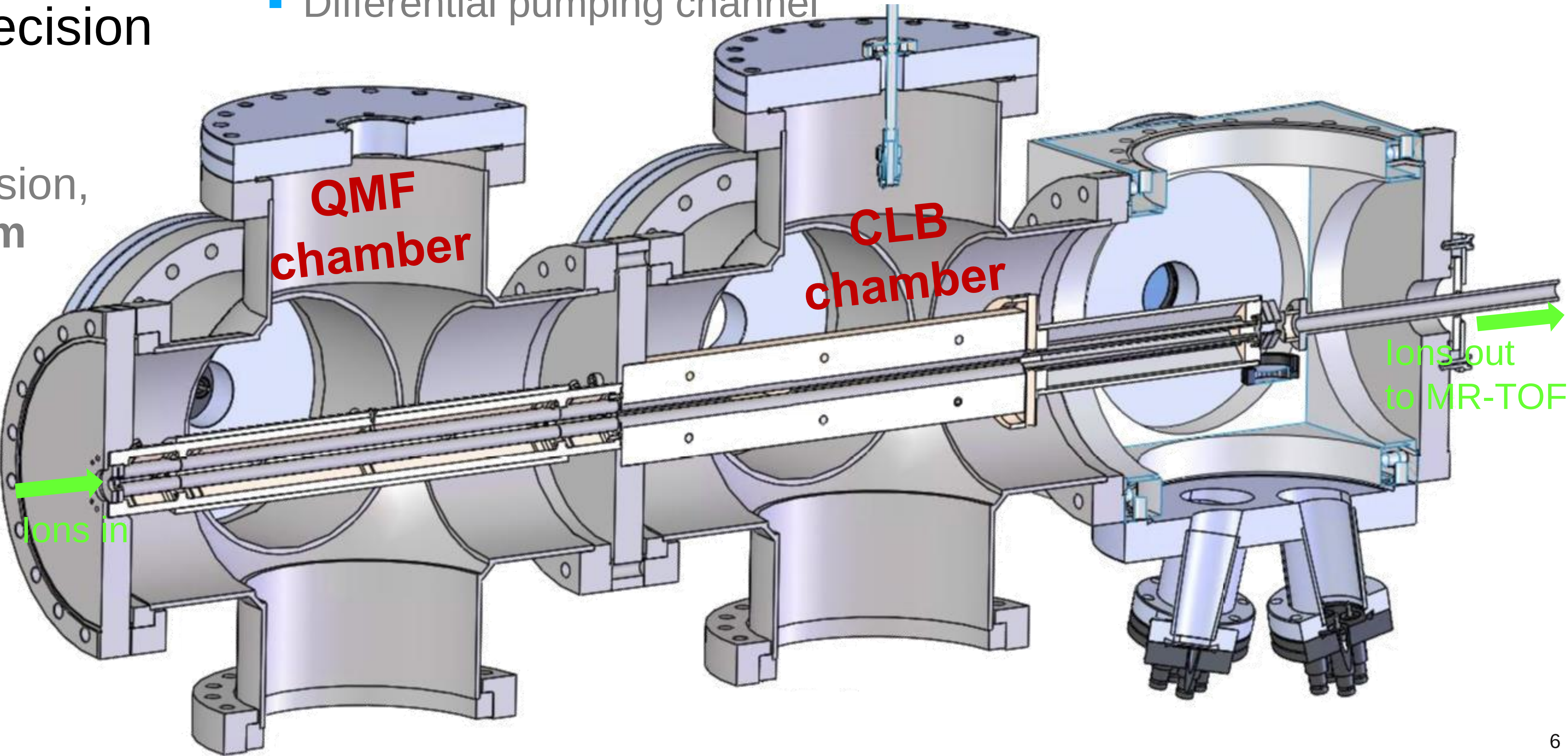


Final LPT design



- Pre-cooler for effective differential pumping:
  - Differential pumping channel

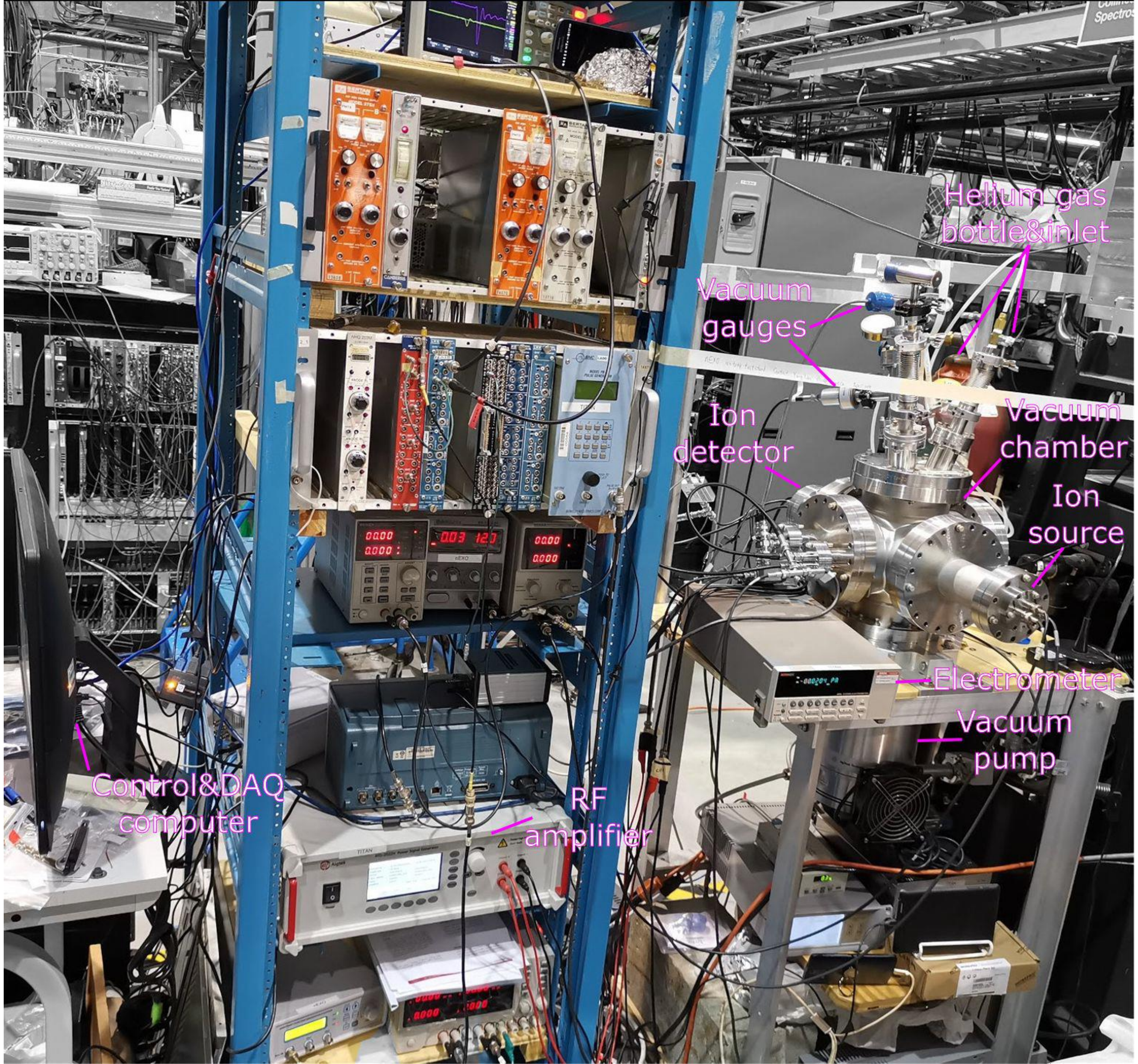
- Mechanical precision and alignment
  - **QMF : <50 µm** positional precision, others ~ **0.1 mm**



Experiments

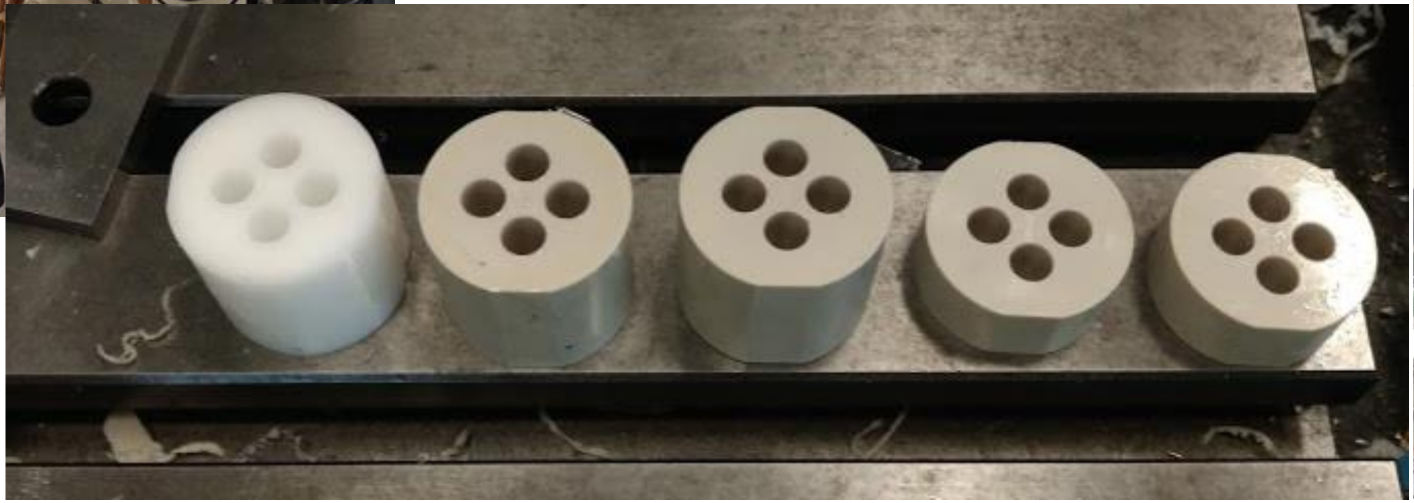
- Experiments with prototypes at TRIUMF
  - Made prototypes of LPT
  - Developed electronics, control and DAQ systems

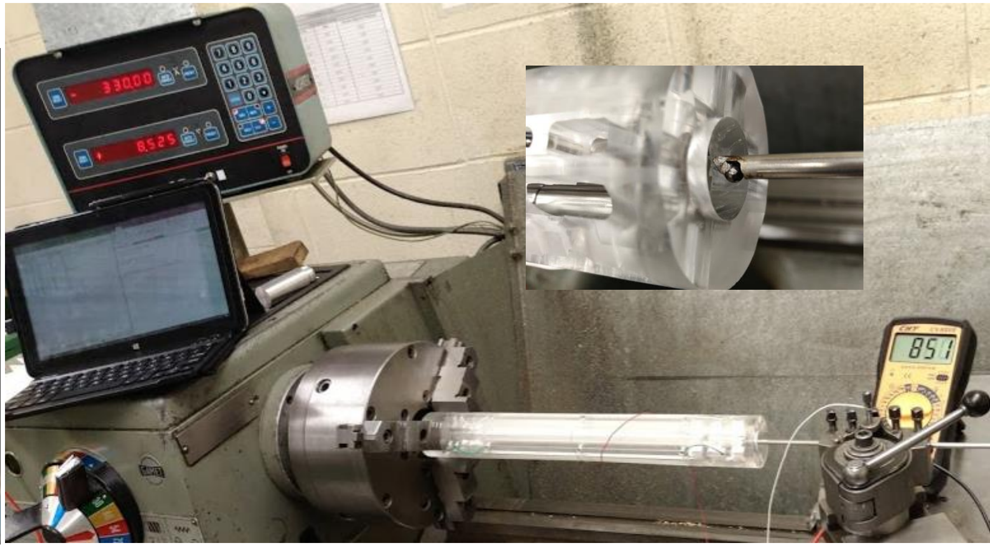
- Final LPT at McGill



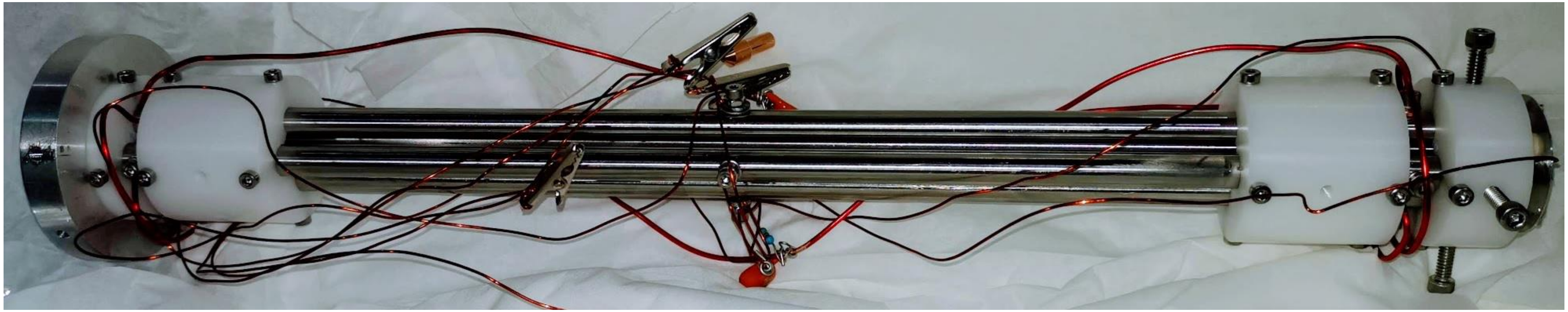
Prototypes

- 100+ happy hours in machine shop



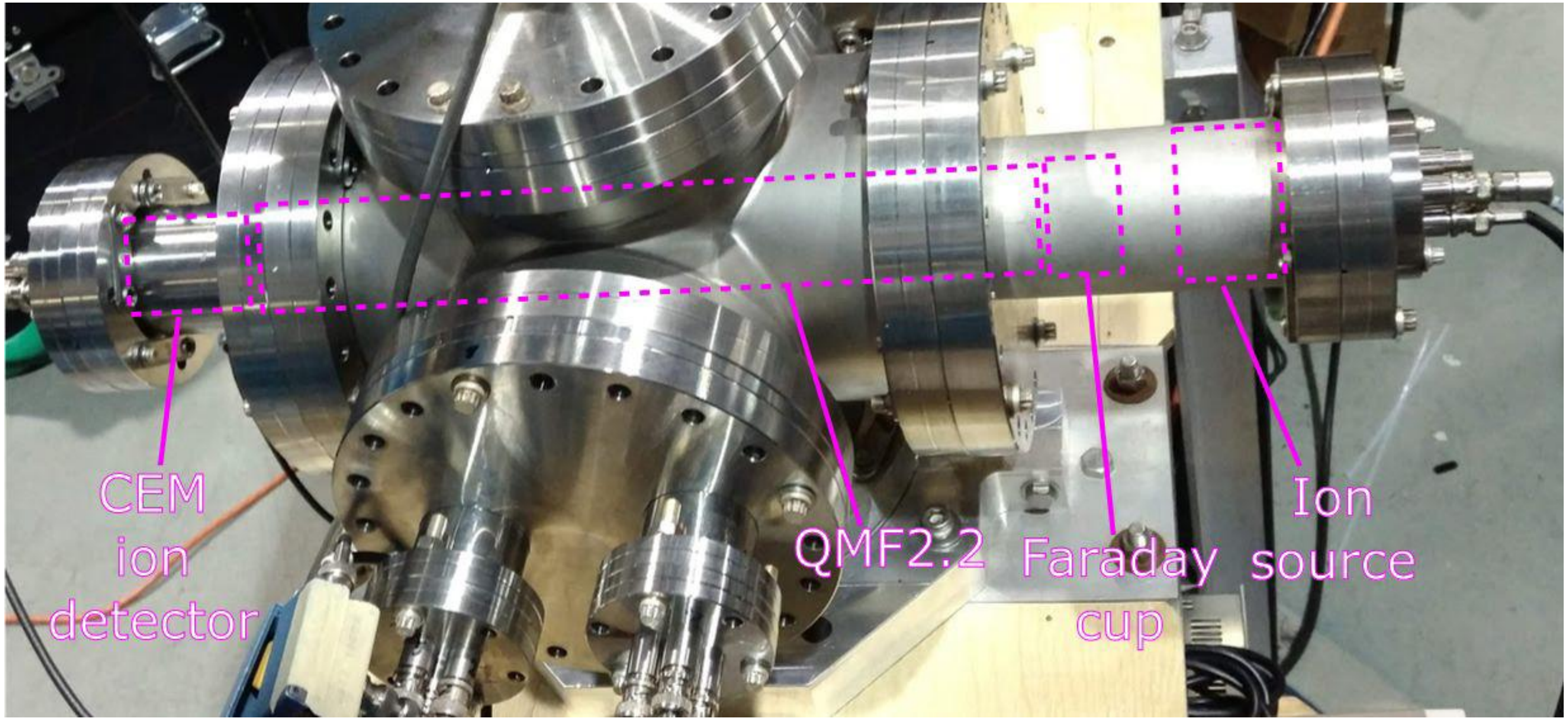


Quadrupole mass filter prototype QMF2.2



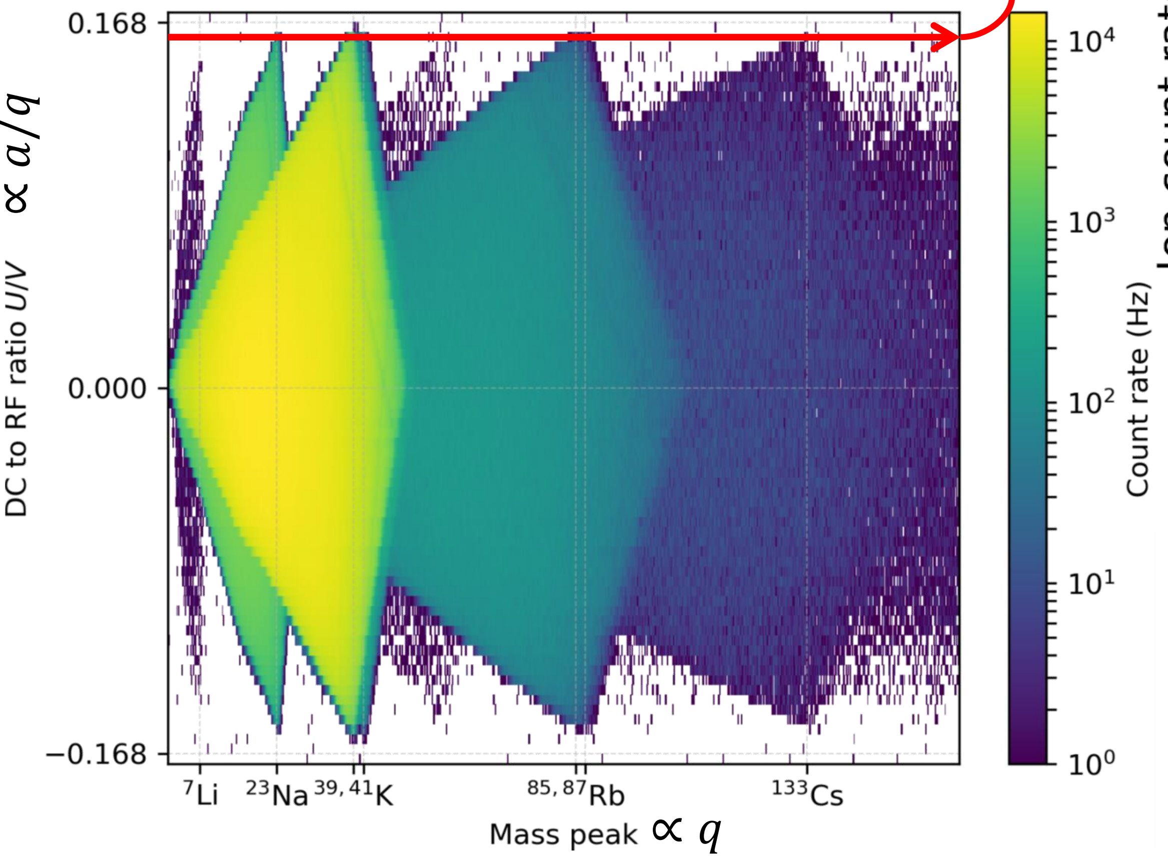
- Third iteration of QMF prototypes
  - ~30 hours each

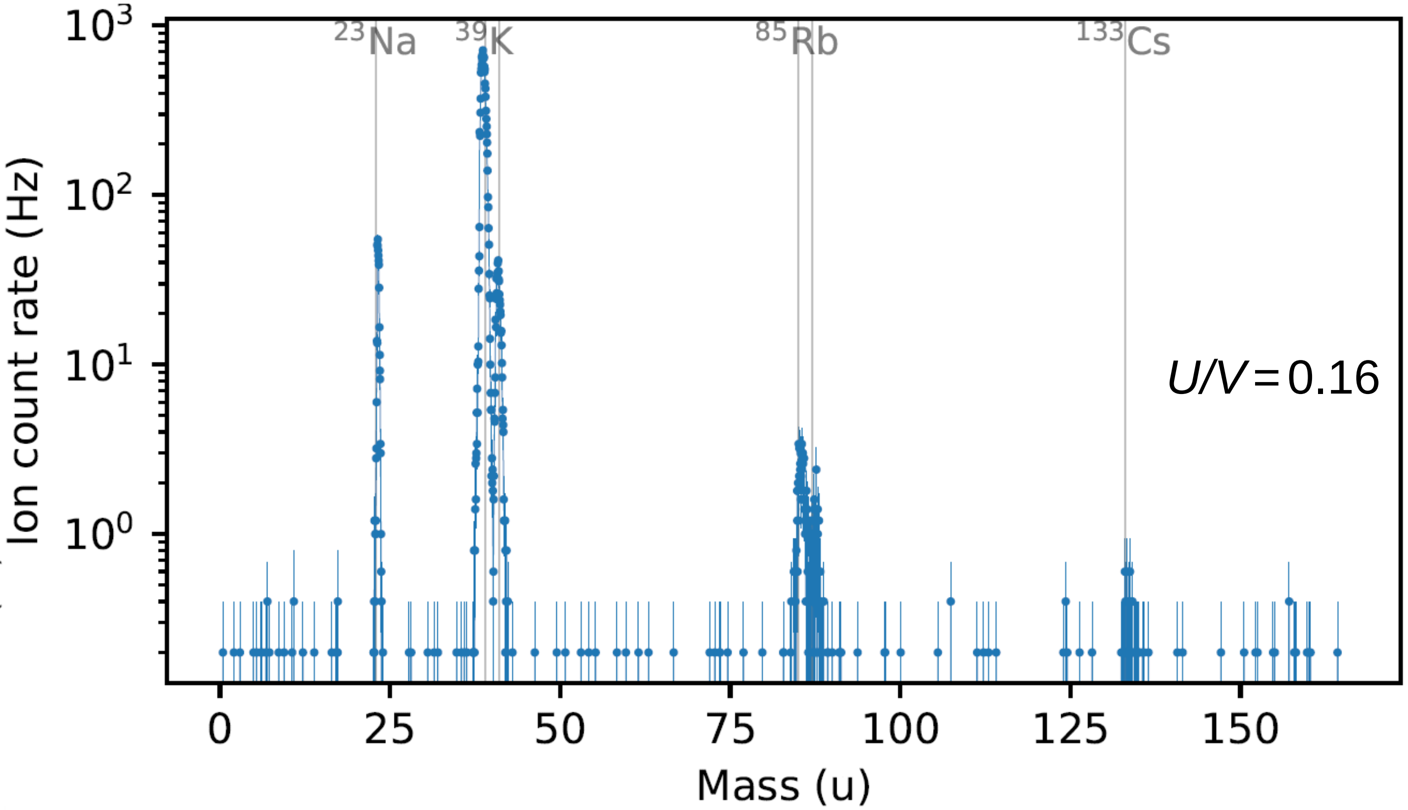
- Quadrupole electrodes have **positional precision around 10 µm**
  - **except one mistake of 150 µm**



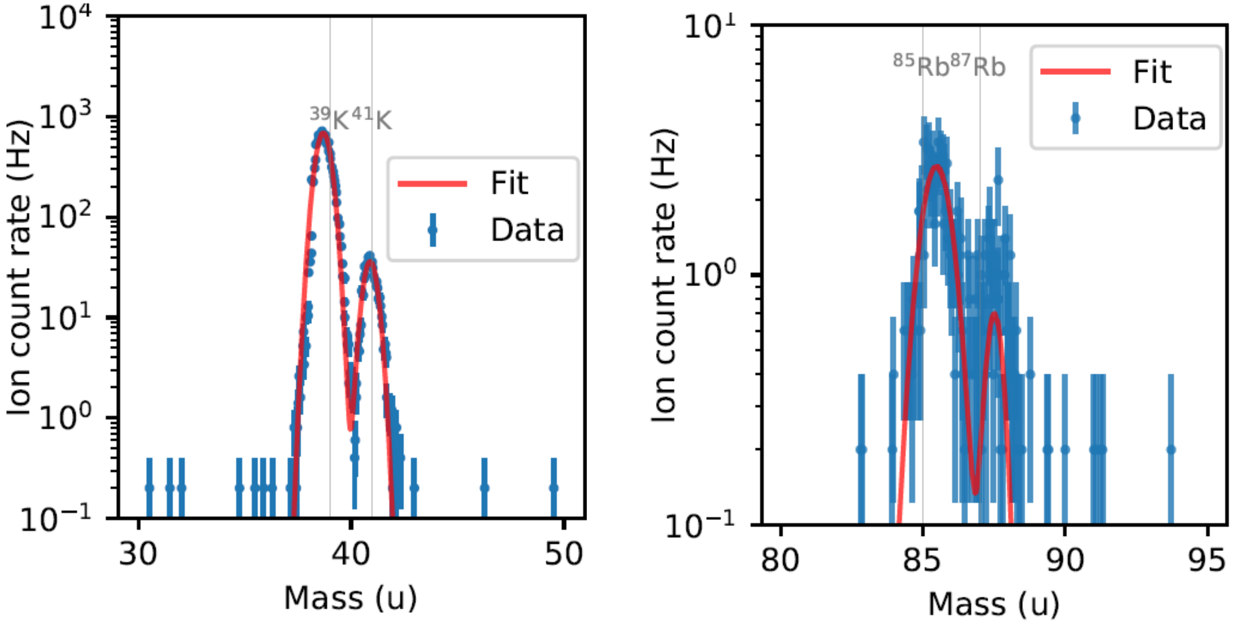
QMF2.2 results

- Ion transmission matches Mathieu stability diagram



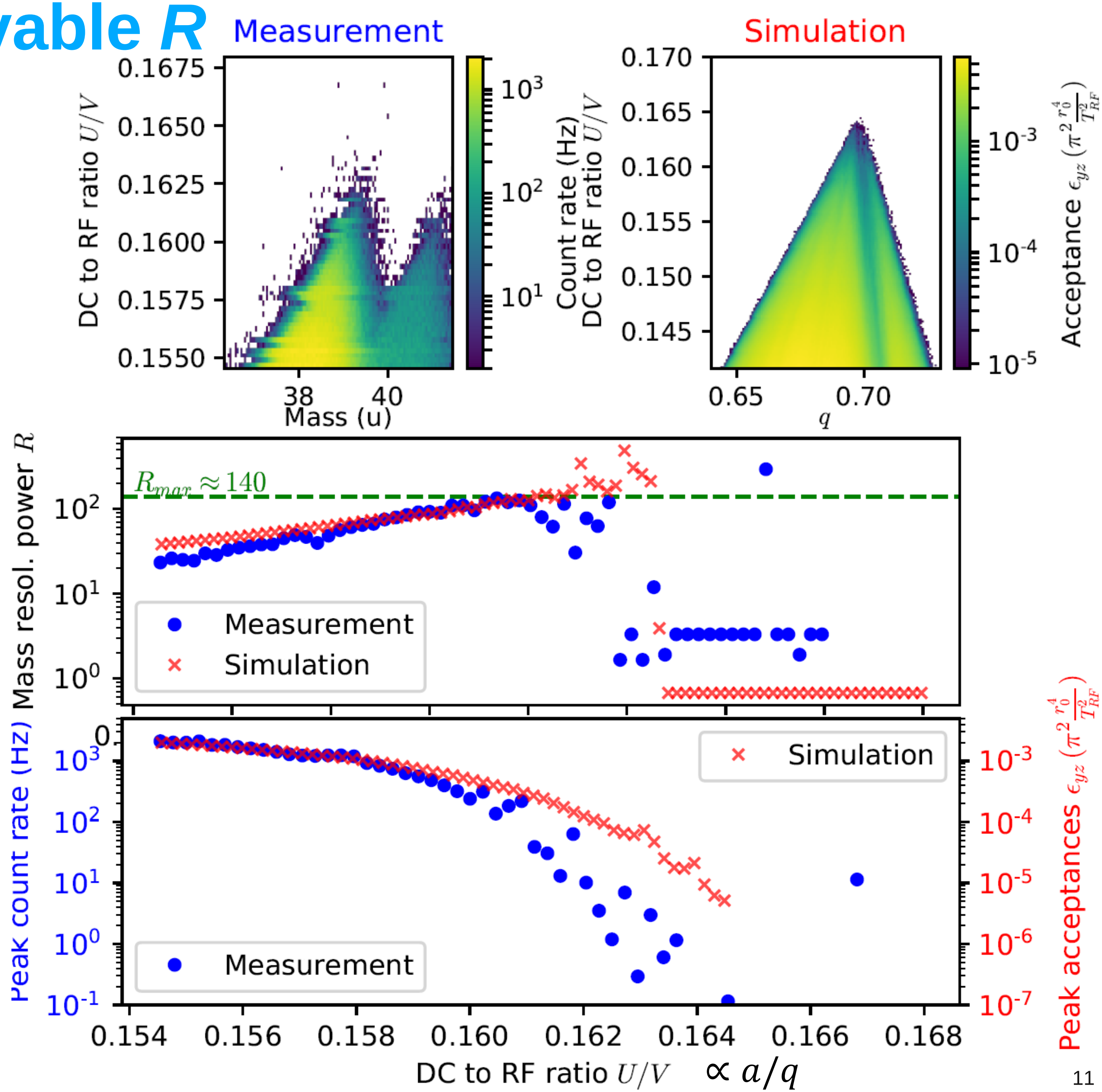


- **Measured isotopic ratio consistent with natural abundances:**
  - ^{39}K/^{41}K=17.0±3.9 (93%/7%=13.3)
  - ^{85}Rb/ ^{87}Rb=3.7±1.2 (72%/28%=2.6)



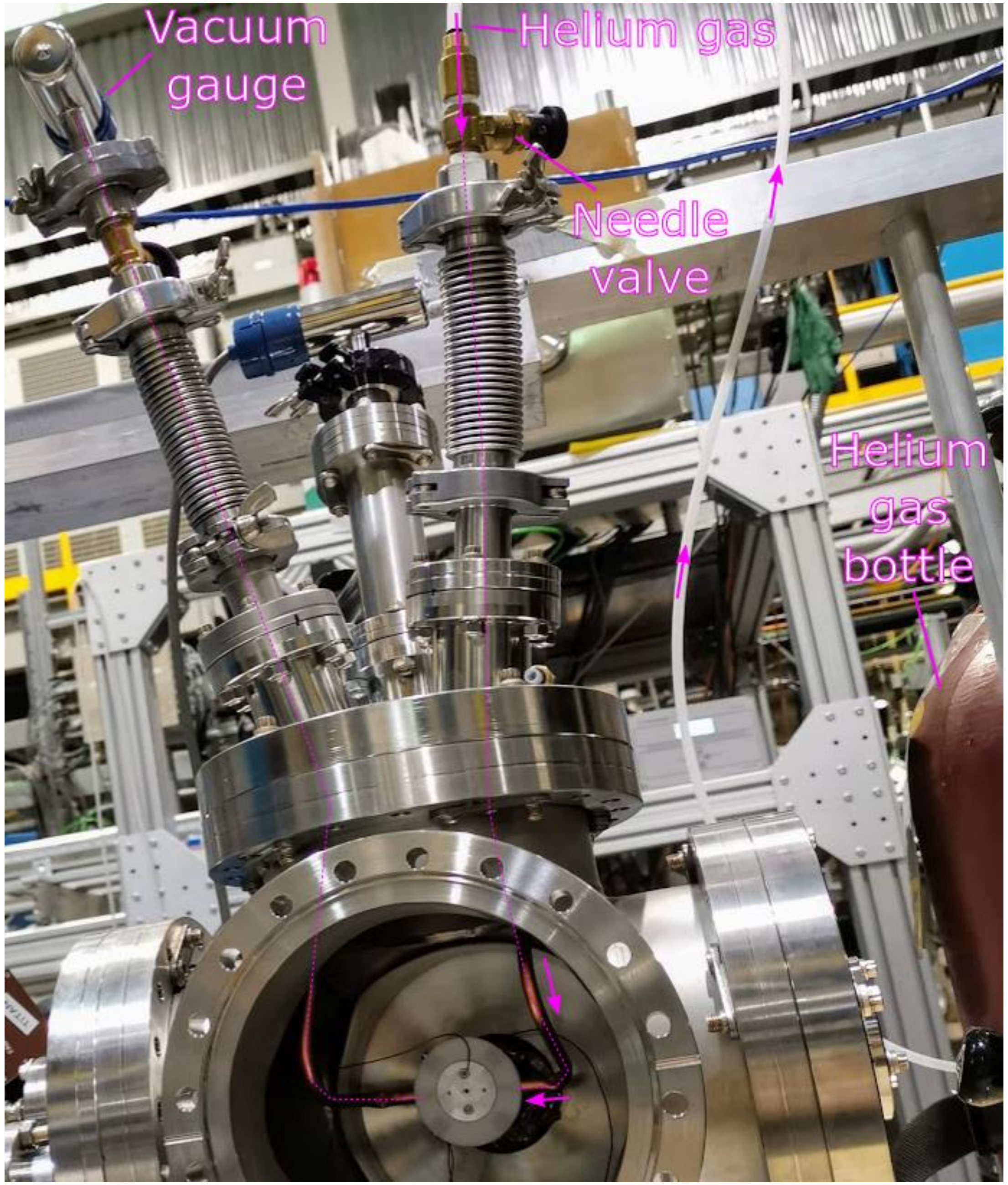
QMF2.2 results: best achievable R

- Detailed measurement around tip of stability diagram
  - Mass resolving power R
  - Ion count rate
    $\propto$ transmission efficiency
    $\propto$ ion acceptance
- Compare with simulations
- **Best achievable mass resolving power R_{max} ≈ 140** ✓ (>80)
  - **Limited by a mechanical error**



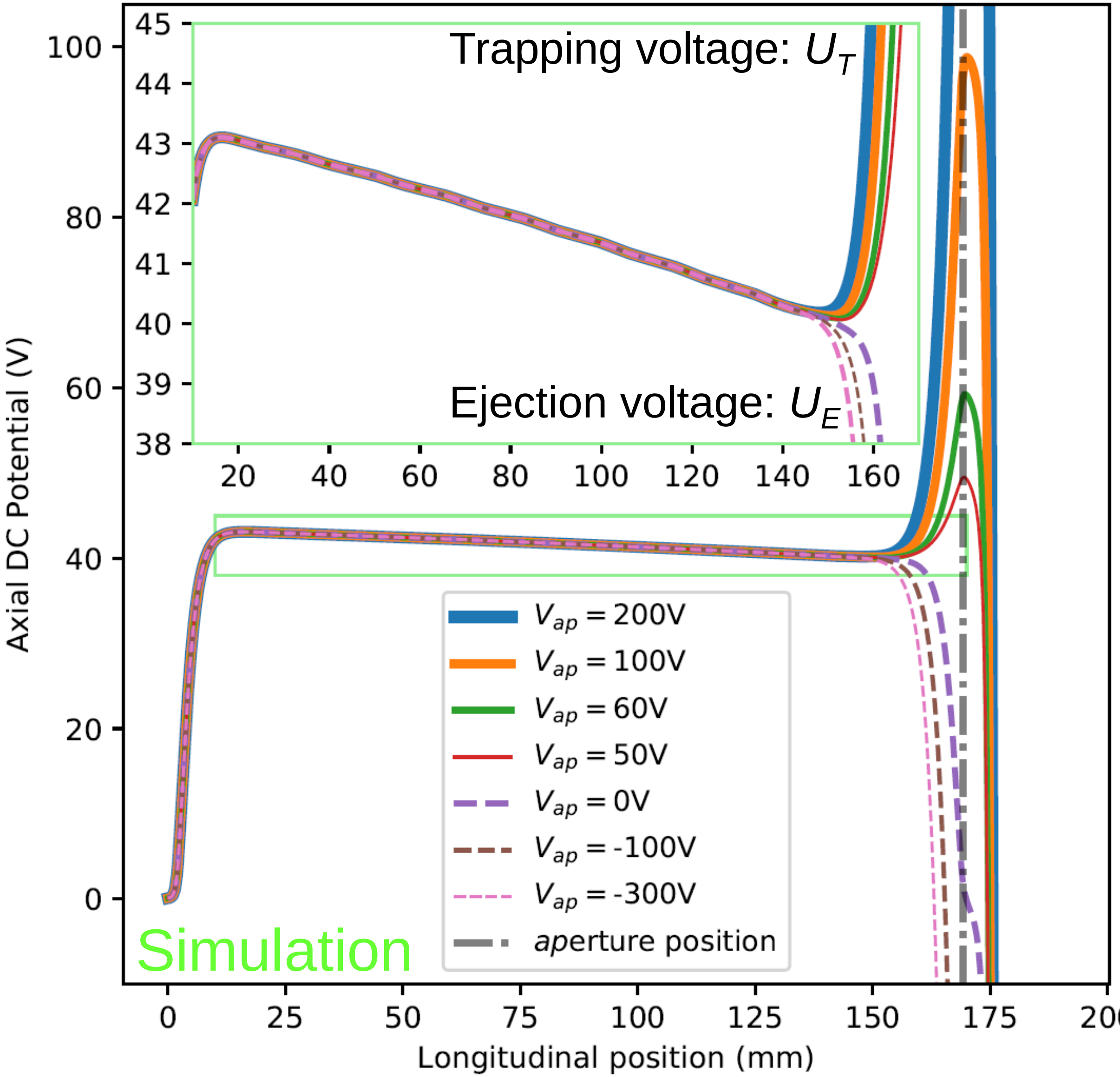
RFQ ion cooler prototype

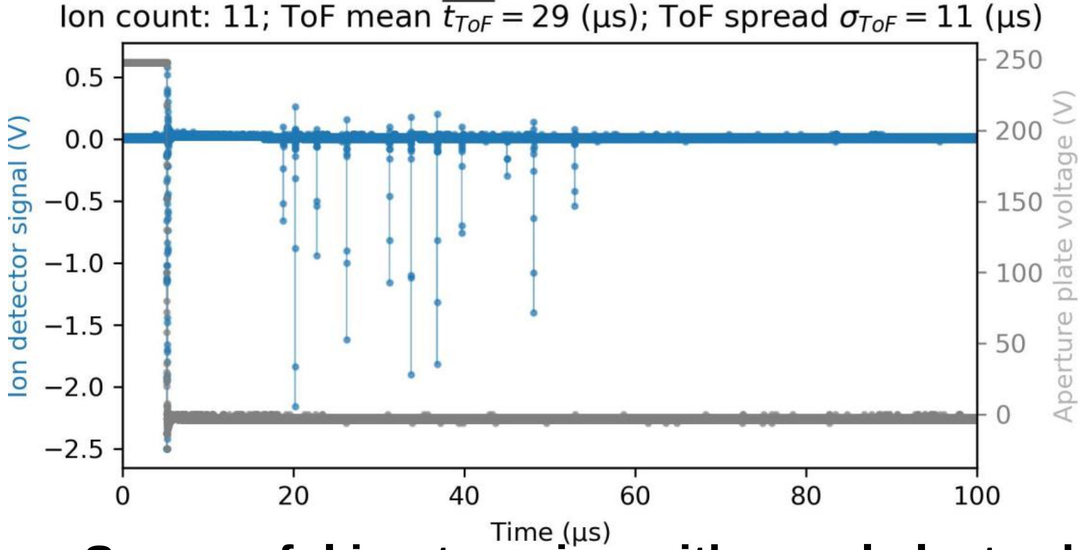
- 3D printing for complicated geometries
  - Fast and cheap
  - Materials vacuum compatible
  - Mechanical precision of 0.1 mm is sufficient



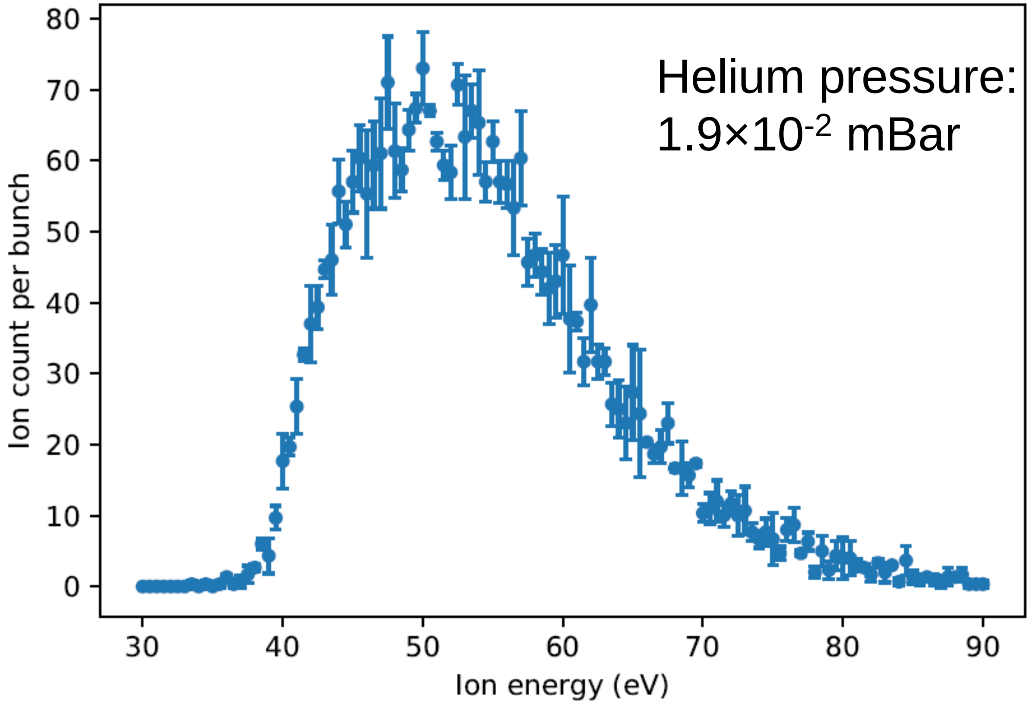
Ion cooler prototype tests

- Ions cooled and trapped at potential minimum
- Ions ejected when V_{ap} switched to low





- **Successful ion trapping with novel electrodes**

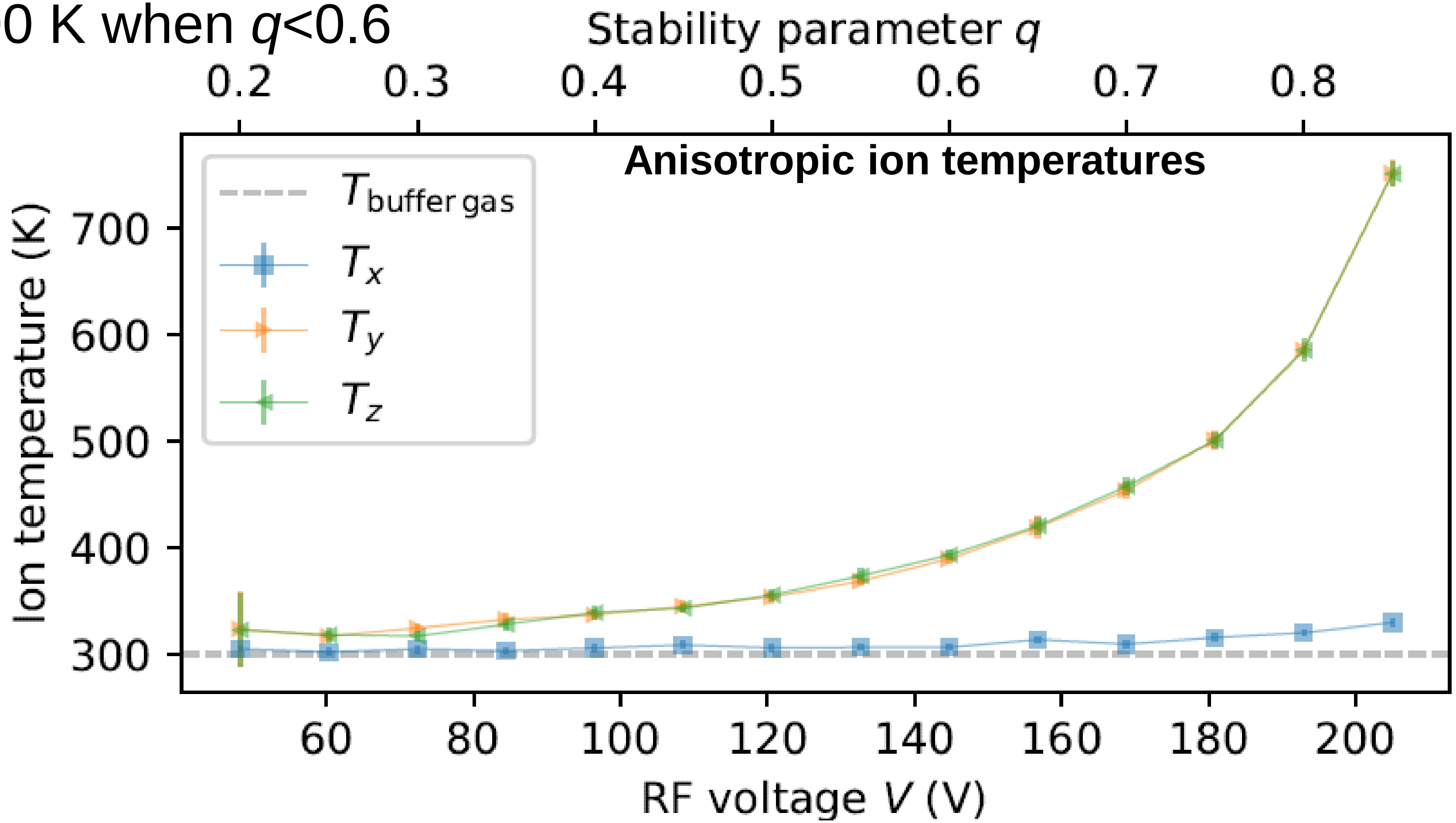


- **Validated ion cooling**

Next: Ion time of flight (ToF) measurements

Ion ToF vs. ion temperature: $\sigma_{t_{TOF}} \propto \sqrt{T_x}$

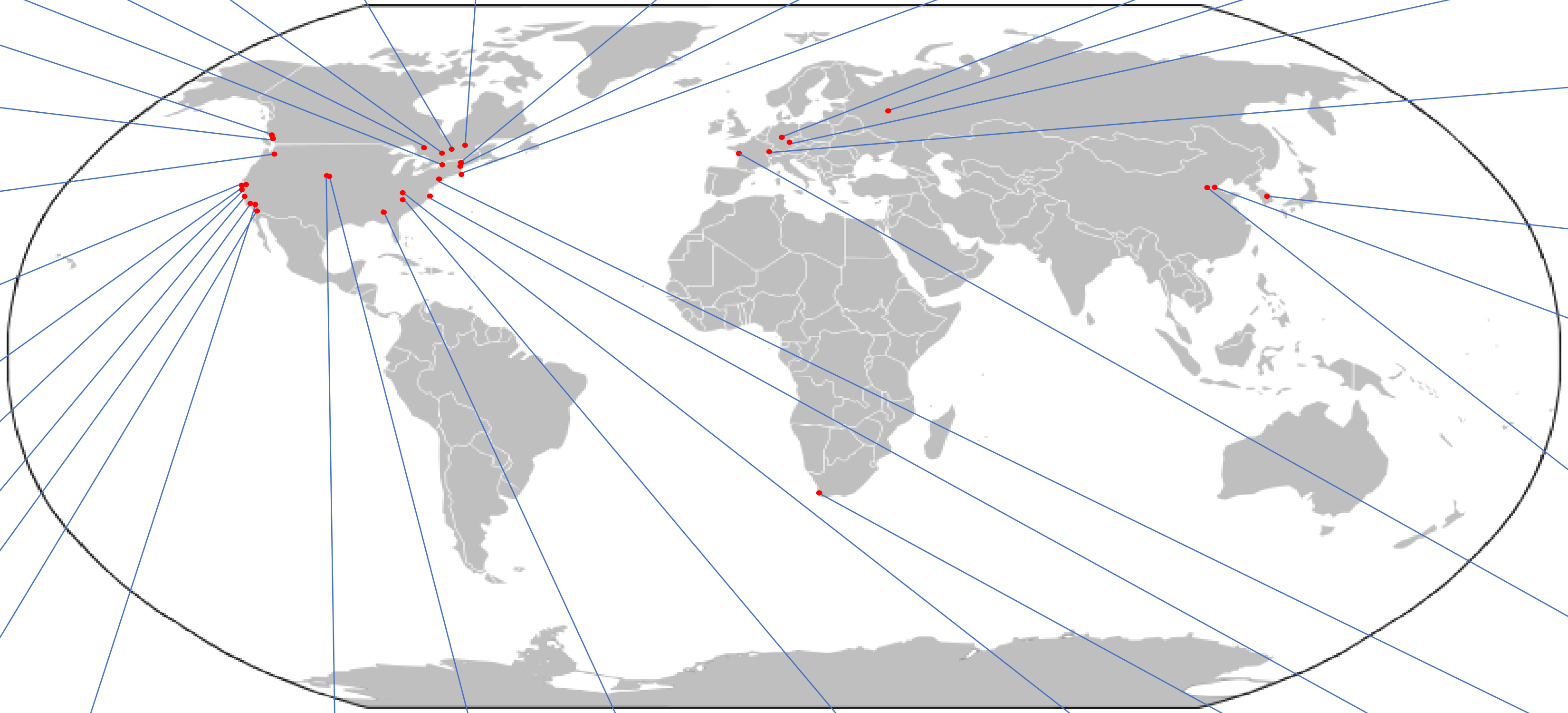
- Ion ToF measurements qualitatively validated simulations
- Ion temperature simulation for laser spec. ion trap and buncher
  - Longitudinal: T_x close to buffer gas temperature
  - Radial: T_y and T_z below 400 K when q<0.6
  - **Laser spectroscopy:** no significant Doppler broadening ✓
  - **Buncher for MR-TOF:** no significant increase in ion energy spread and time spread ✓



- **LPT meets requirements. Being commissioned at McGill.**

Conclusion and outlook

- **Barium tagging** helps nEXO to reach the ultimate background level
- A special **linear Paul trap** has been designed for barium tagging
  - Ion trapping properties studied and meet requirements
- Prototypes built for experimental studies
  - **QMF prototype has R_{max} ≈ 140**, exceeding requirement (R=80)
  - **Validated novel cooler for ion trapping, cooling and ejection**
    - Ion ToF measurements agrees qualitatively with simulations
    - Simulated ion temperatures meet requirements for LSIT and buncher
- Final LPT set up and being commisioned at McGill
  - Will be combined with RF funnel and MR-TOF for barium tagging studies



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Rensselaer

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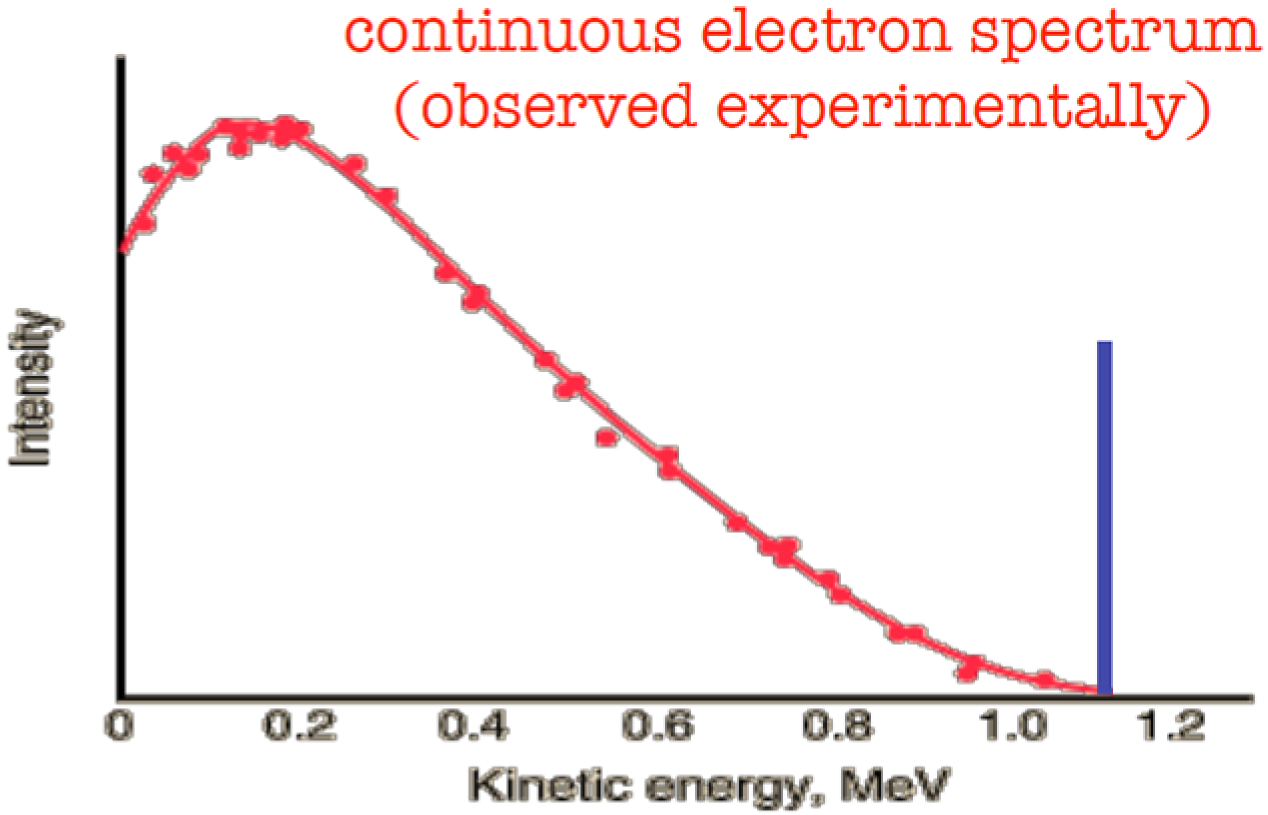
Also thanks to the TITAN group at TRIUMF for discussions and equipment!

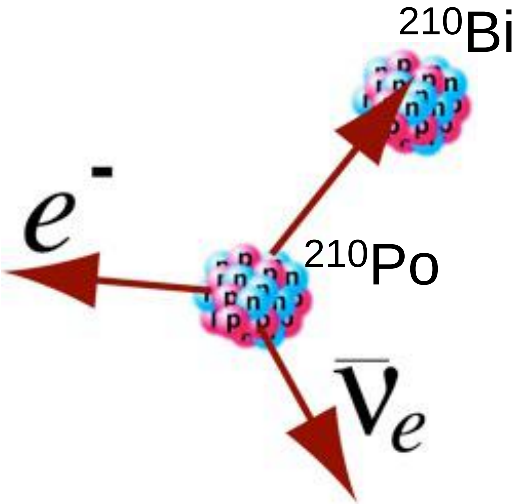
Spare slides

Neutrino physics … without neutrinos

- Neutrinos in beta decay (β)
  - Missing energy/momentum
  - “A particle that cannot be detected”

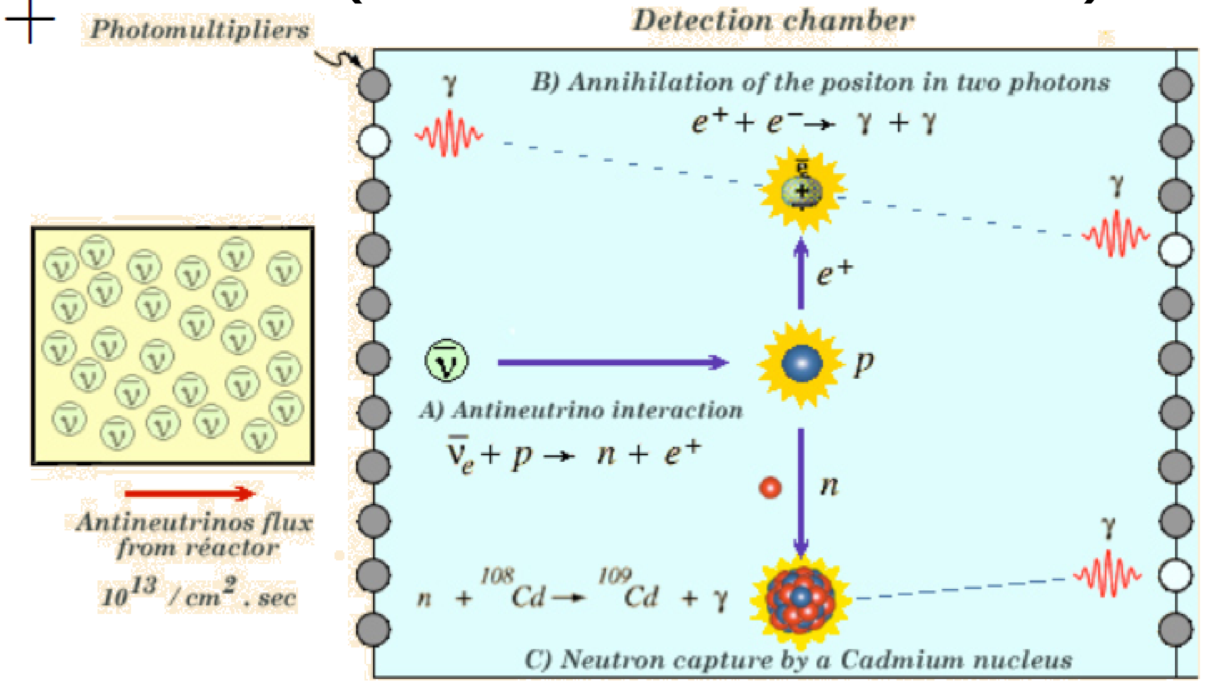
Neutrino proposed by Wolfgang pauli in 1930





Neutrino experiments

- First detection in 1956 at a nuclear reactor (Reines and Cowan)
  - Inverse β decay: $\bar{\nu}_e + p \rightarrow n + e^+$

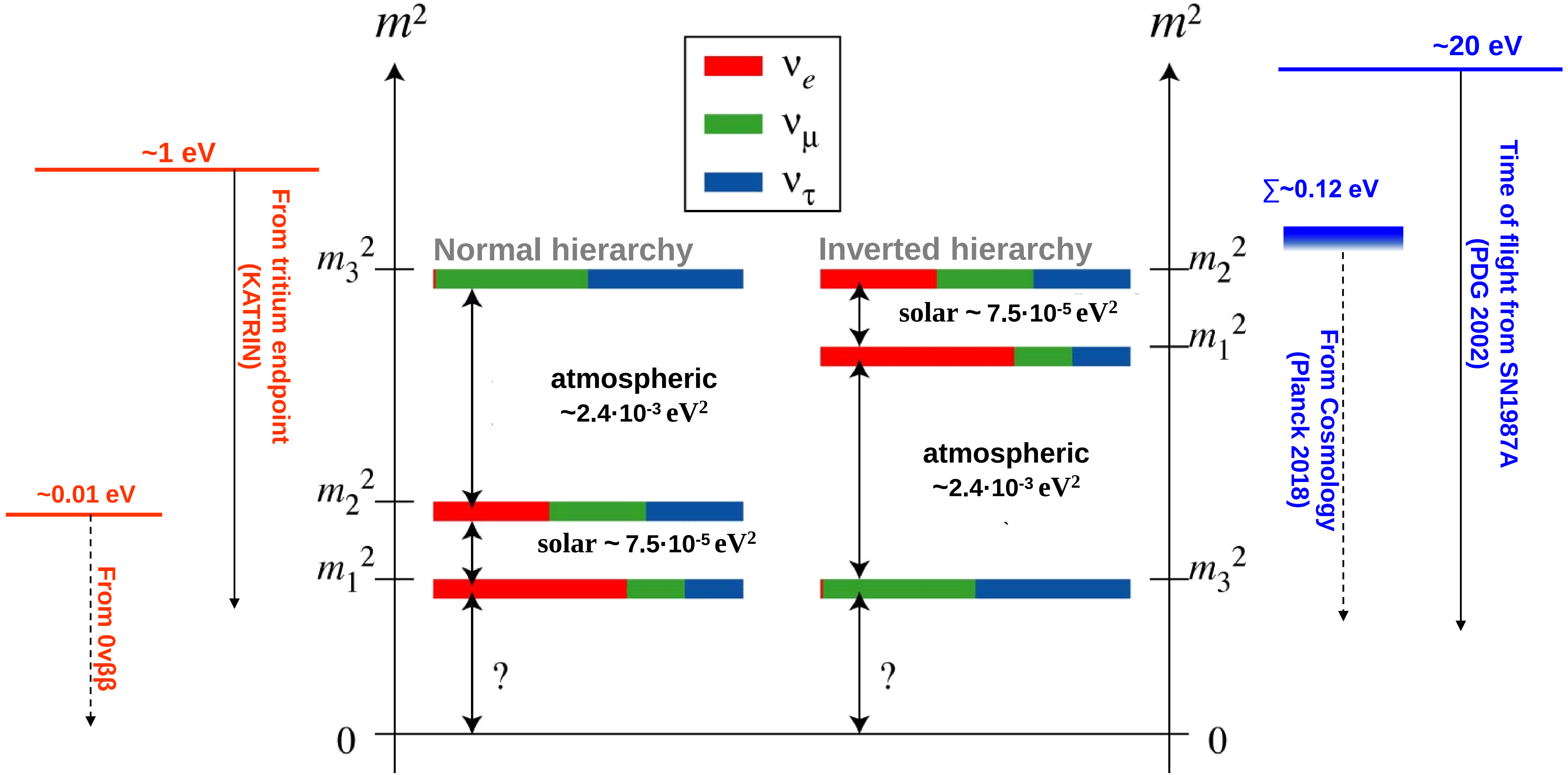


- Solar neutrino problem: 1960s to 2002
  - Detected solar neutrinos only 1/3 of expectation
  - Caused by neutrino oscillation

Flavor states — PMNS matrix — Mass states

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Mass scale of neutrinos

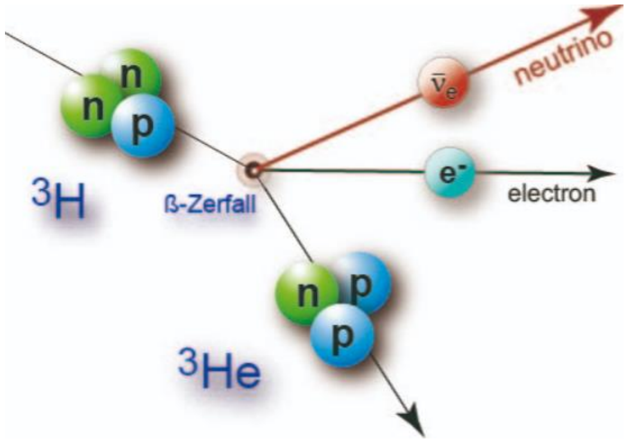


- Non-zero mass confirmed by neutrino oscillation experiments
- **Absolute mass scale to be measured**

Slide courtesy of G. Gratta

Neutrino mass

- Absolute mass scale measurement
  - Direct approach:
    Beta decay spectrum end point



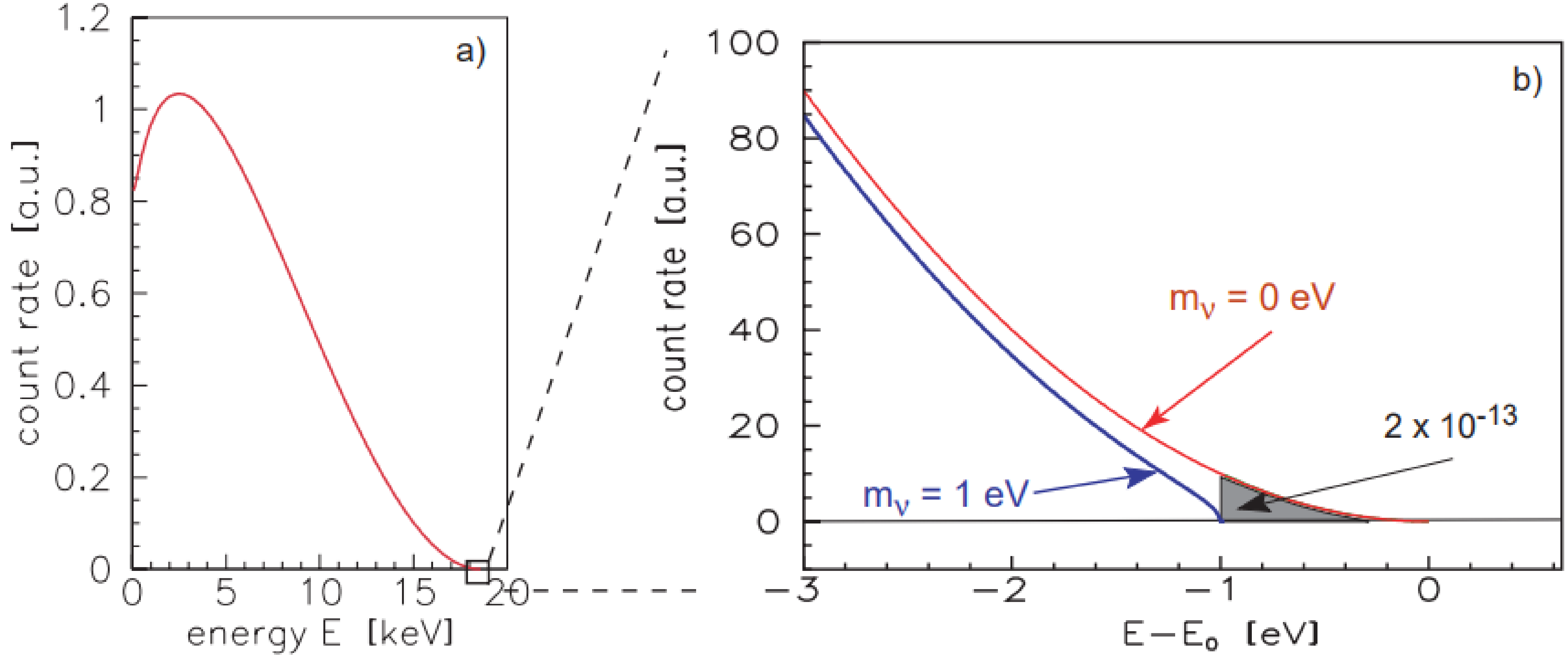


Figure credit: KATRIN collaboration (2001)

Neutrino mass

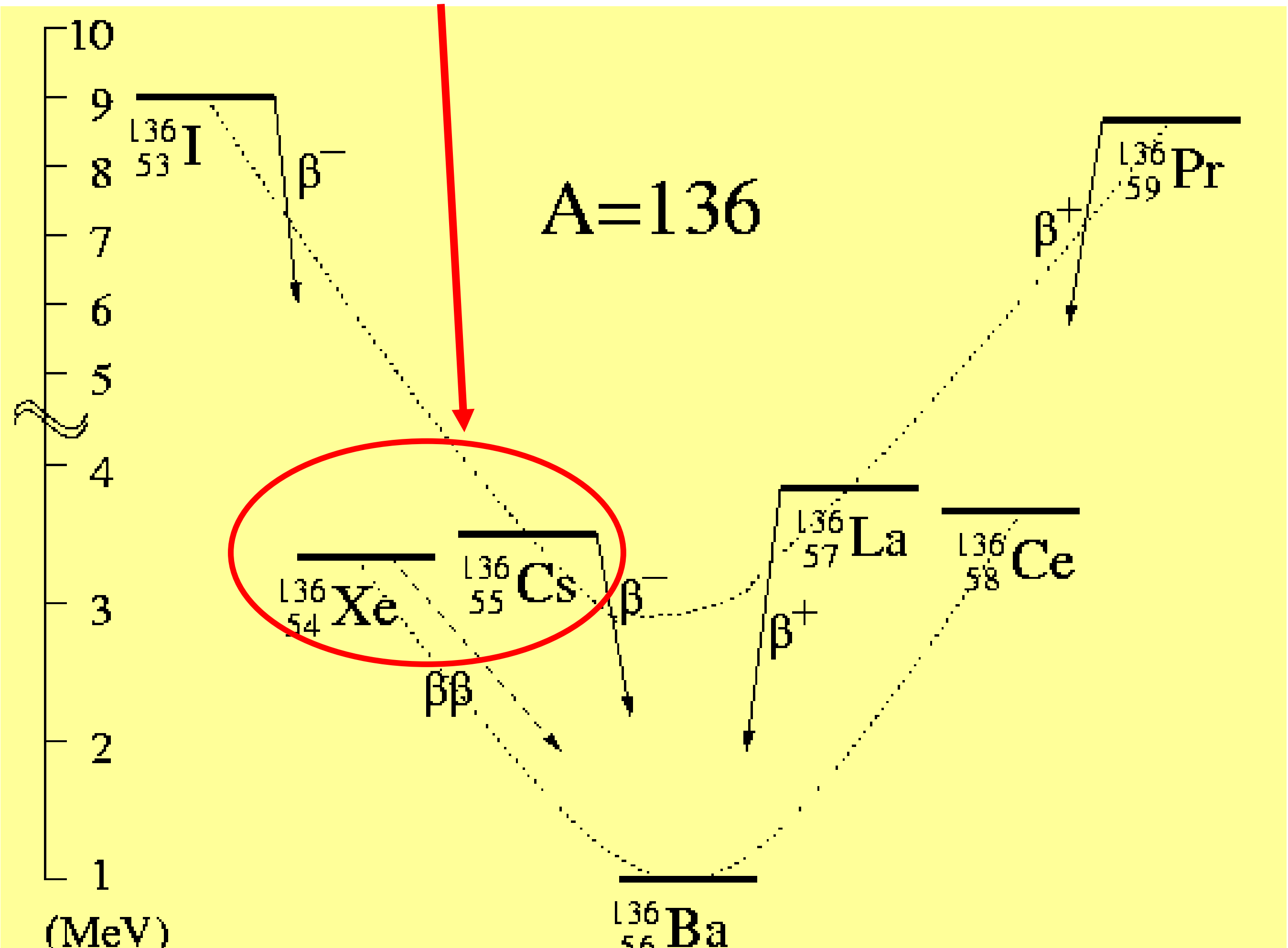
- Beta decay spectrum end point
  - Mainz and Troitsk: $m_{\nu_e} \leq 2.2$ eV
  - Next generation experiment: KATRIN
    - Aiming at 0.2 eV
    - 2019 result: $m_{\nu_e} \leq 1.1$ eV

Science 356 (2017) 6345

- Neutrinoless double beta decay
  - **Sensitive to neutrino mass below 0.01 eV**

Double beta decay (ββ)

- ββ is a second order process
- Detectable if first order β decay is energetically forbidden



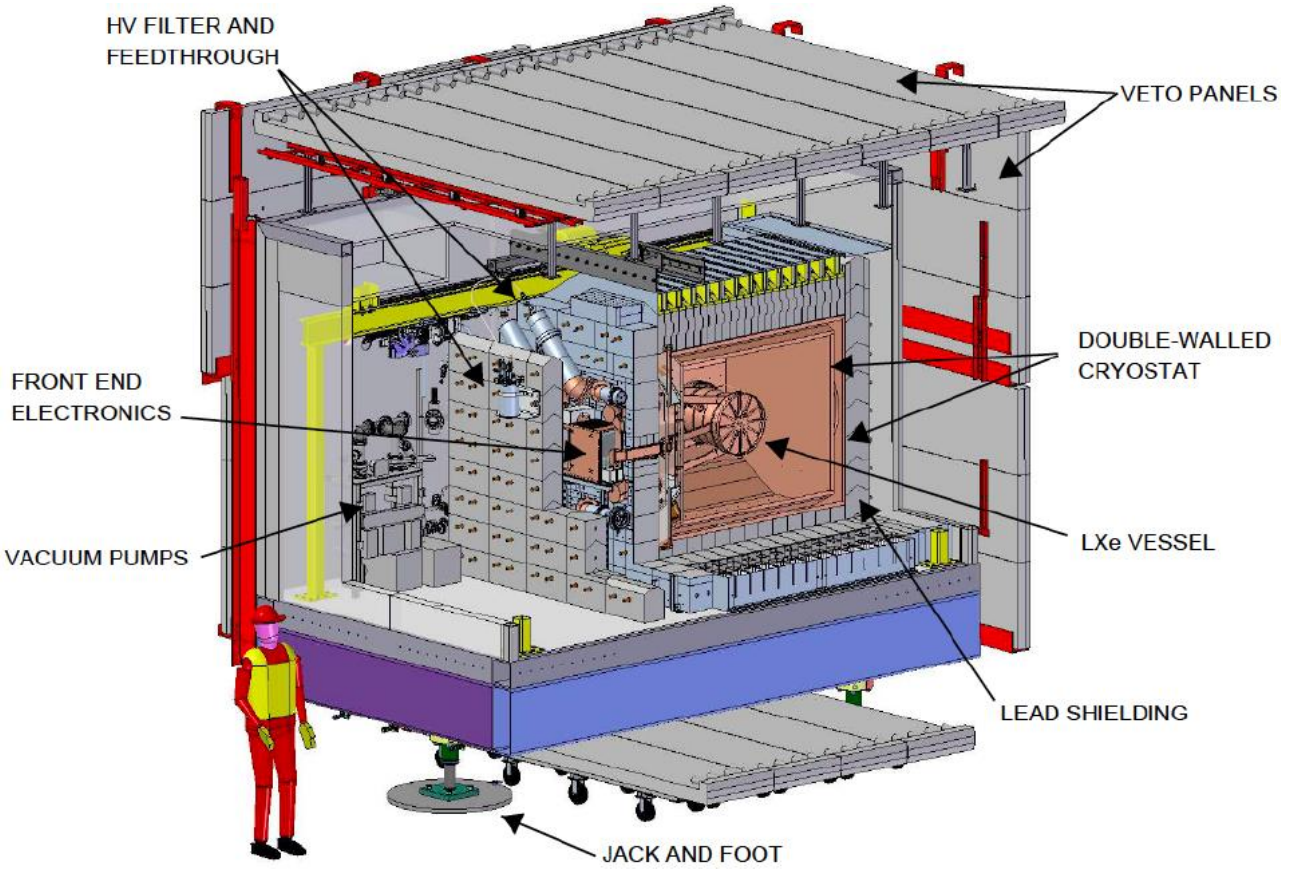
Slide courtesy of G. Gratta

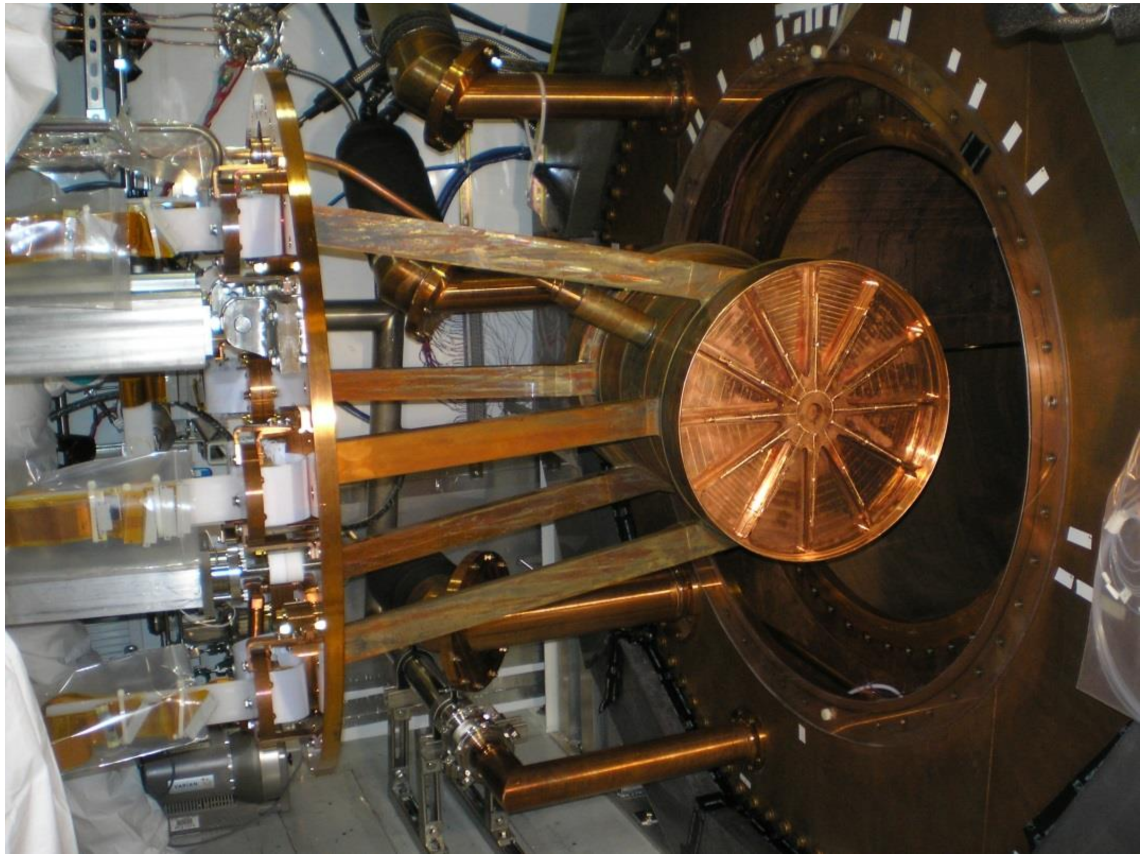
Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abundance (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

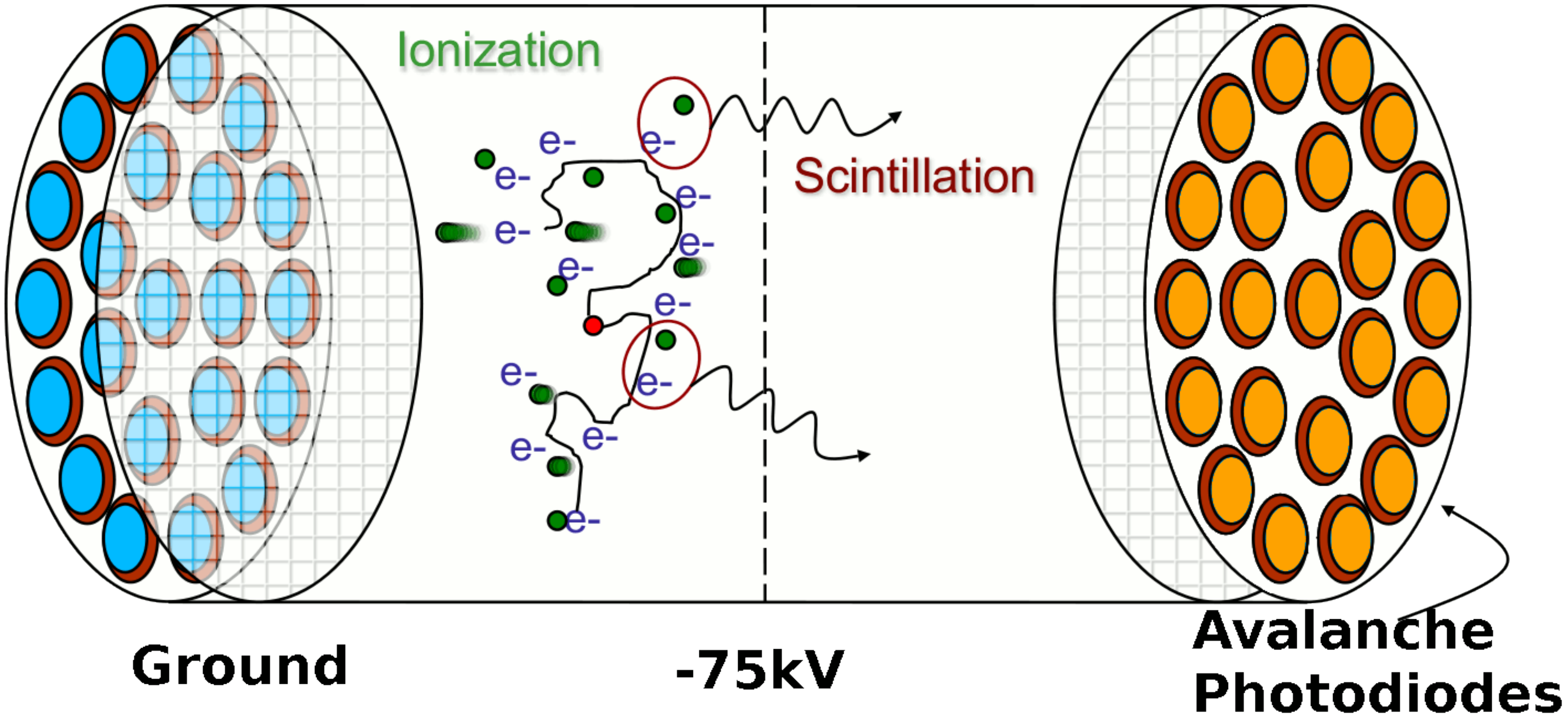
EXO-200

- Located at Waste Isolation Pilot Plant (WIPP), New Mexico
- 655 m underground (1600 m.w.e)
- 175 kg of liquid xenon in a Time Projection Chamber (TPC) cooled to 167 K





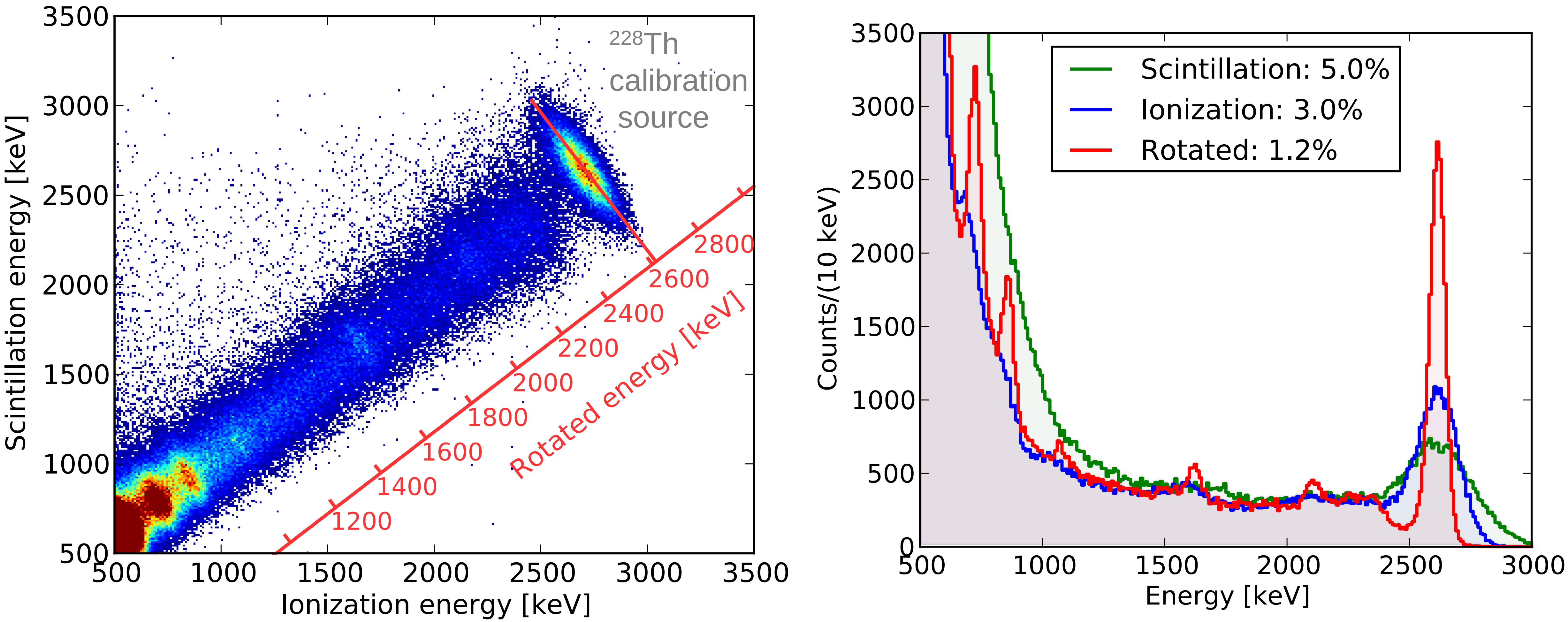
EXO-200 TPC



- Measurement of both ionization and scintillation
- Reconstruct events 3D locations
  - Distinguish true ββ decay from backgrounds
  - Locate daughter isotope ^{136}Ba for tagging (future plan)

EXO-200 energy resolution

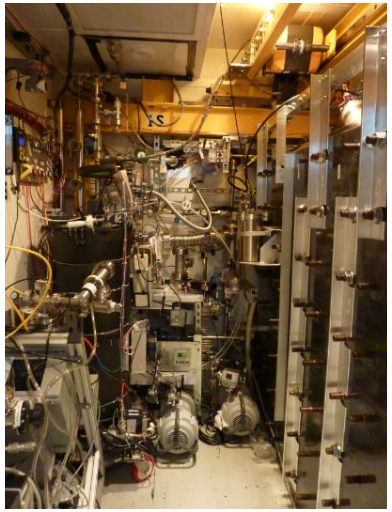
- Combining ionization and scintillation to enhance energy resolution
  - Energy resolution ~ 1.25% at Q value in rotated axis

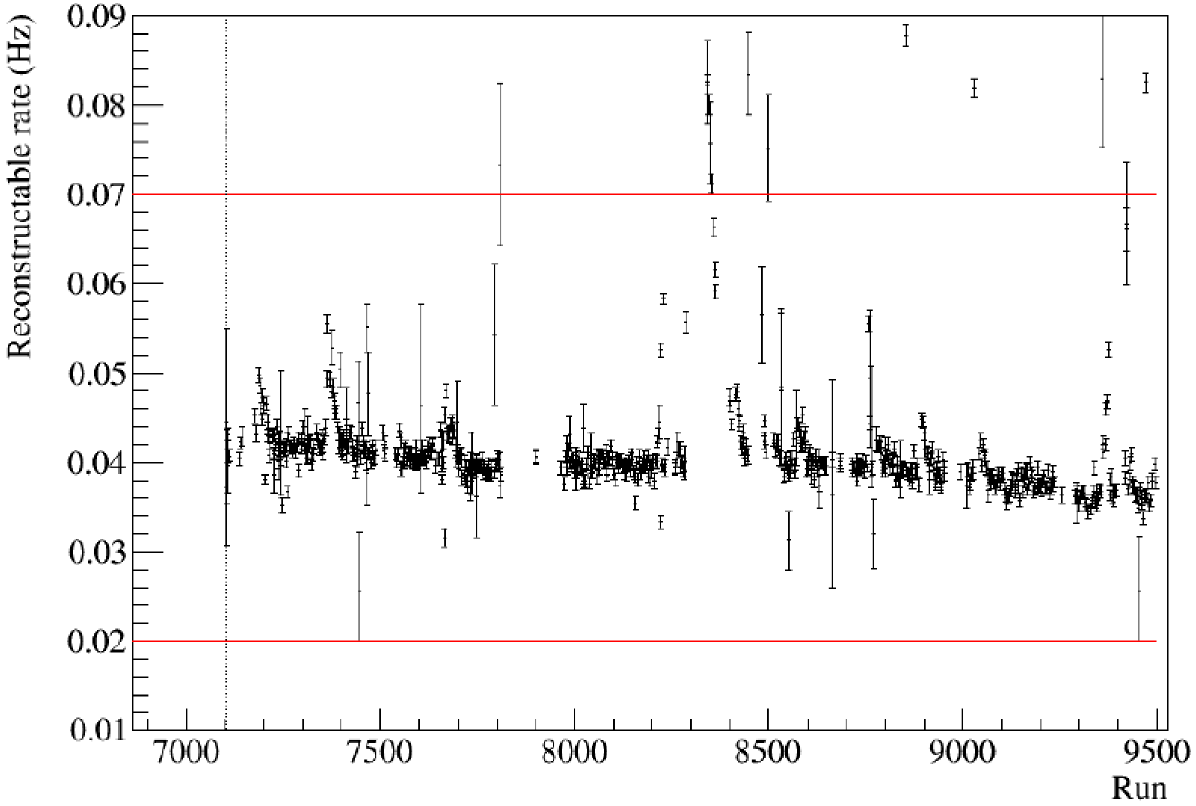


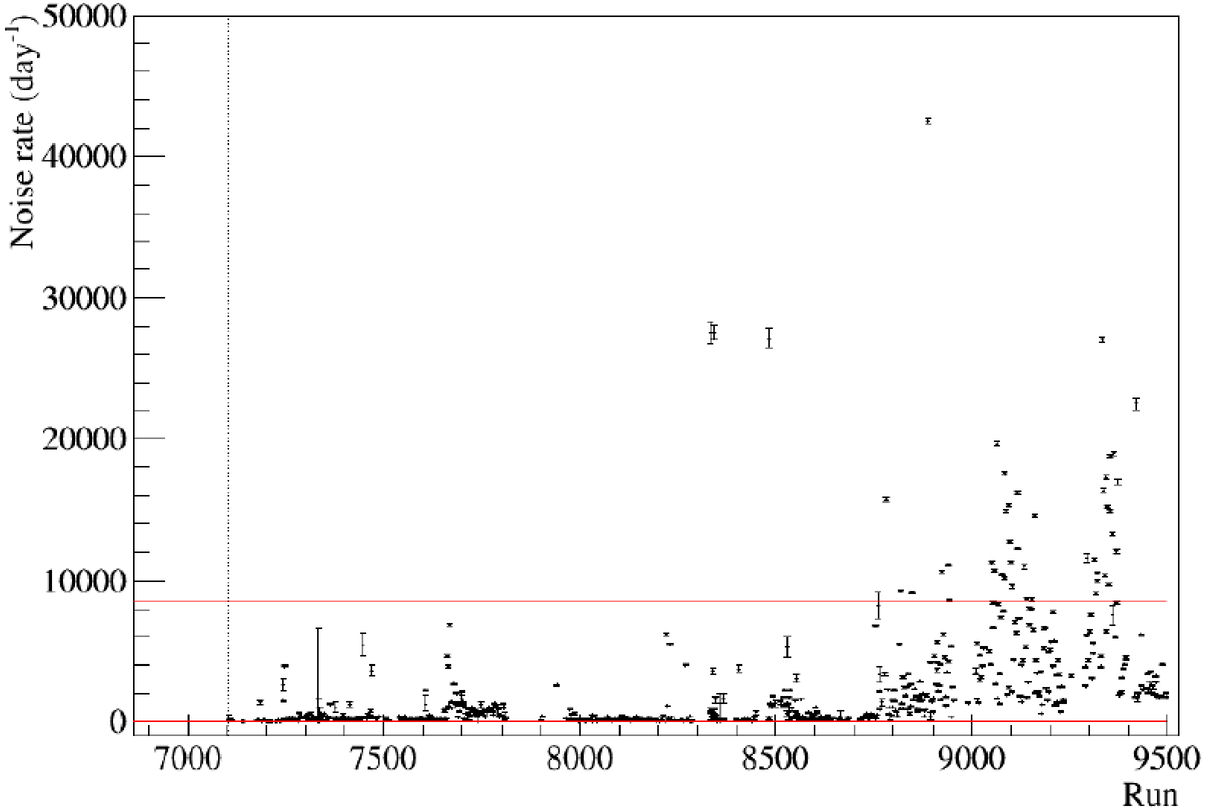
EXO-200 phase-II data

- Phase-II data taking: May 2016 to December 2018
- Underground shift: December 2017
- Data quality analyzer: from Jan 2017 to Dec 2018
  - Ensured EXO-200 operation and data taking

655 m under ground







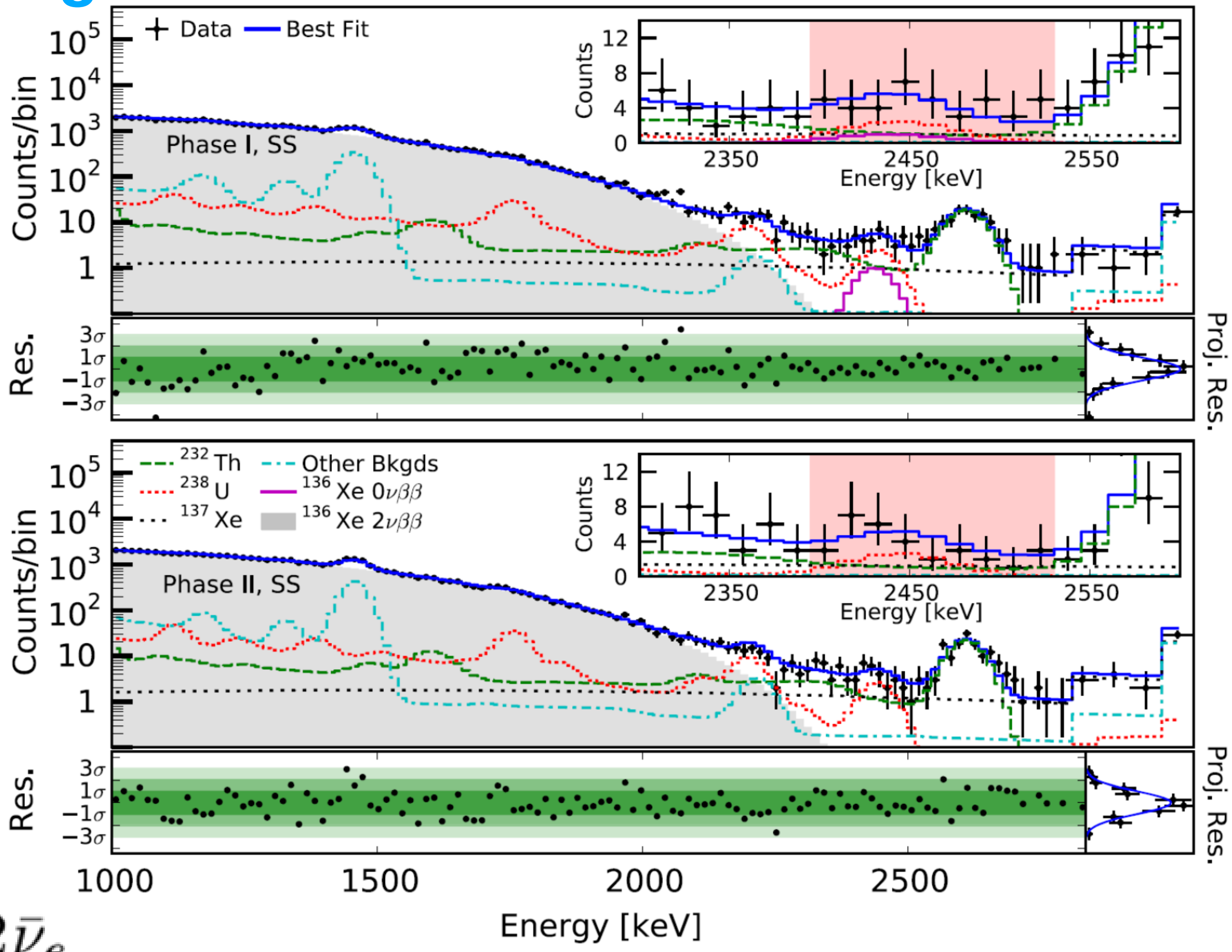
2019 result from complete dataset: $T_{1/2}^{0\nu\beta\beta} > 3.5\times10^{25}$ yr

PRL 123 (2019) 161802

EXO-200 results and backgrounds

- EXO-200 experiment:
  - 200 kg of liquid xenon
  - Data: phase I: 2011 to 2014, phase II: 2016 to 2018
  - Weekly data quality analysis: Jan 2017 to Dec 2018
- No evidence for *0νββ*
- $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr
  - One of the best results
- nEXO: 5 tonnes xenon
- Lowest background level
  - **Barium tagging**

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$
$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$



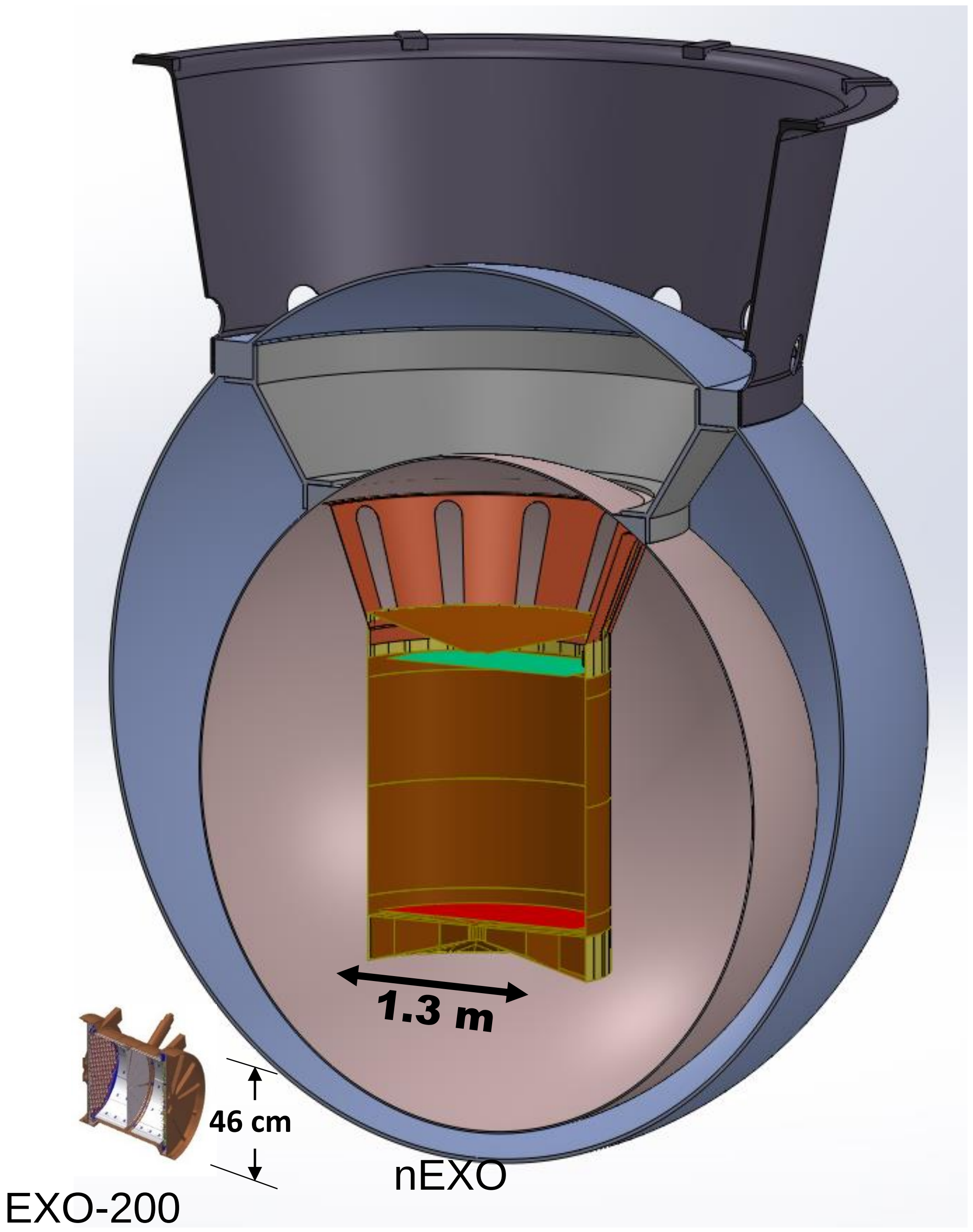
Physical review letters, 123(16):161802, 2019

EXO-200 → nEXO

- Enriched xenon 200 kg → 5000 kg
- Underground: 655 m → 2070 m
- Improved energy resolution
- **Barium tagging**

2νββ: $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$

0νββ: $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$

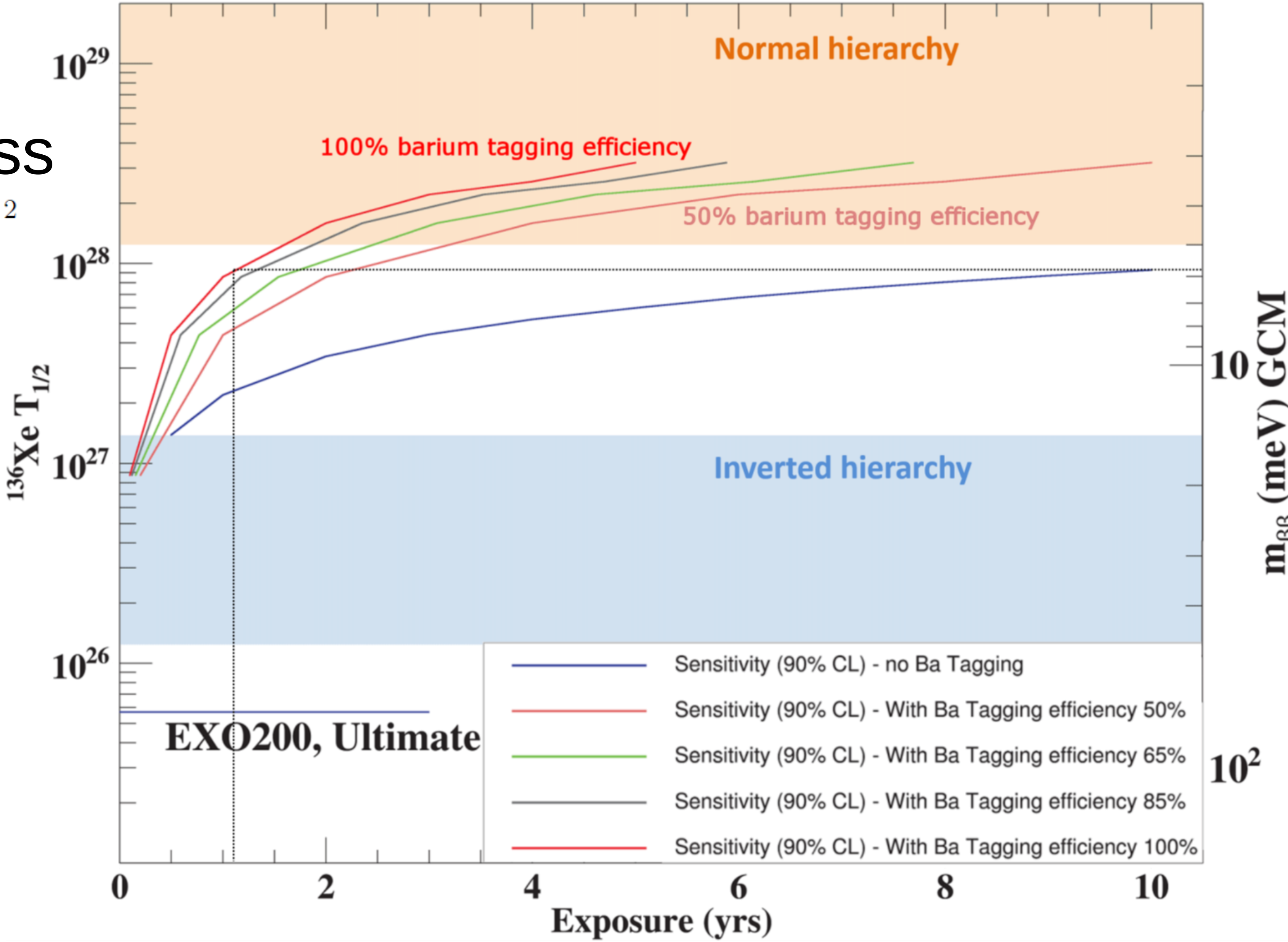


nEXO sensitivity with barium tagging

- *0νββ* vs. neutrino mass

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G|M|^2\langle m_{\beta\beta}\rangle^2 \approx 10^{28}\left(\frac{0.01\,eV}{\langle m_{\beta\beta}\rangle}\right)^2$$

$$\langle m_{\beta\beta}\rangle = \sum_{i=1}^{3} m_i U_{ei}^2$$



Electric potential in a LPT

- Spatial harmonics: $\phi(r,\theta) = \sum_{n=0}^{\infty} A_n \phi_n$

$$\phi_0 = A_0$$

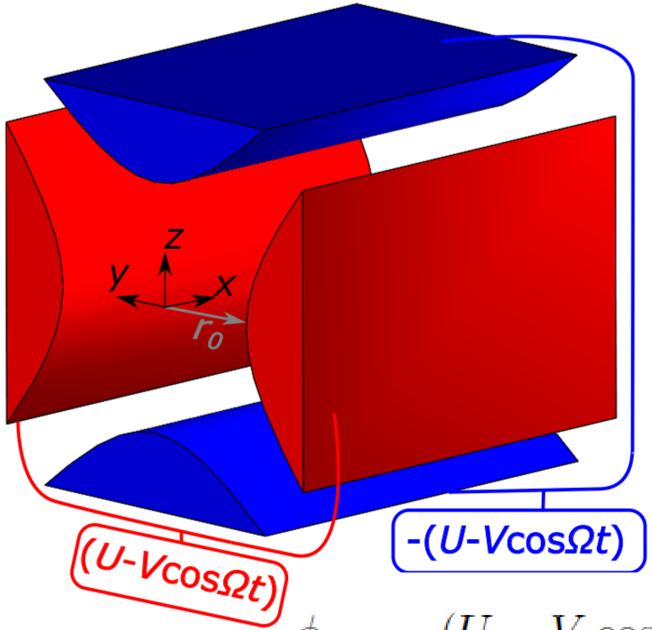
$$\phi_2 = A_2 \frac{y^2 - z^2}{r_0}$$

$$\phi_6 = A_6 \frac{x^6 - 15x^4y^2 + 15x^2y^4 - y^6}{r_0^6}$$

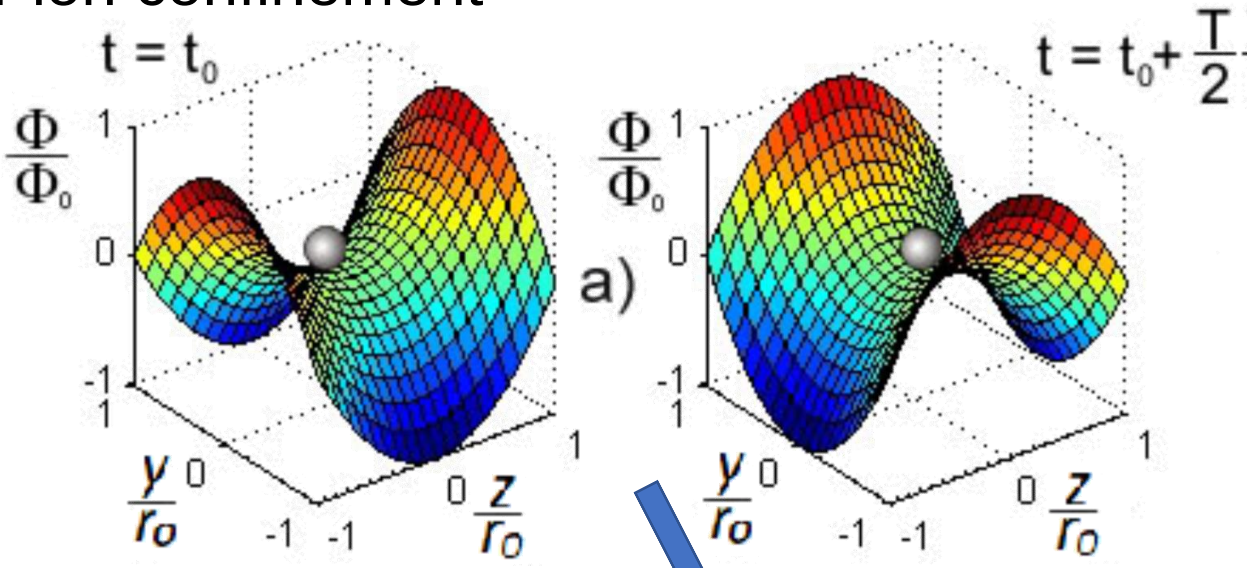
$$\phi_{10} = A_{10} \frac{x^{10} - 45x^8y^2 + 210x^6y^4 - 210x^4y^6 + 45x^2y^8 - 7^{10}}{r_0^{10}}$$

LPT: ion confinement in radial directions

- Radio frequency quadrupole (RFQ) for ion confinement

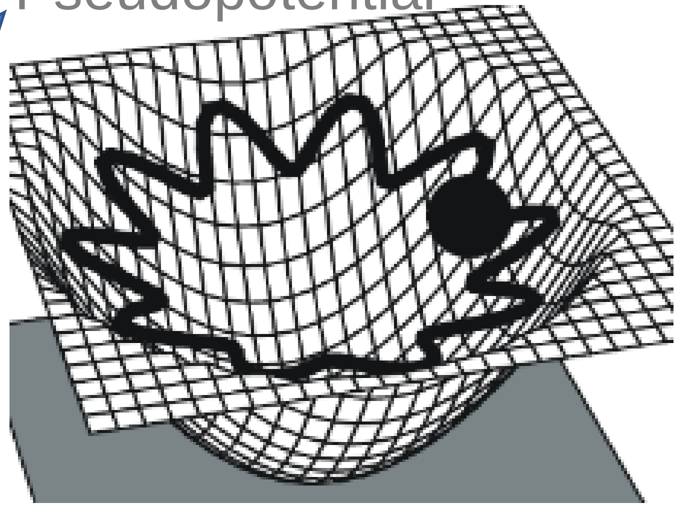


$$\phi_{RF} = (U - V\cos\Omega t)\frac{(y^2 - z^2)}{r_0^2}$$



Vary at radio frequency

Pseudopotential



Micromotion: Ω

Figure credit: Molhave (2000)

Macromotion: *ω=βΩ/2*

- Ion's equation of motion:

$$m\frac{d^2y}{dt^2} = \frac{-2ey}{r_0^2}(U - V\cos\Omega t)$$

$$m\frac{d^2z}{dt^2} = \frac{2ez}{r_0^2}(U - V\cos\Omega t)$$

$$\xi = \frac{\Omega t}{2}$$

$$a_y = -a_z = \frac{8eU}{m\Omega^2 r_0^2}$$

$$q_y = -q_z = \frac{4eV}{m\Omega^2 r_0^2}$$

$$u = y \text{ or } u = z$$

Mathieu equation:

$$\frac{d^2u}{d\xi^2} + (a - 2q\cos 2\xi)u = 0$$

Mathieu parameters:

$a \propto U, q \propto V$

$$\beta \approx \sqrt{(a + \frac{1}{2}q^2)} \quad (\beta \ll 4)$$

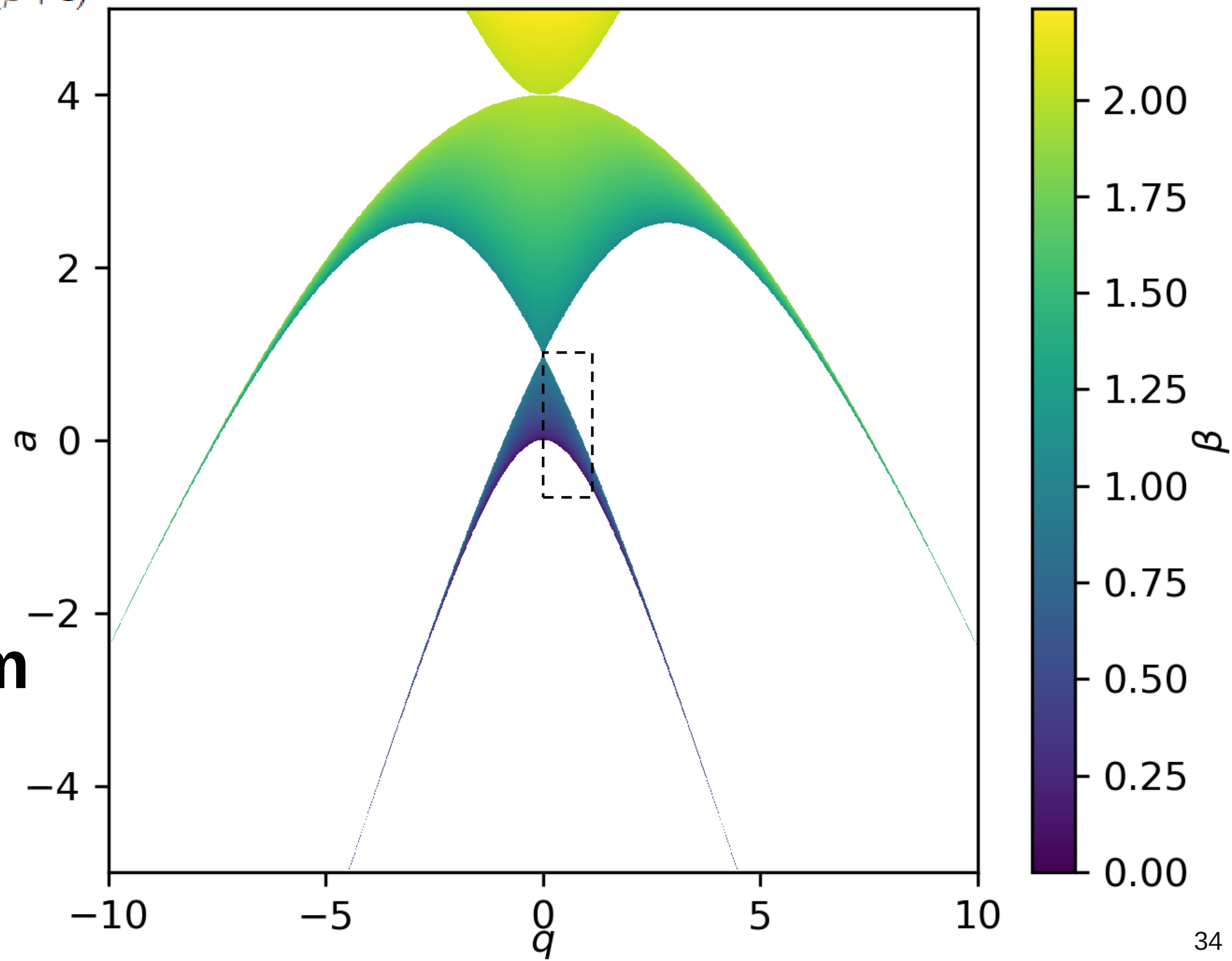
Mathieu equation: analytical solution from first principles

$$u(\xi) = A \sum_{n=-\infty}^{\infty} C_{2n} \cos[(\beta + 2n)\xi] + B \sum_{n=-\infty}^{\infty} C_{2n} \sin[(\beta + 2n)\xi], \quad \xi = \frac{\Omega t}{2}$$

- Stable solution & ion confinement: β is a real and non-integer number

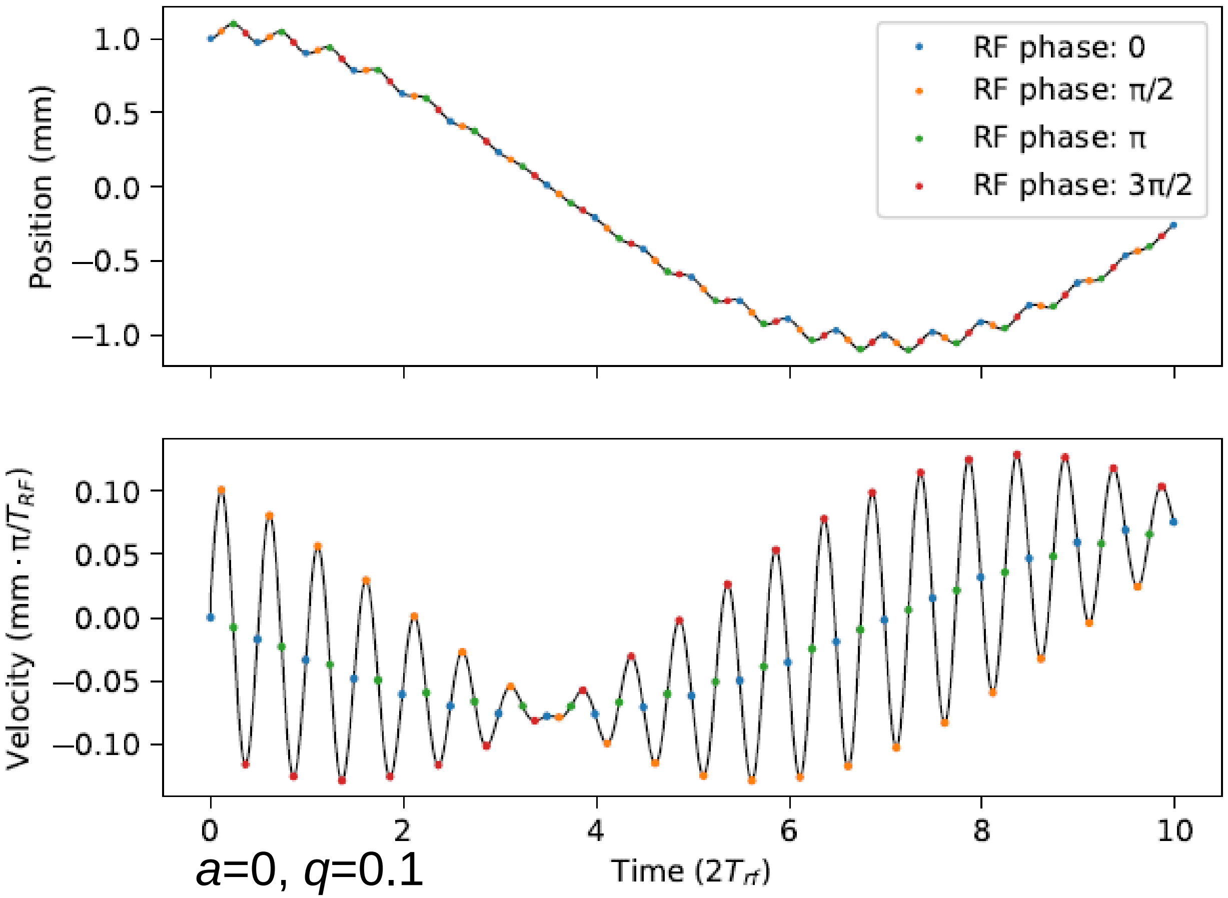
$$\beta = \sqrt{a - \frac{q^2}{a - (\beta-2)^2 - \frac{q^2}{a-(\beta-4)^2-\cdots}} - \frac{q^2}{a - (\beta+2)^2 - \frac{q^2}{a-(\beta+4)^2-\cdots}}}$$

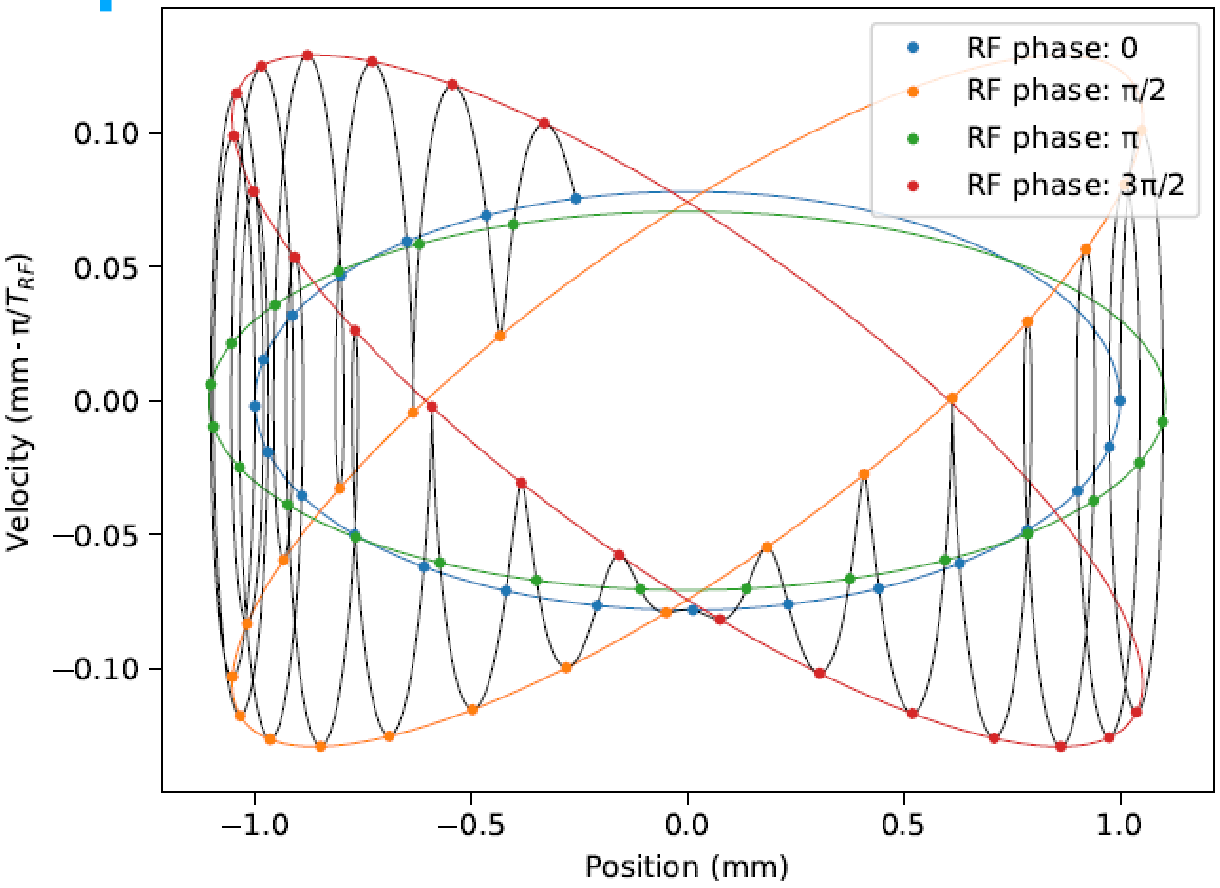
- β: no analytical solution
  - Only approximations in literature
- New approach: iterative method
  - $\beta_0 = 1 + 0j,\ \beta_{n+1} = \beta(a, q, \beta_n)$
  - $n = 1000$, convergence < 10^{-15}
  - **Analytical solution of β for any (q, a)**
- **First detailed Mathieu stability diagram**
  - **Exact analytical solution of beta**
  - **Analytical solution for ion motion**

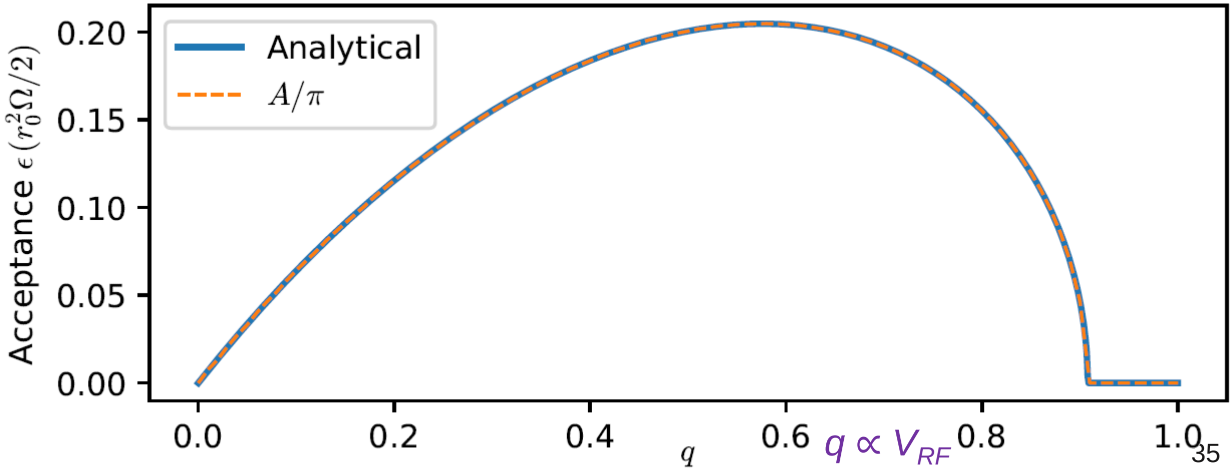


Ion motion and ion acceptance ellipses ϵ

- Analytical solution of Mathieu equation



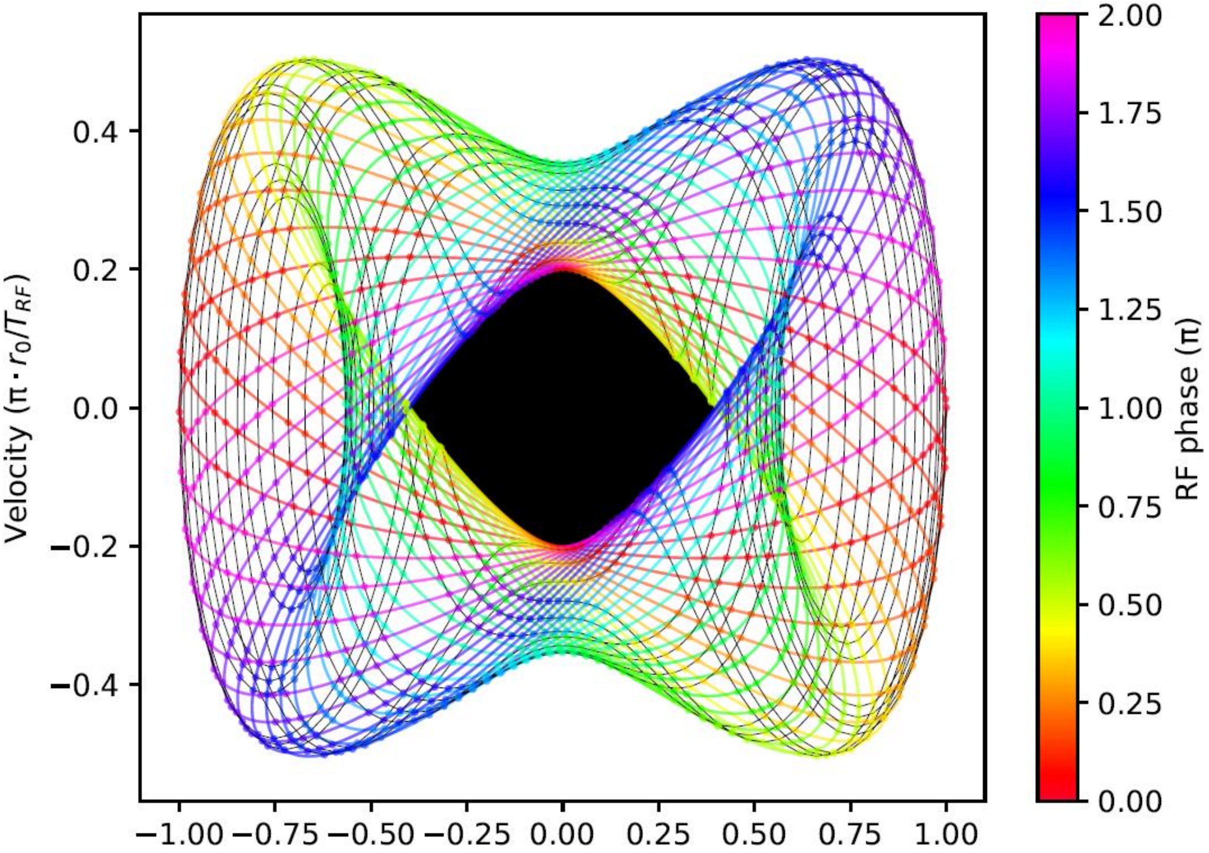




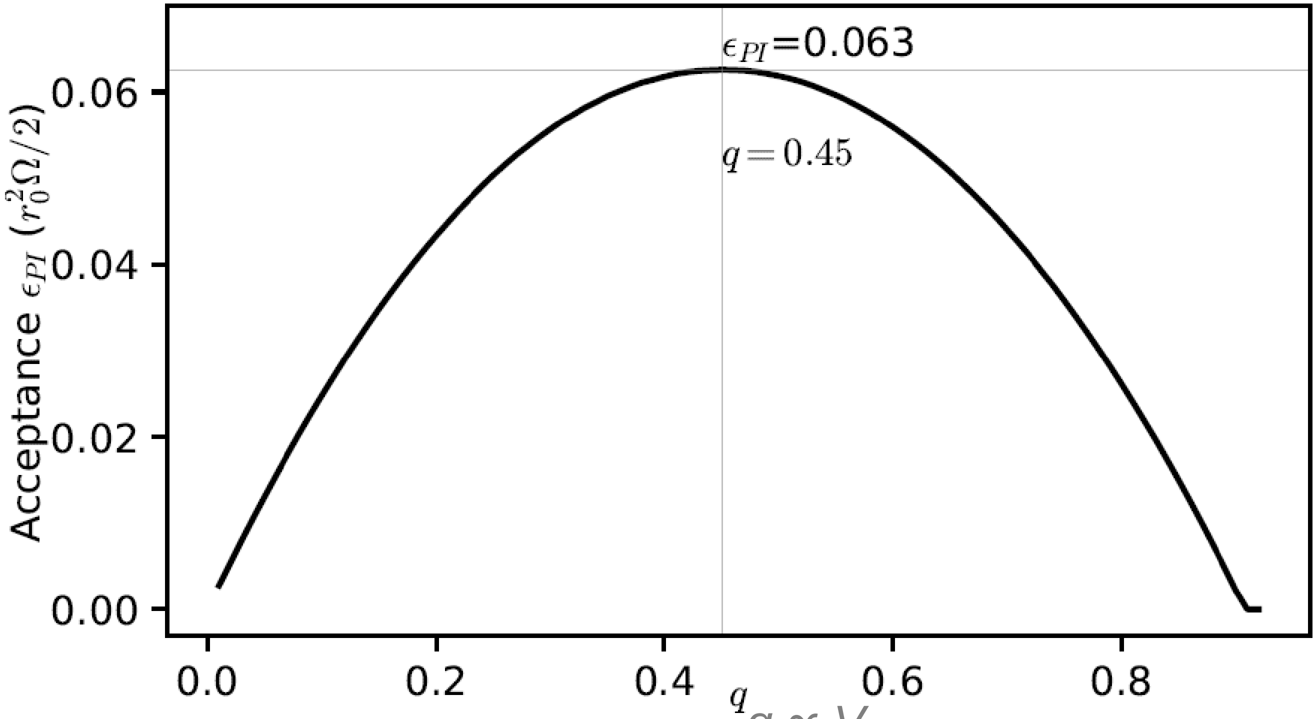
- Ion acceptance ϵ: area of ellipses in phase space
- **Analytical solution of acceptance for any (q,a)**
- Maximum ion transmission: a=0, $q \approx 0.6$

Phase-independent ion acceptance ϵ_{PI}

- To capture all extracted ions
  - Accept ions at any RF phase
  - **ϵ_{PI} : overlapped ion acceptance**



a=0, *q*=0.5



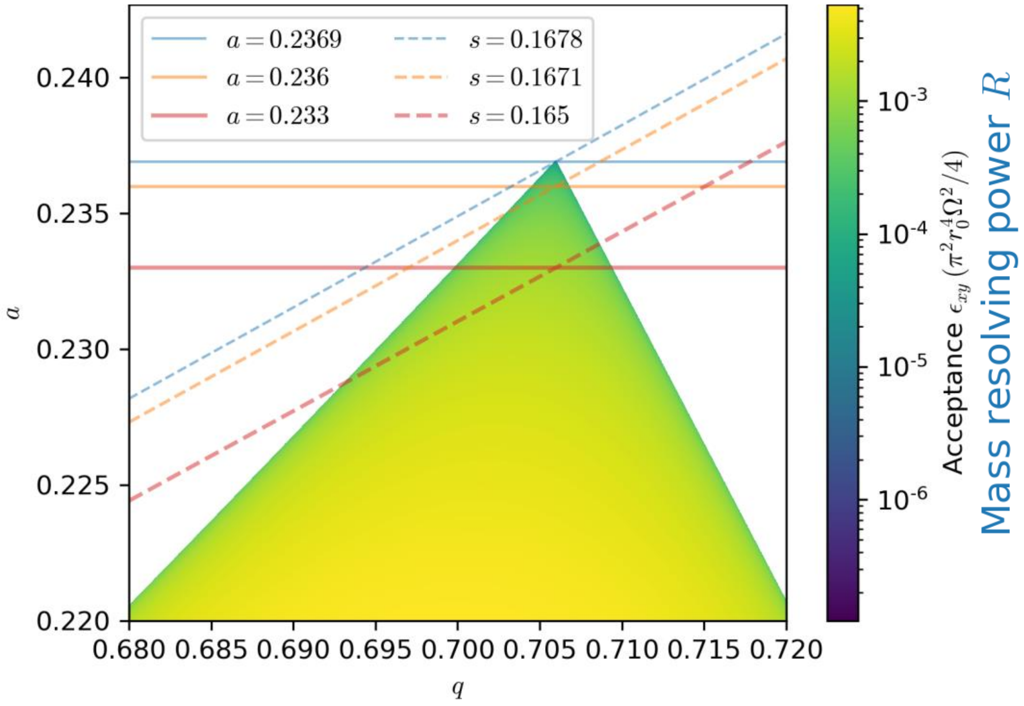
$q \propto V_{RF}$

LPT design parameters:

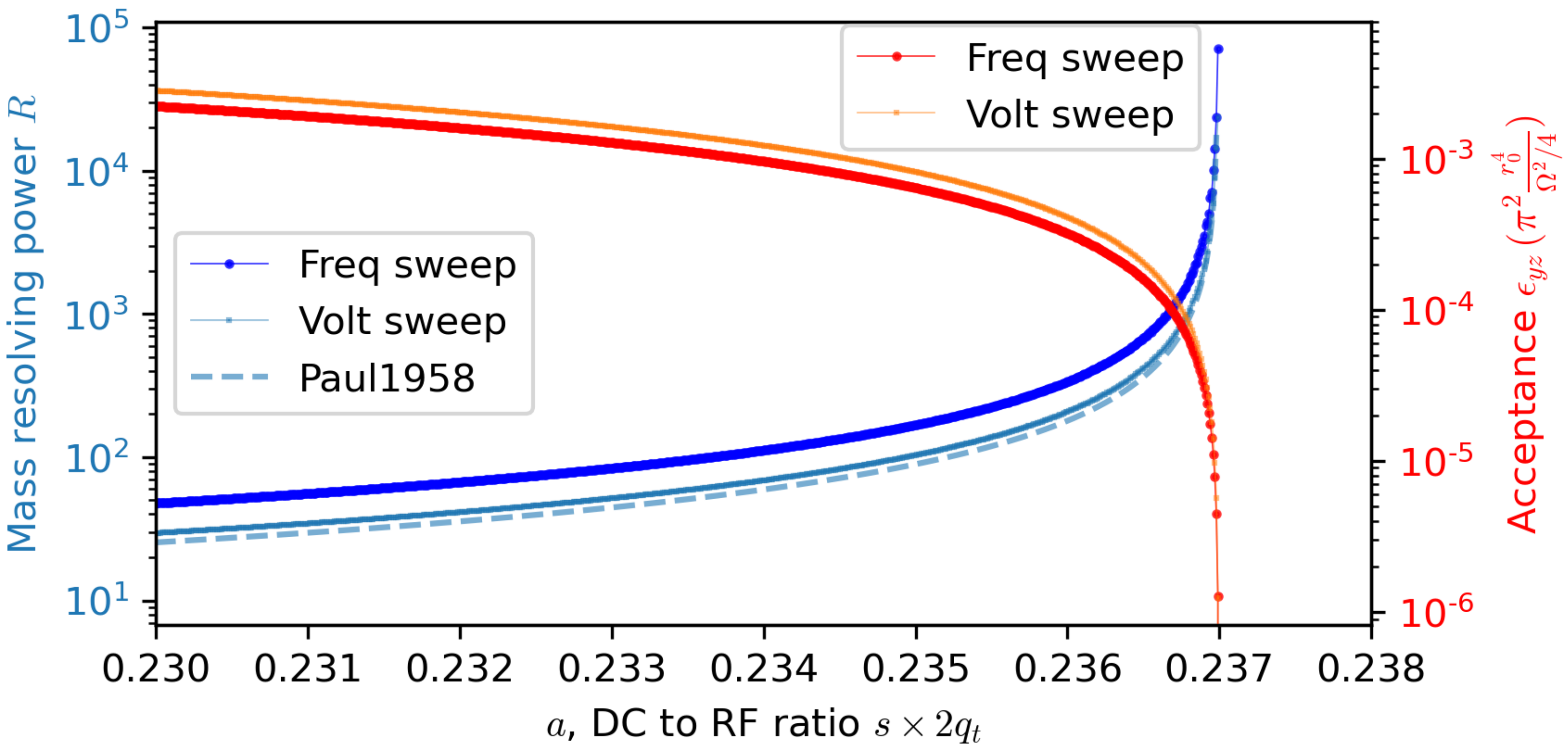
- ***q=0.45***, r_0=3.51 mm, *f*=1 MHz, V_{RF}=77 V:
  - **ϵ_{PI}= 2.44 mm·mm/μs,**
- **can captures >99% of extracted ions** ✓
  - 2D Gaussian distributed
  - $\epsilon_{PI} \approx \epsilon_{4rms}$
- **Meets requirement**

Ion acceptance of quadrupole mass filter (QMF)

- Ion acceptance ϵ analytically calculated for any (*q*,*a*)



- When ions are abundant and uniformed distributed, ion transmission rate ***T*** is proportional to ***ϵ*: *T*∝*ϵ***

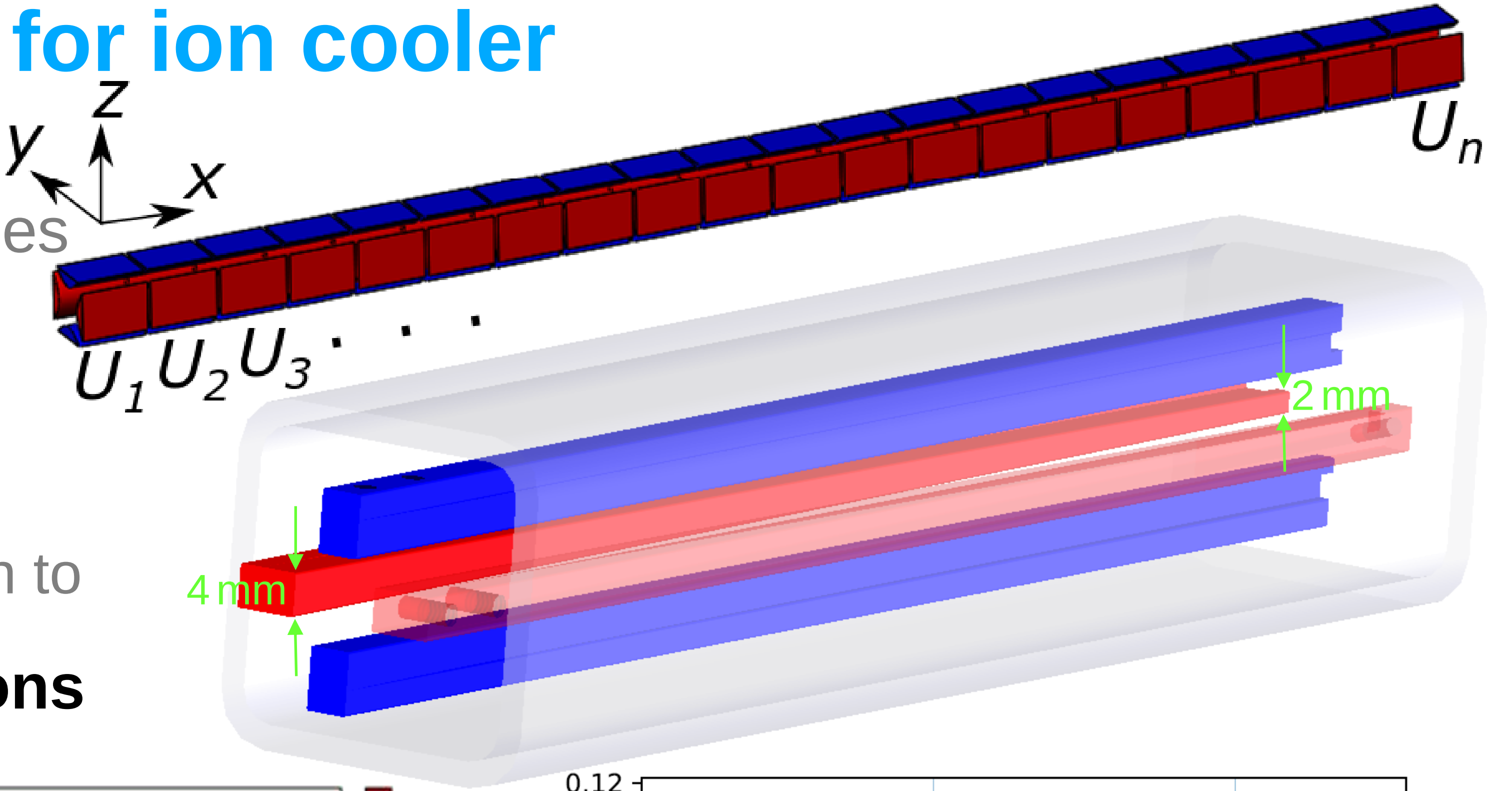


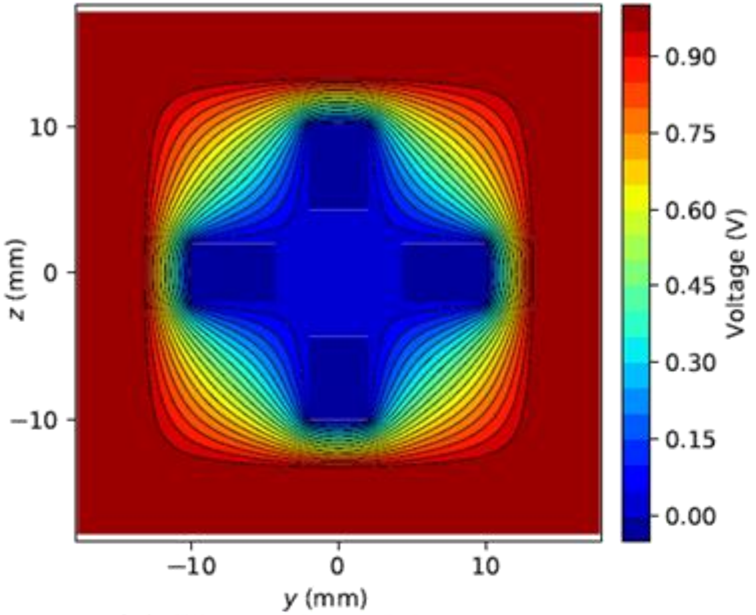
- For validating simulations and experiments
  - **Mass resolving power *R* (*m*/*Δm*)**
  - **Ion transmission rate *T***

A manuscript prepared for submission to *Physical Review Letters*

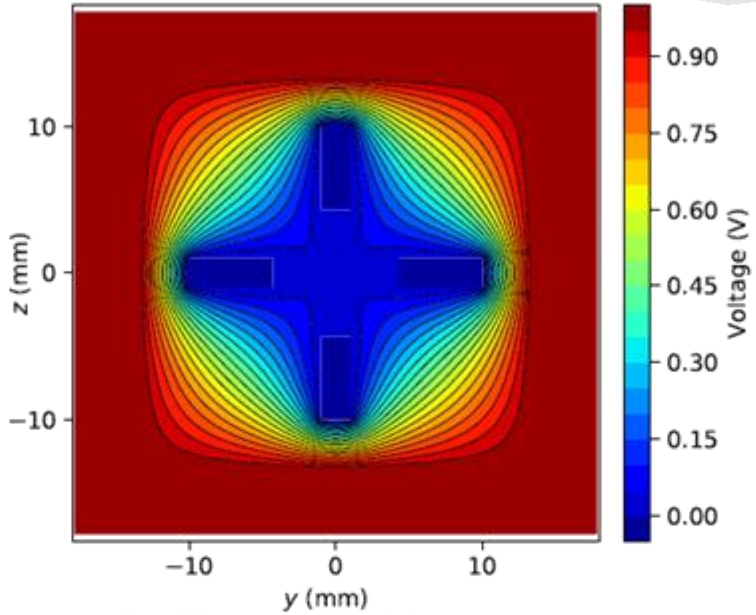
Novel electrode geometry for ion cooler

- Classical design
  - Segmented quadrupole electrodes to form potential gradient
- **Novel design**
  - Tapered electrodes
    - Varying electric field penetration to form potential gradient
  - **Simplified electrical connections**

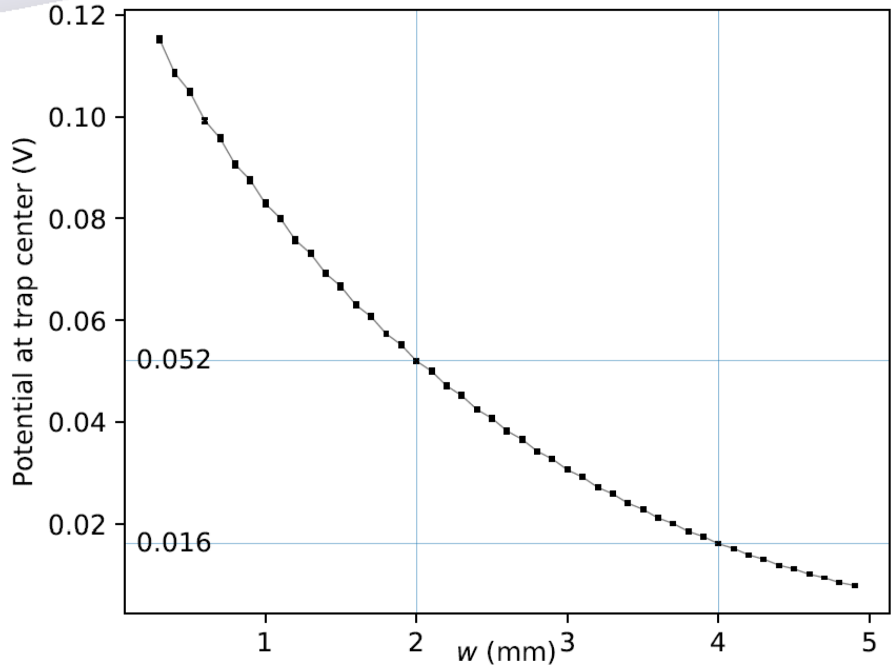




(a) Electrode width $w = 4\,\mathrm{mm}$

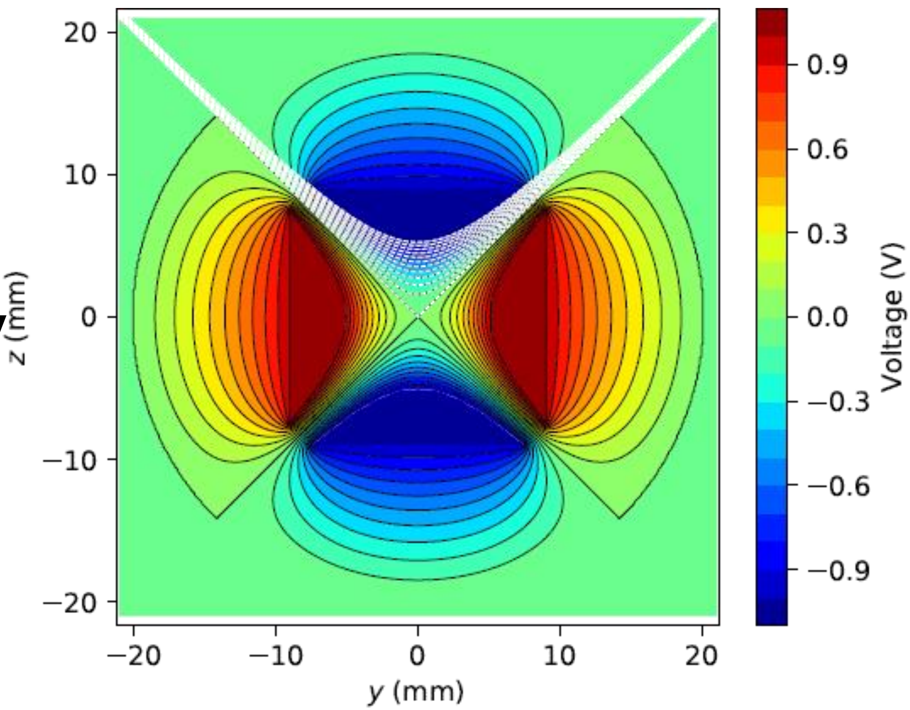


(b) Electrode width $w = 2\,\mathrm{mm}$

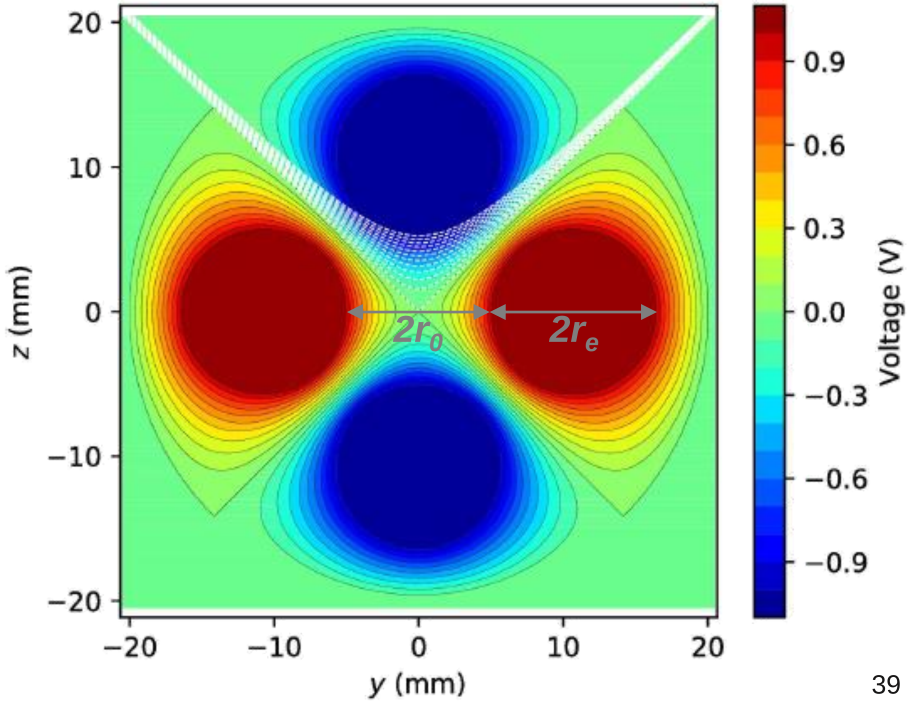


A realistic LPT: electrode geometries

- Hyperbolic shape is ideal but mechanically difficult

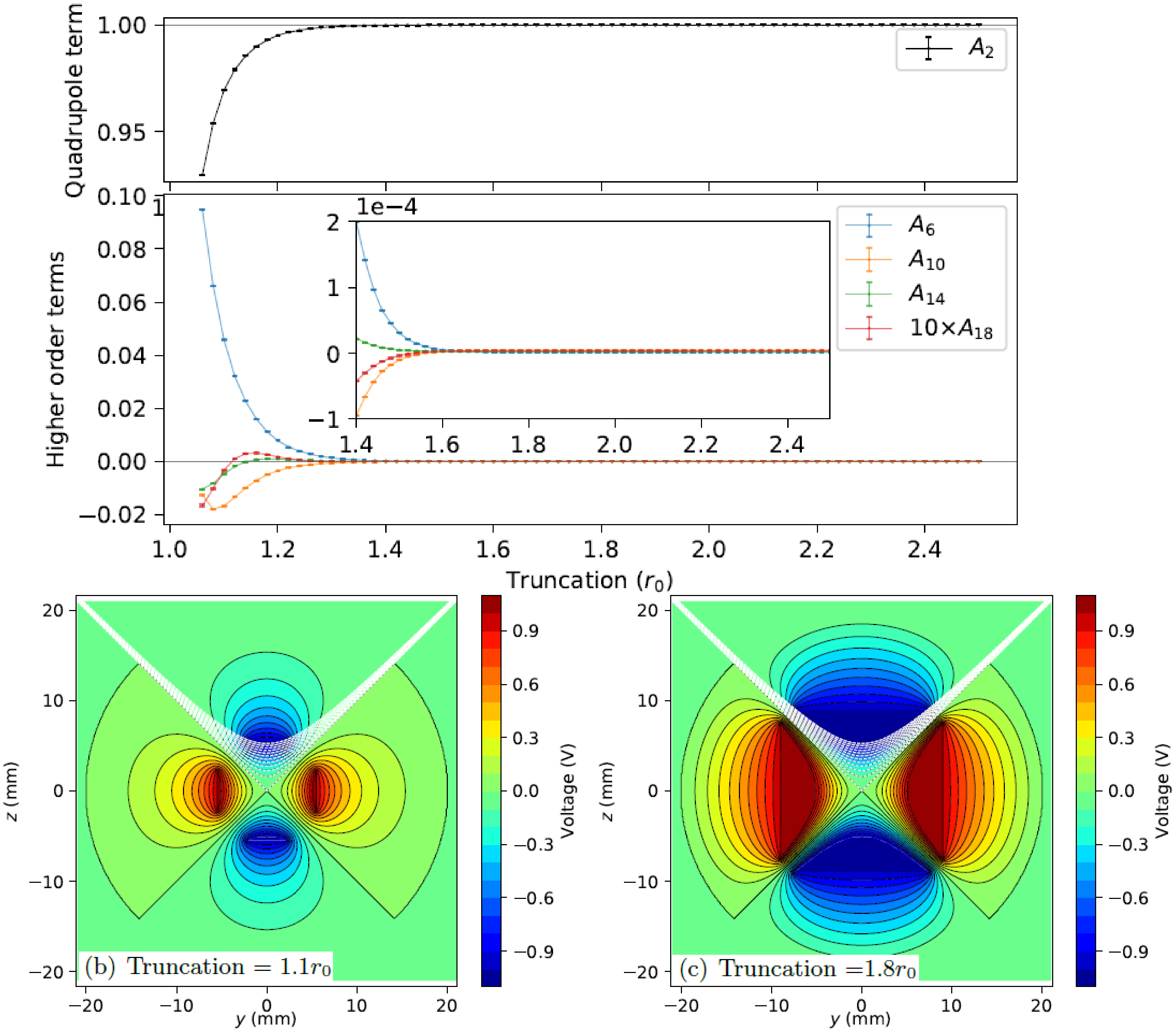


- Round electrodes are easier to machine and assemble
  - Studied electric potential
    - Purity of quadrupole potential
    - Effects on ion transmission
  - **Optimum parameter: r_e/r_0=1.13**



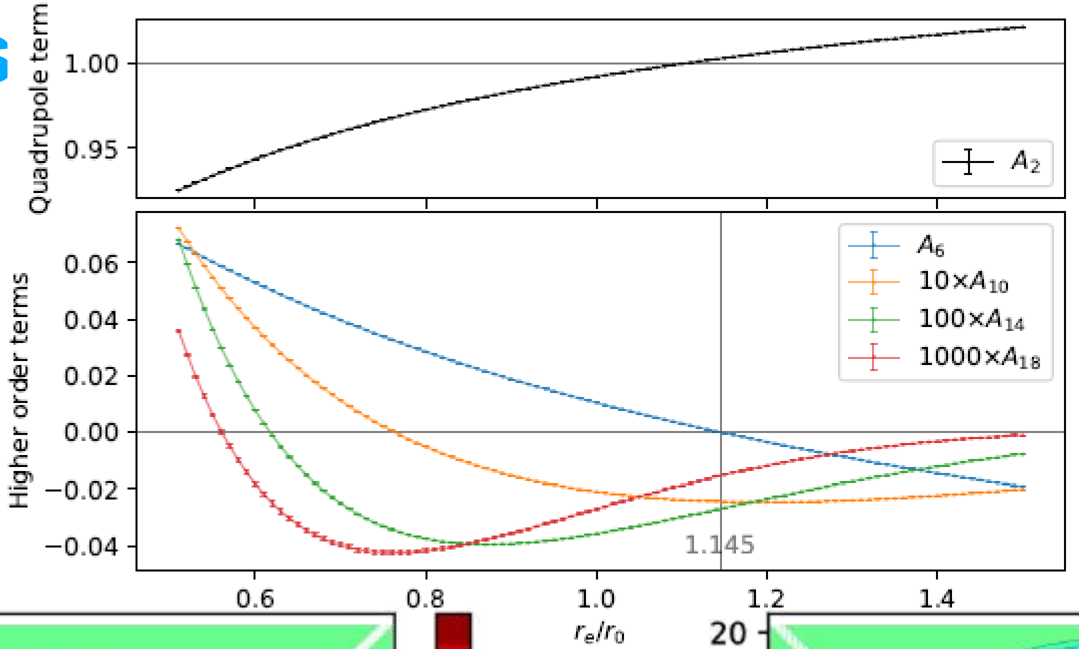
Truncated hyperbolic electrodes

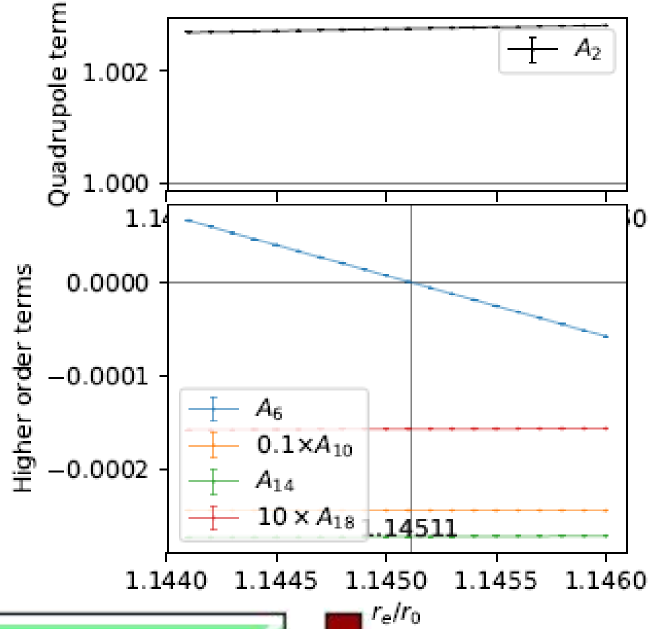
- Ideal quadrupole potential when truncated at > 1.8r_0

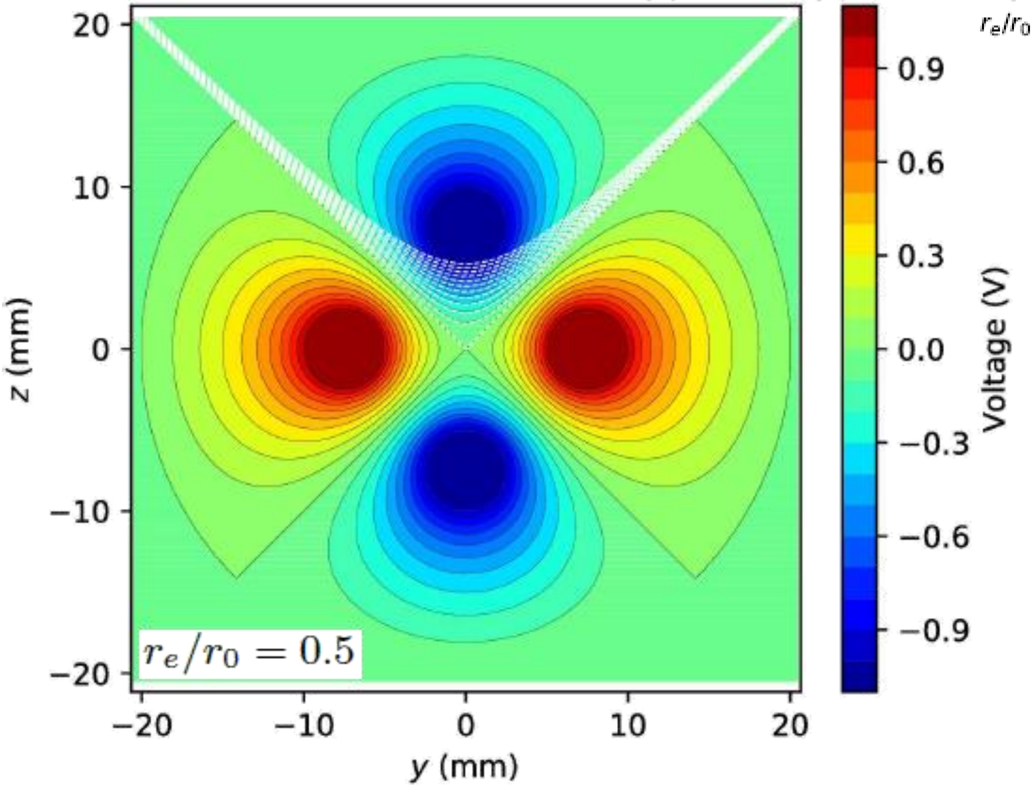


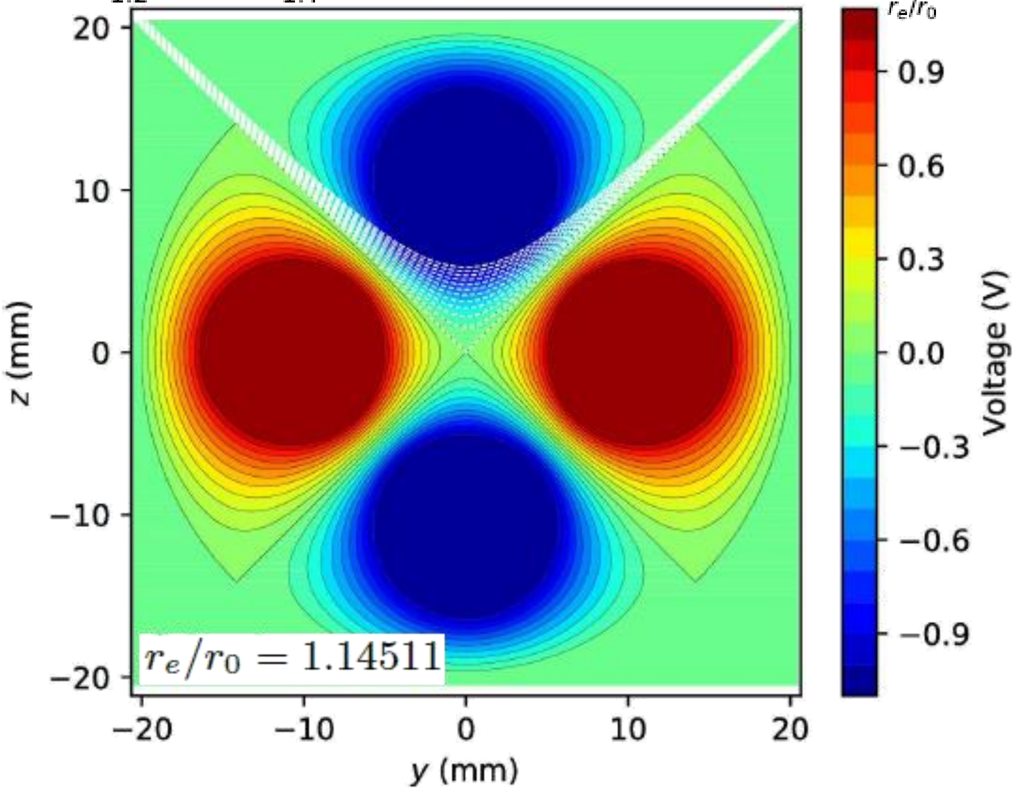
Round electrodes

- “Magic ratio” r_e/r_0=1.14511 for A_6=0
- However, not best for ion transmission



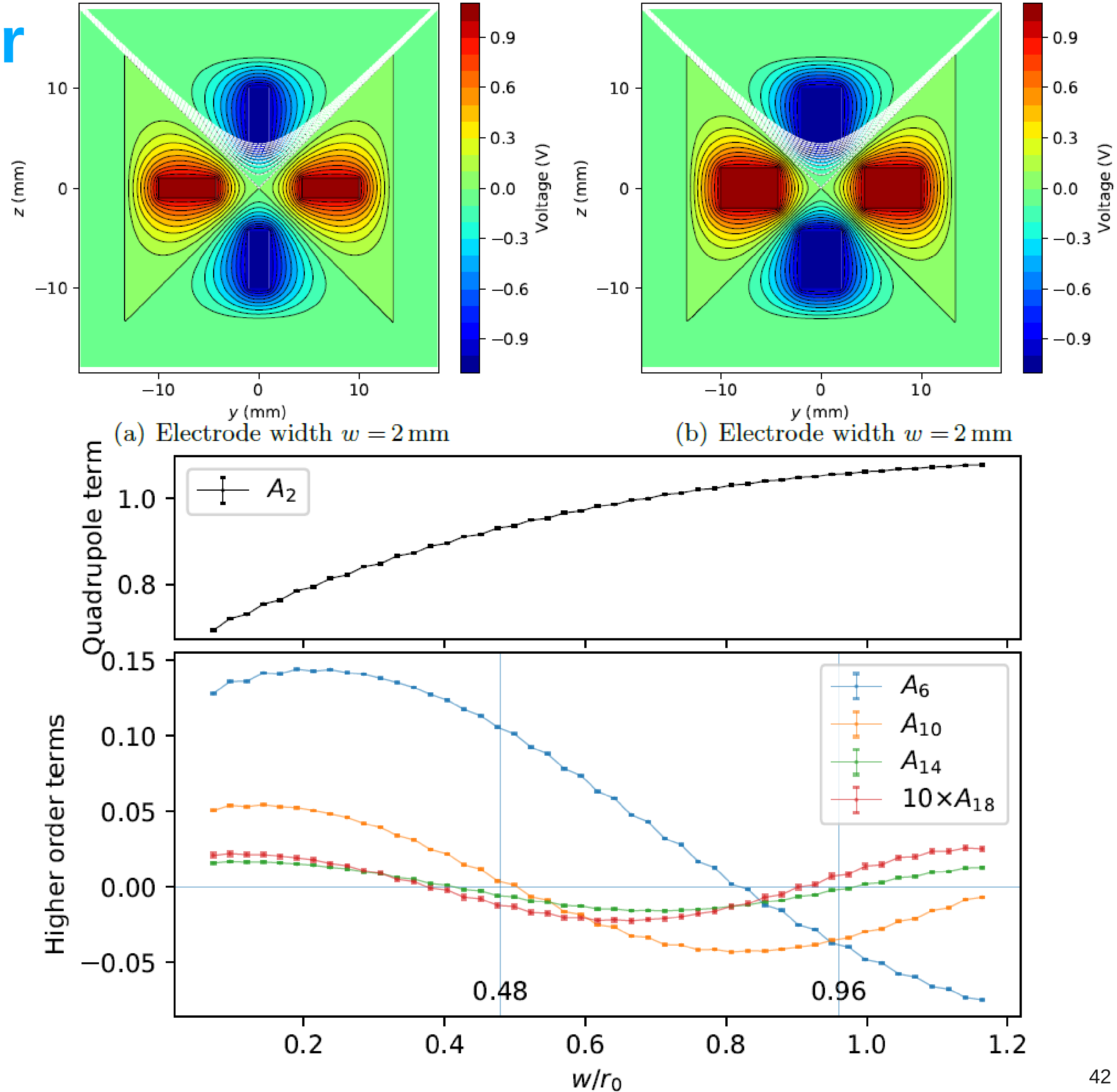






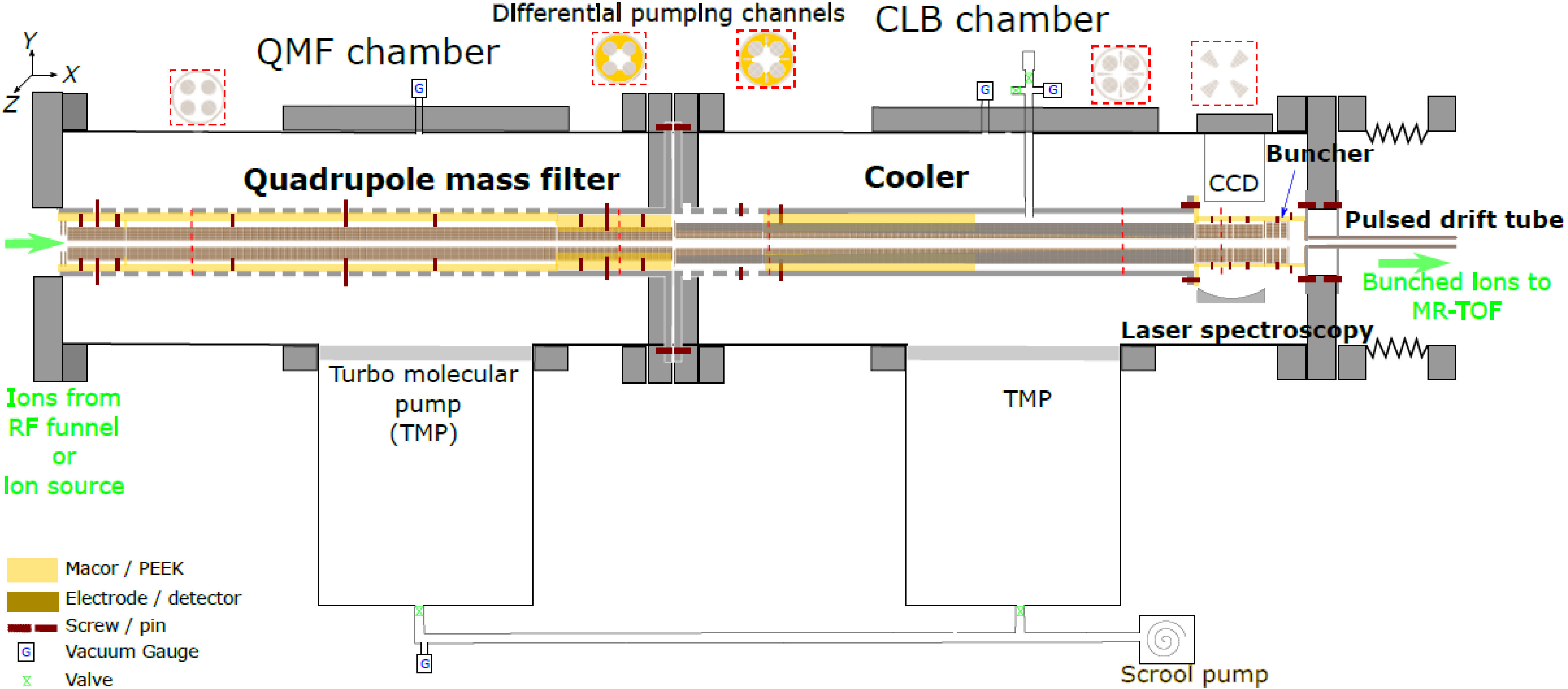
Novel electrodes for cooler

- Tapered quadrupole to also provide DC potential gradient
- Varying electric field penetration

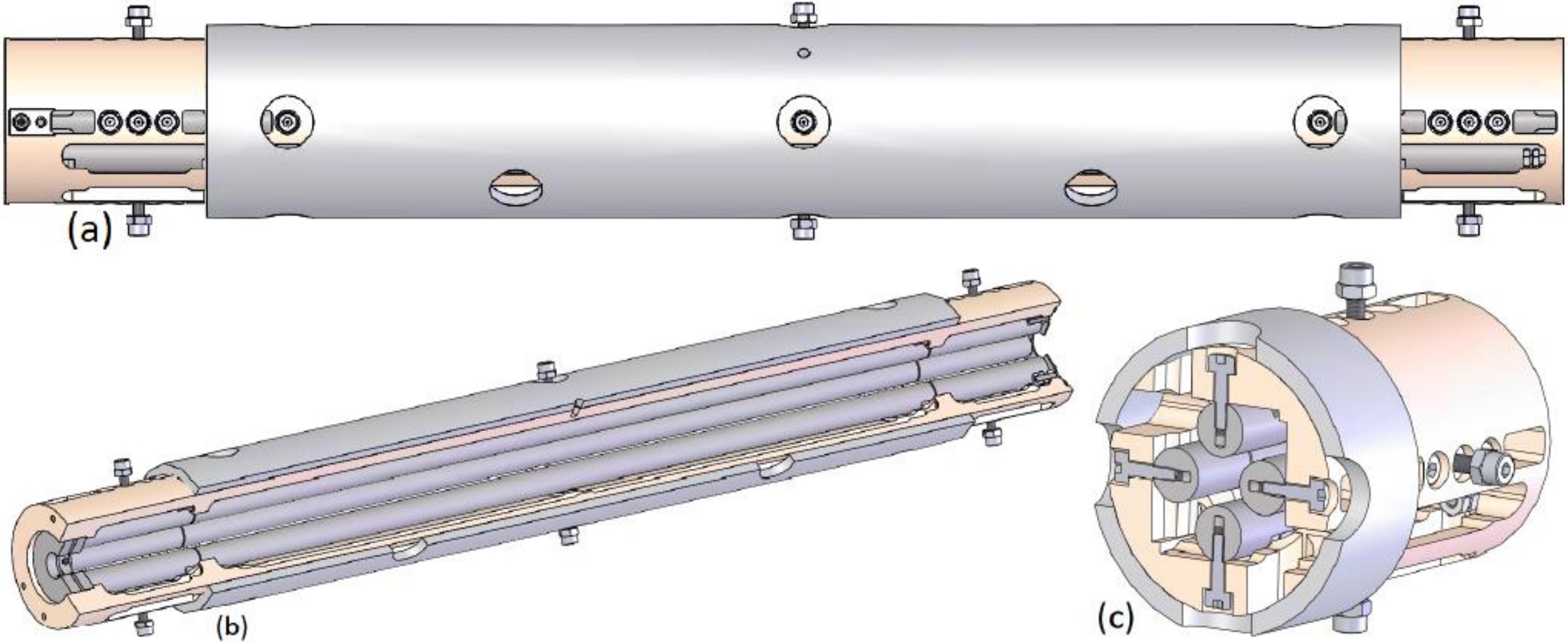


LPT conceptual design

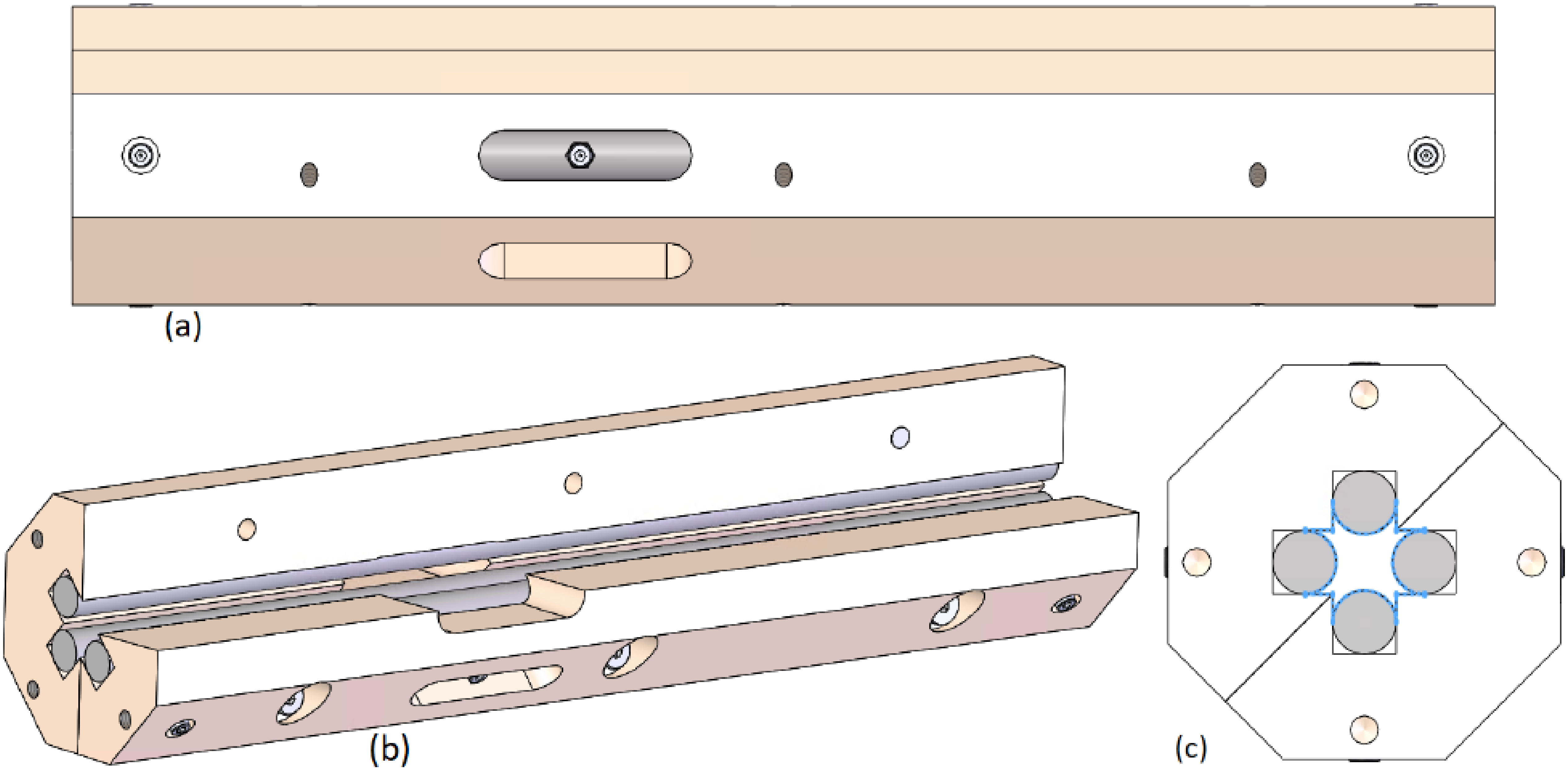
- Ensure mechanical precision and alignment
  - QMF needs **<50 µm** positional precision, others **~ 0.1 mm**
- Effective differential pumping:
  - Apertures and long channels



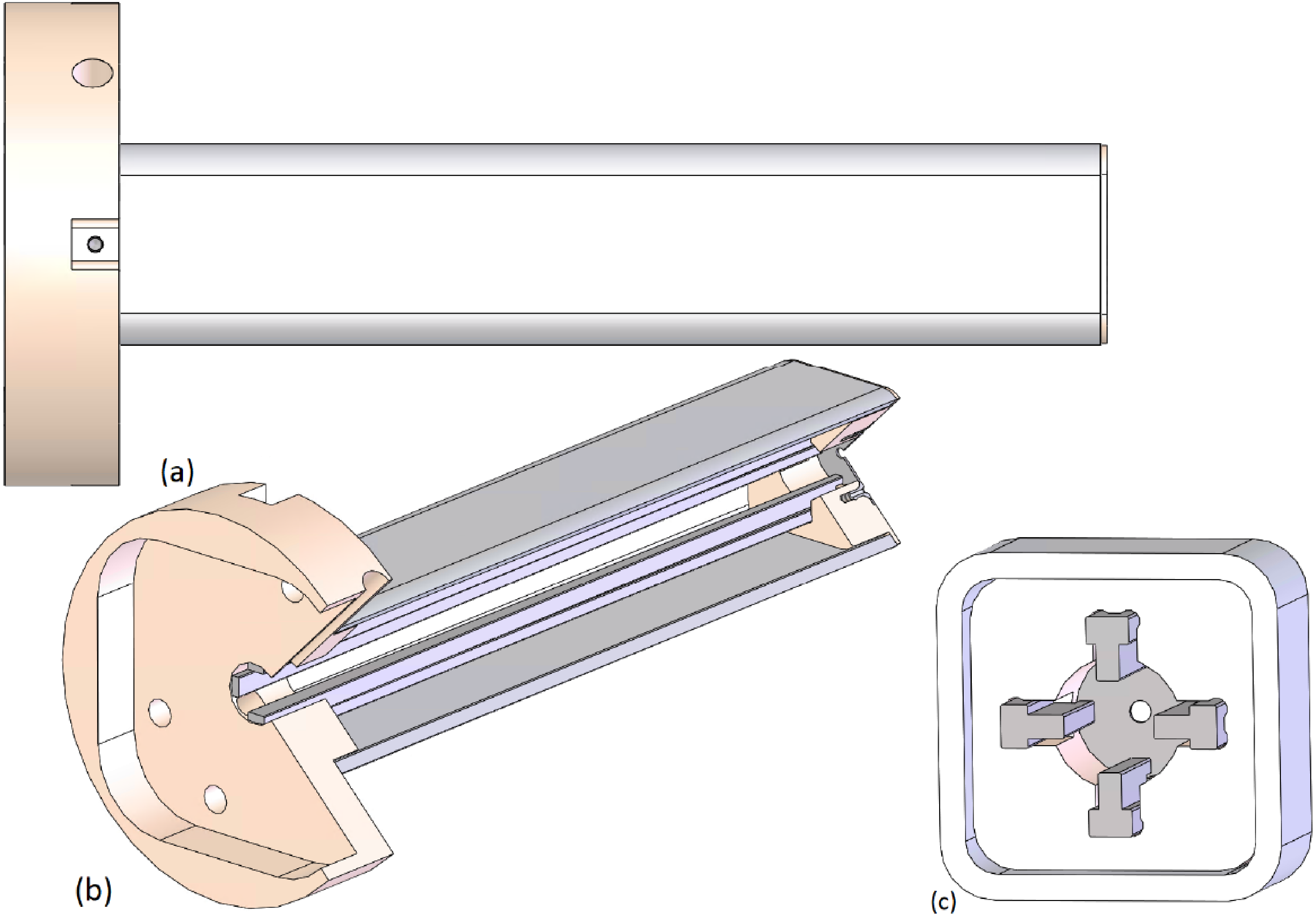
QMF design



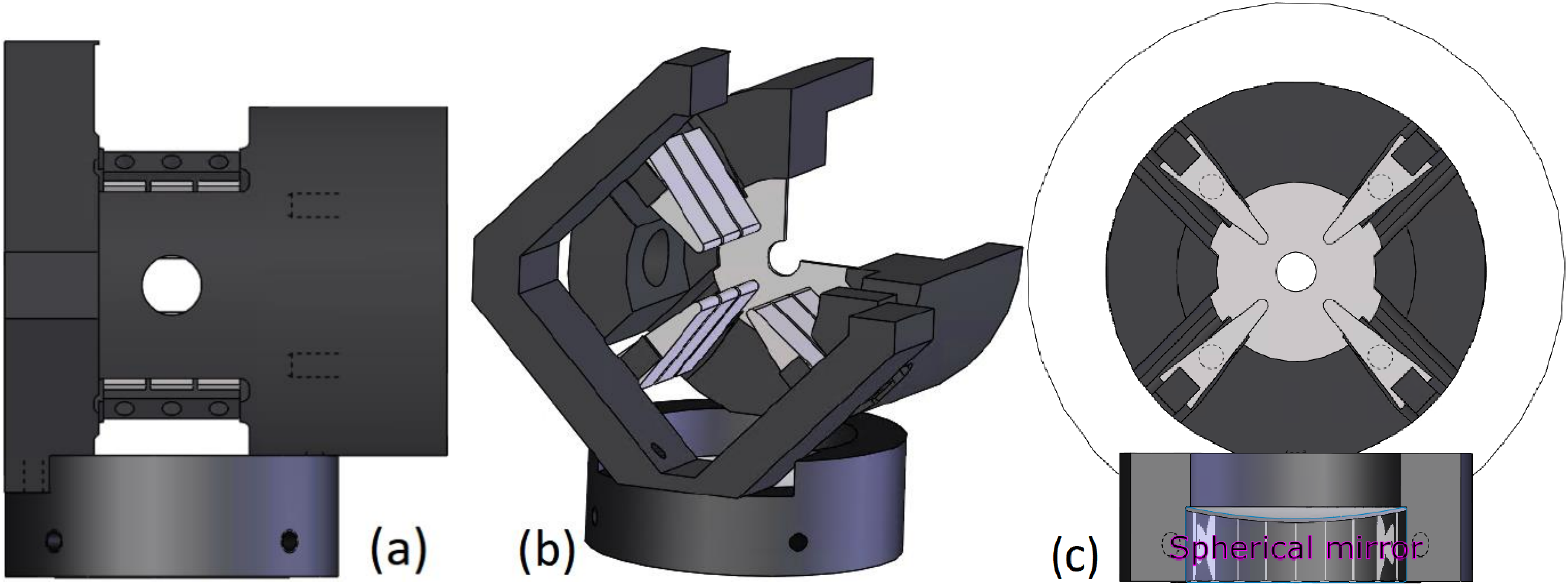
Pre-cooler design



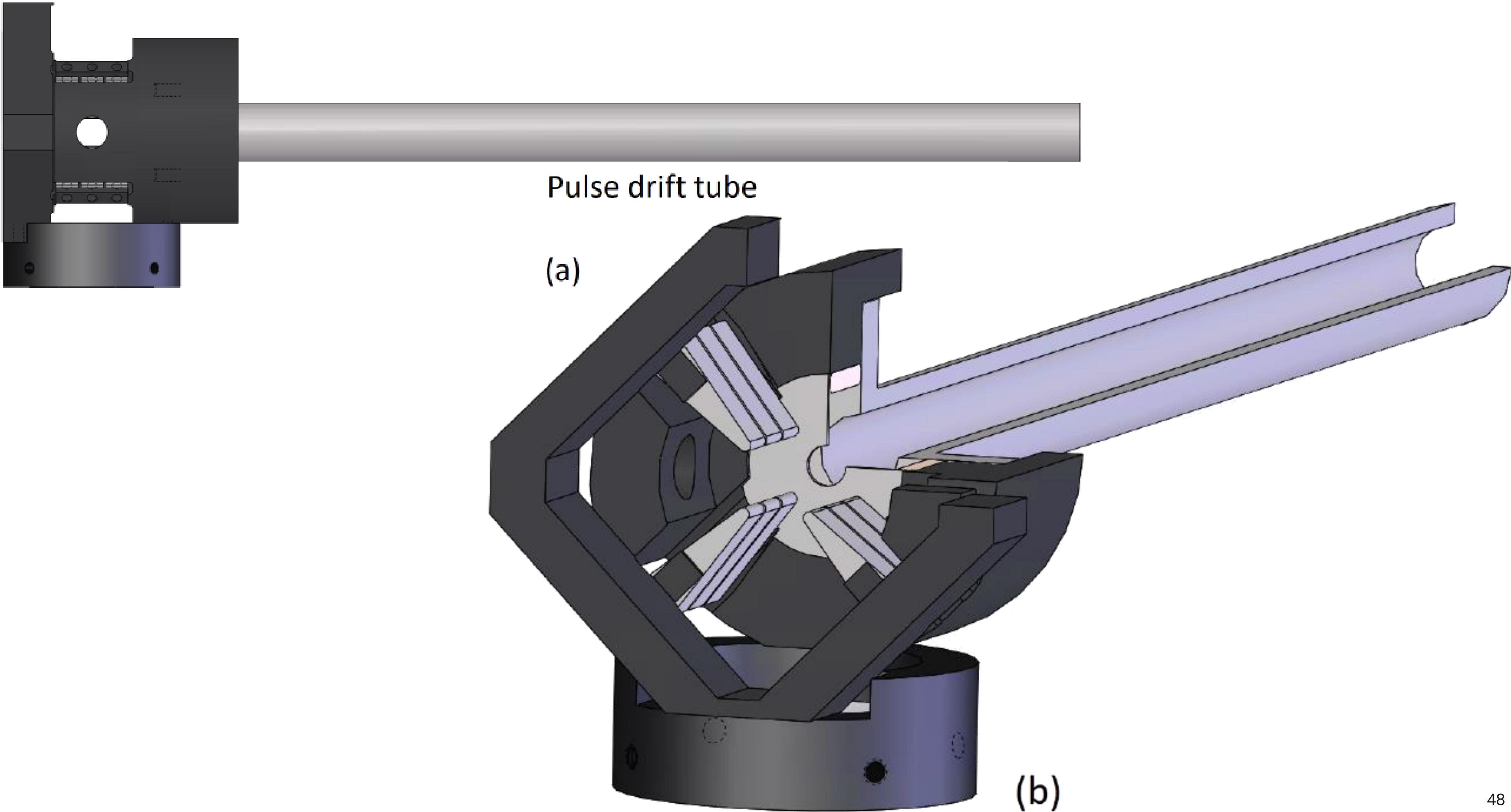
Ion cooler design



Laser spectroscopy ion trap design

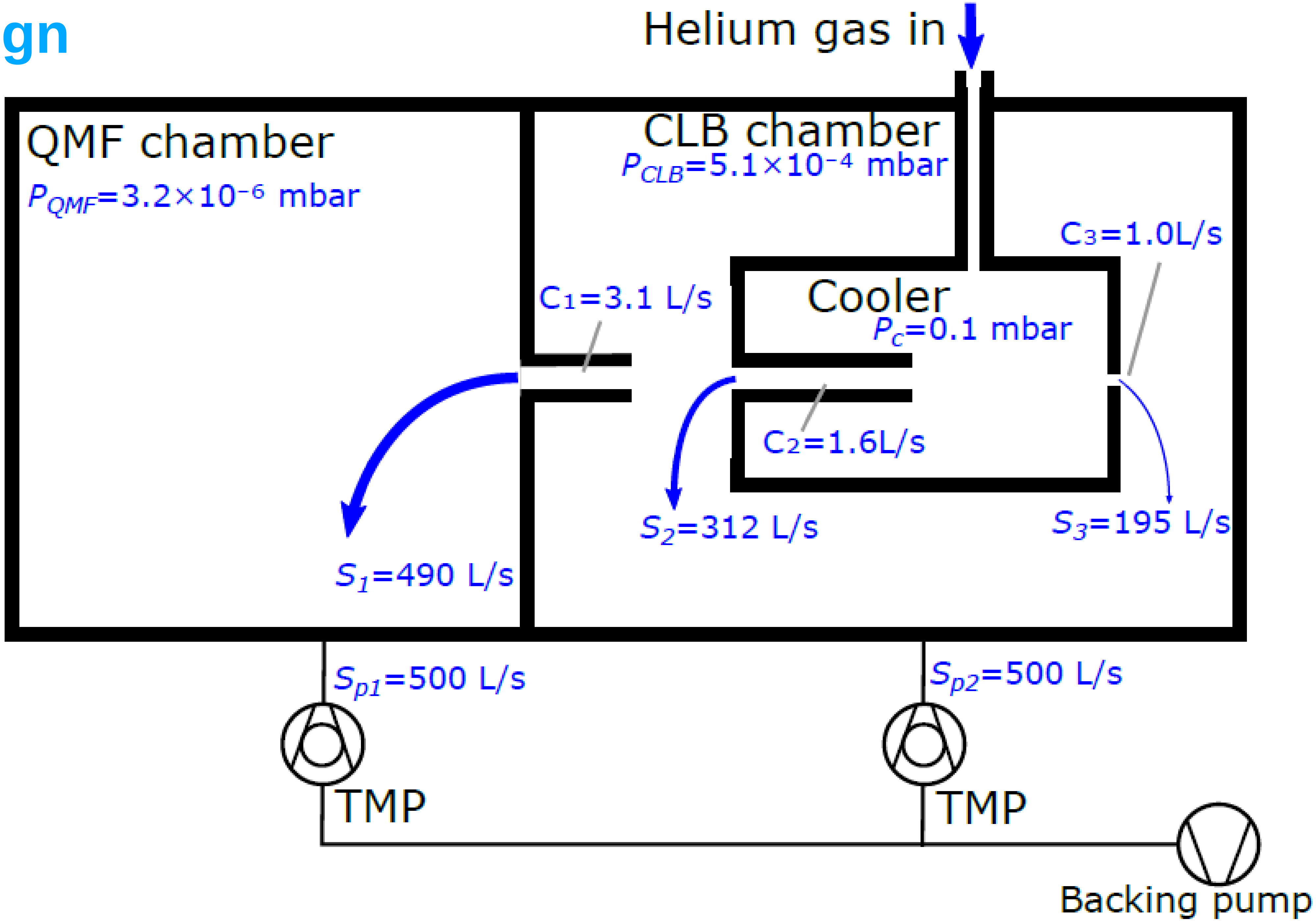


Ion buncher design



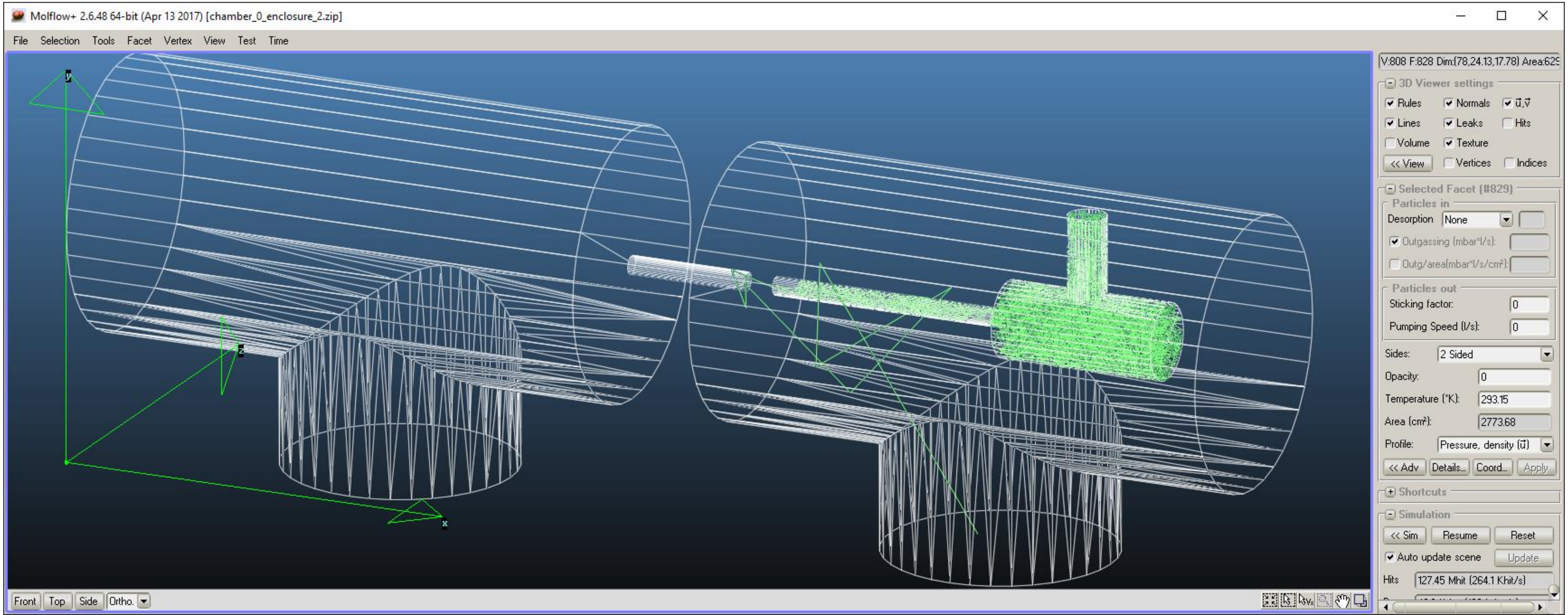
Vaccum design

- Different pressure requirements
- Differential pumping through apertures and channels



Vacuum simulation

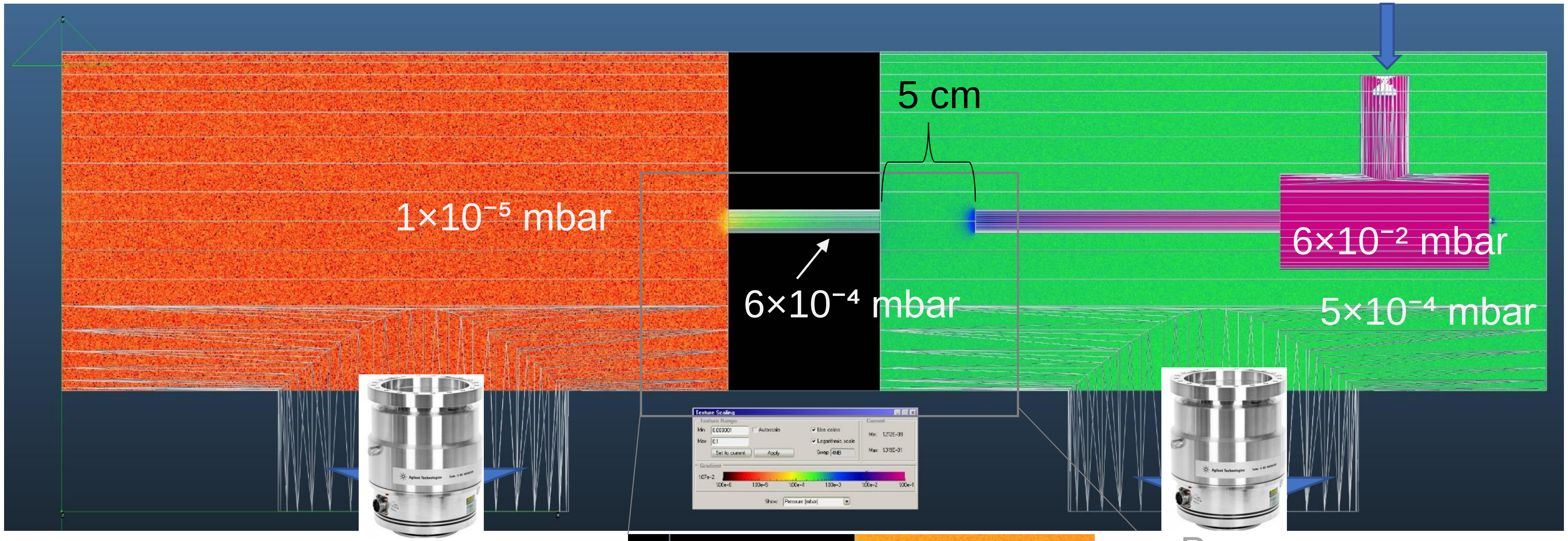
- Tool: Molflow+ (https://molflow.web.cern.ch)
  - Molecular flow simulation using ray-tracing
- Simplified geometry



Vacuum simulation

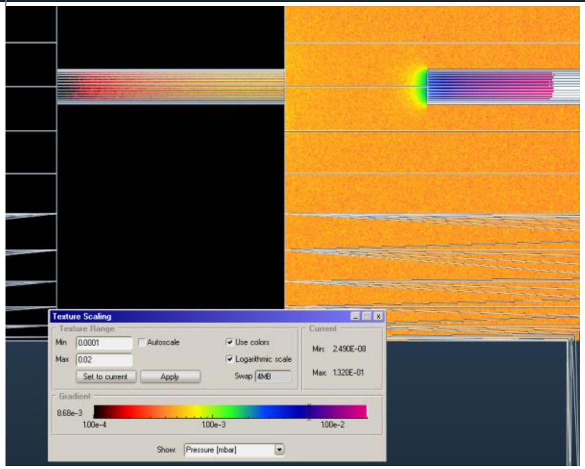
- Tool: Molflow+ (https://molflow.web.cern.ch)
  - Molecular flow simulation using ray-tracing

Helium gas in



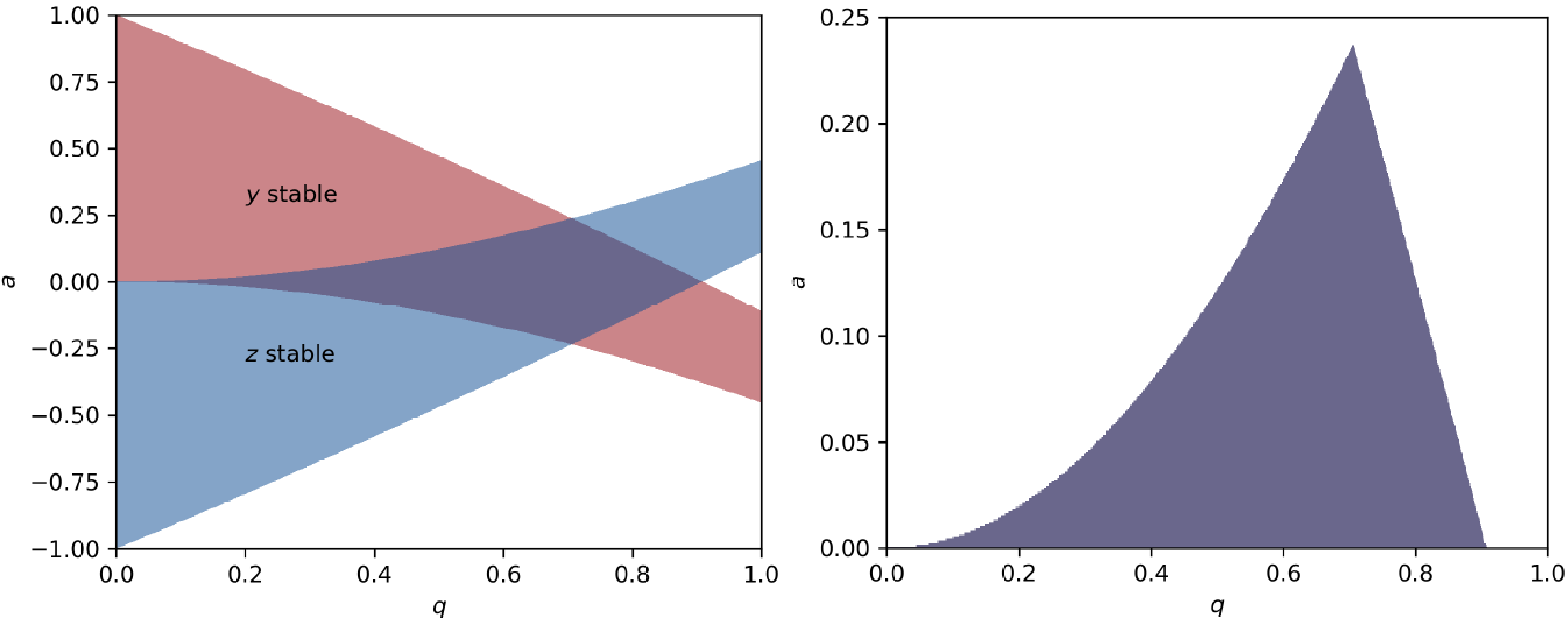
Pump

Pump



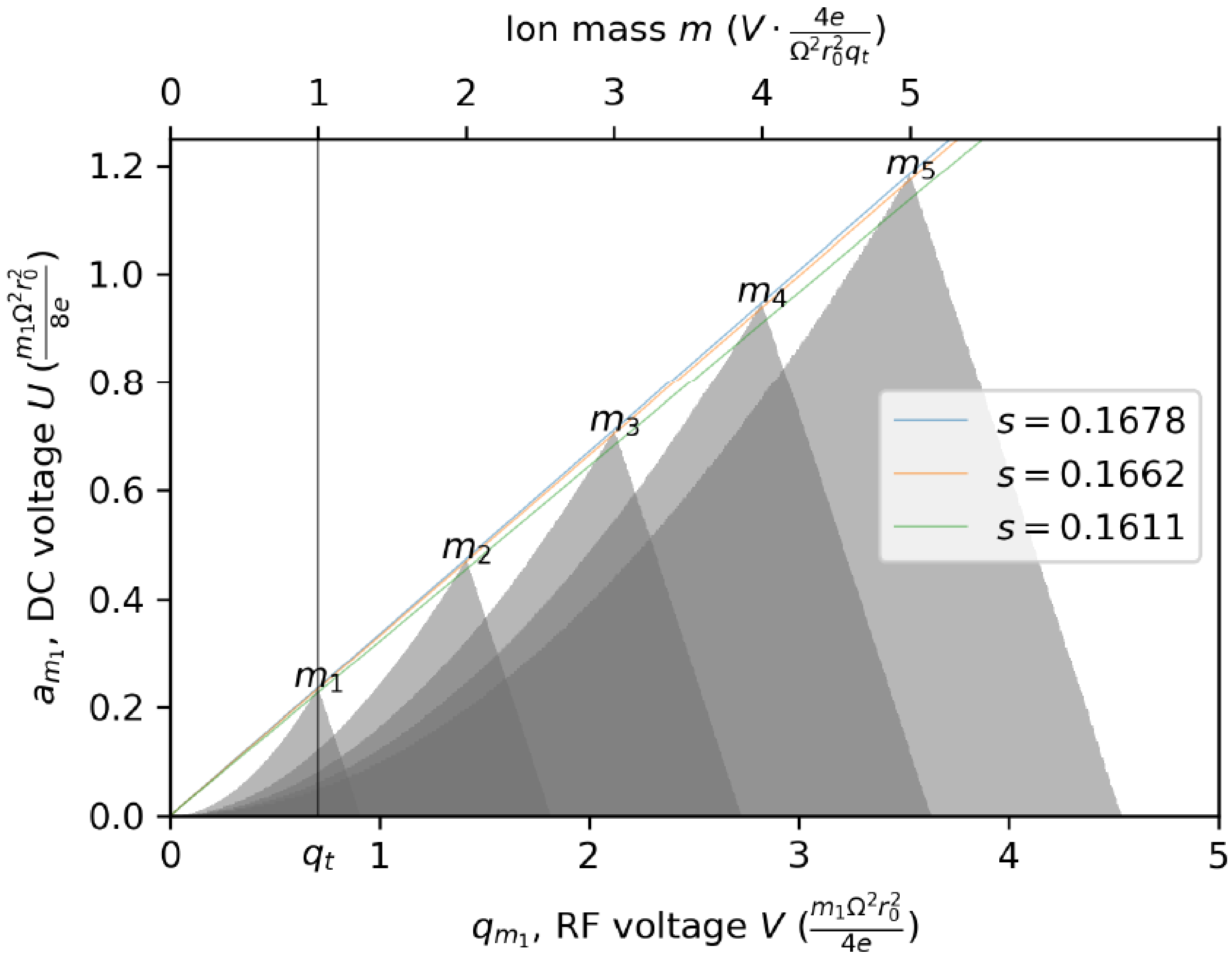
Avoid gas buildup

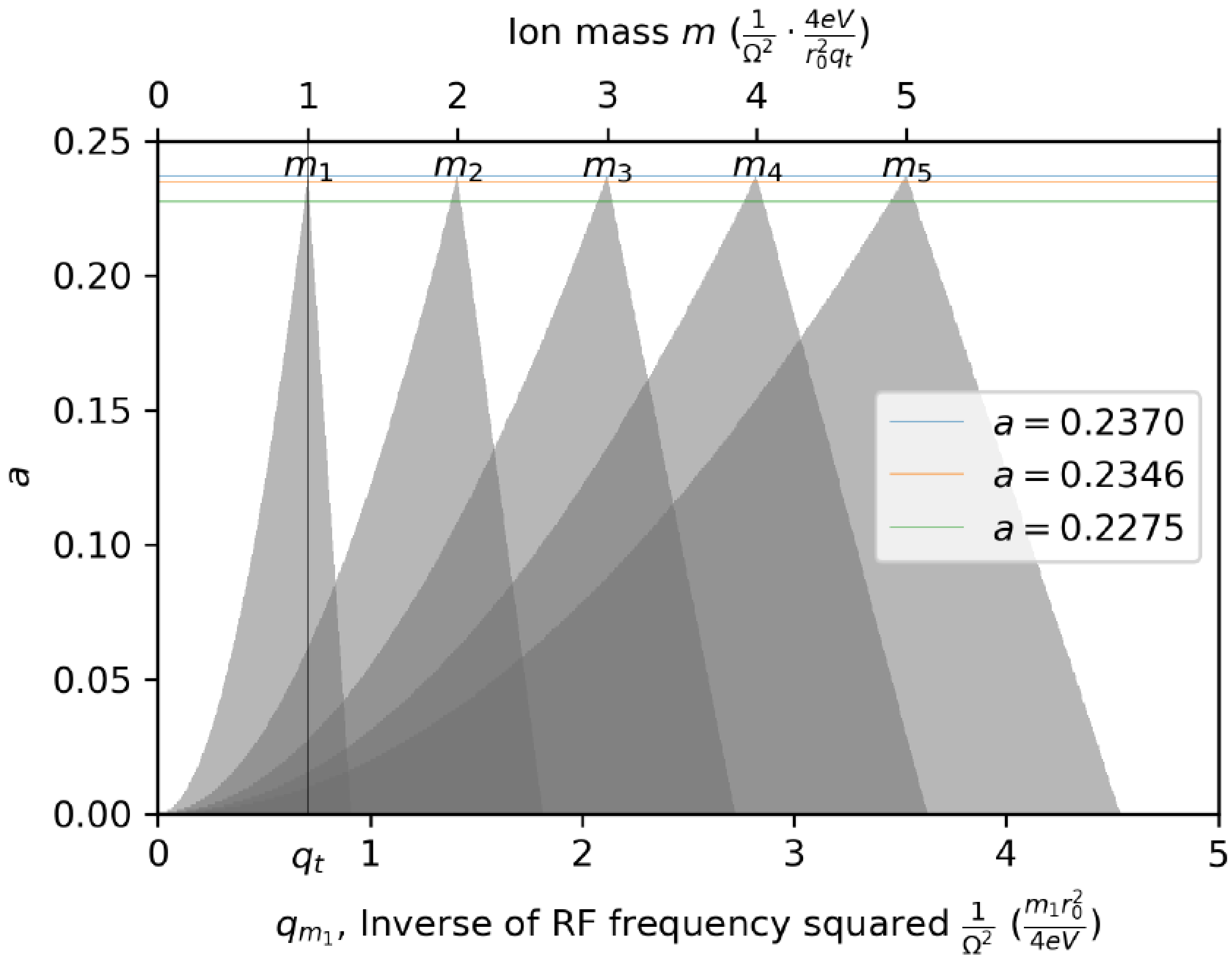
QMF stability diagram



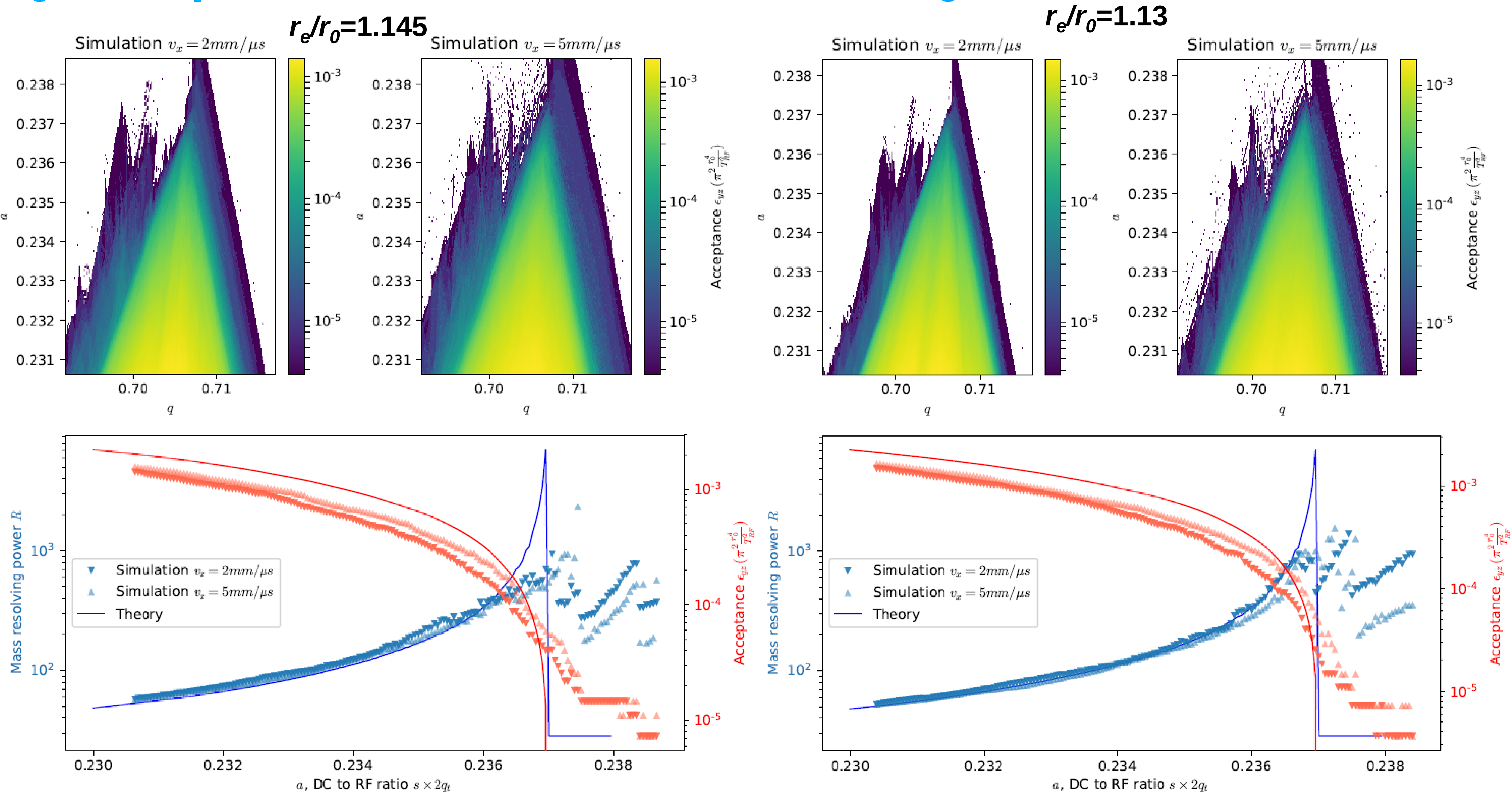
QMS mass scan

- Voltage scan vs. Frequency scan

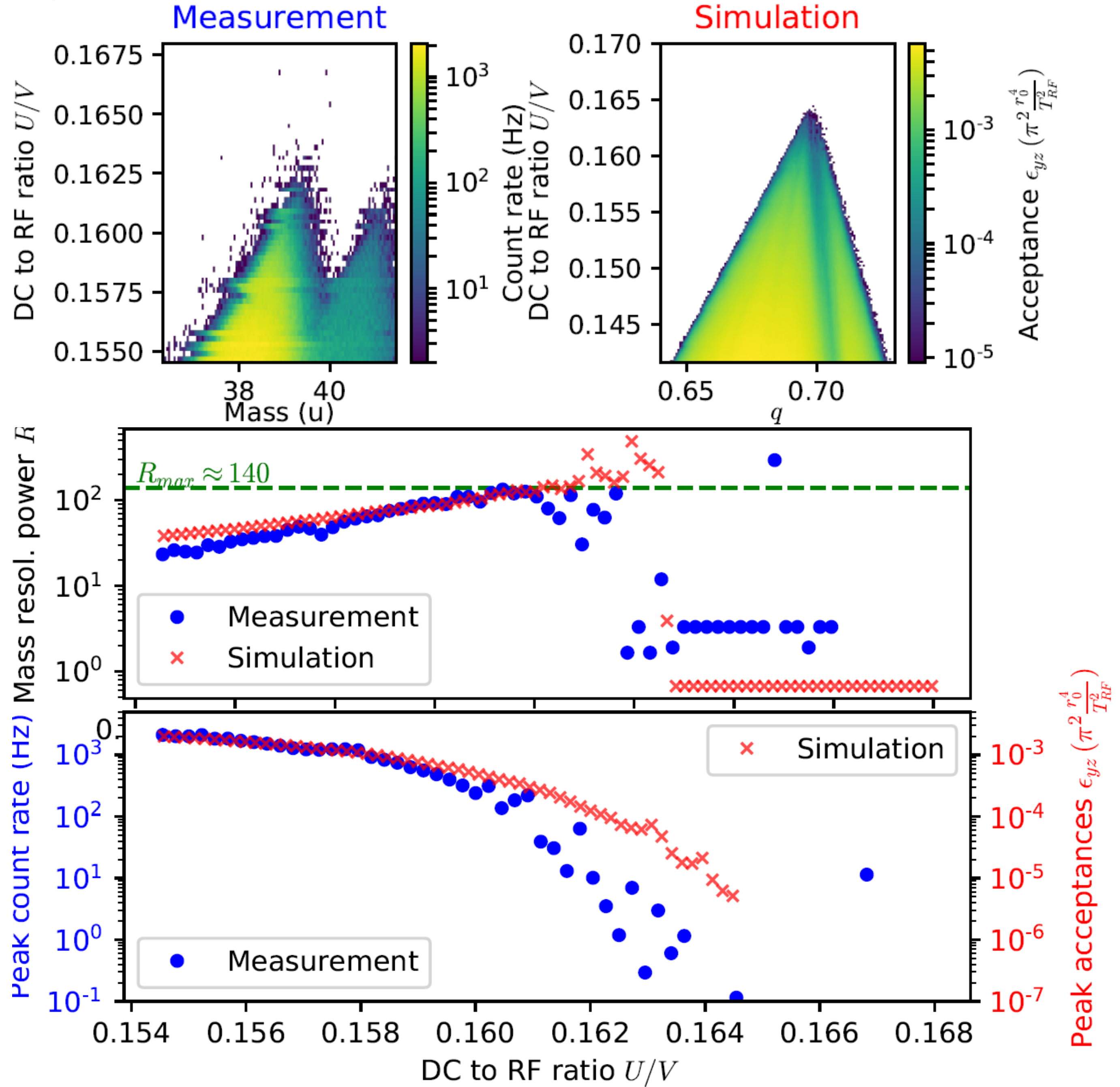




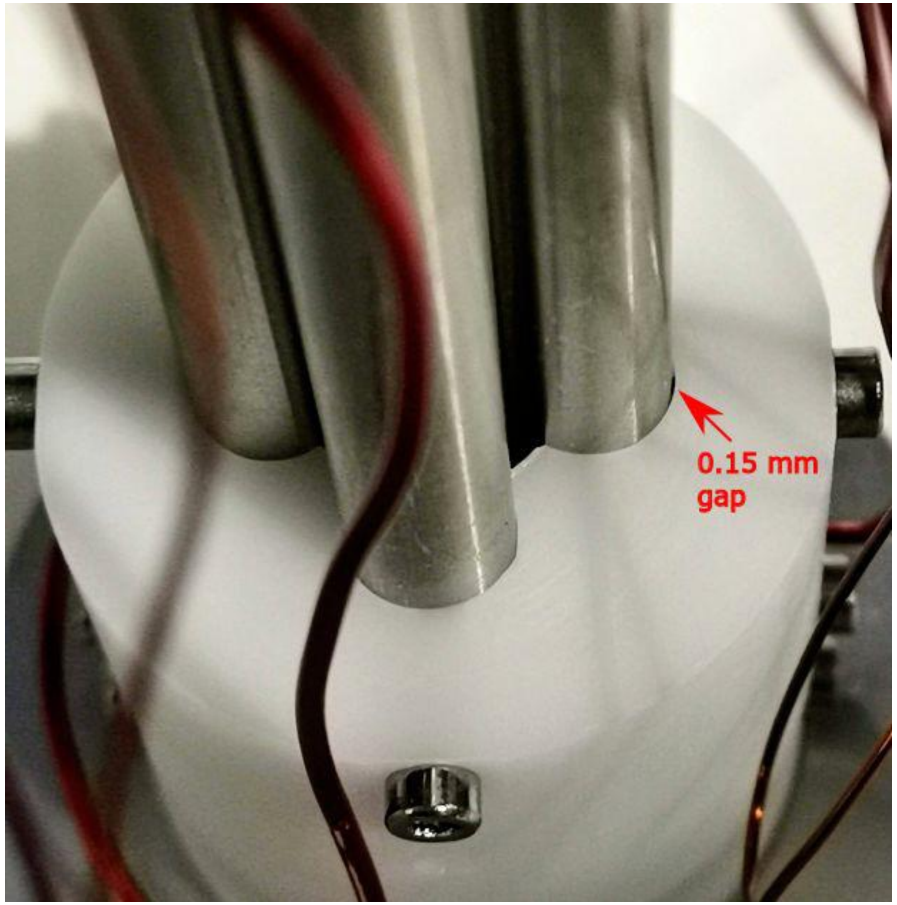
Quadrupole electrode simulations for QMF



QMF2.2 results: best achievable *R*



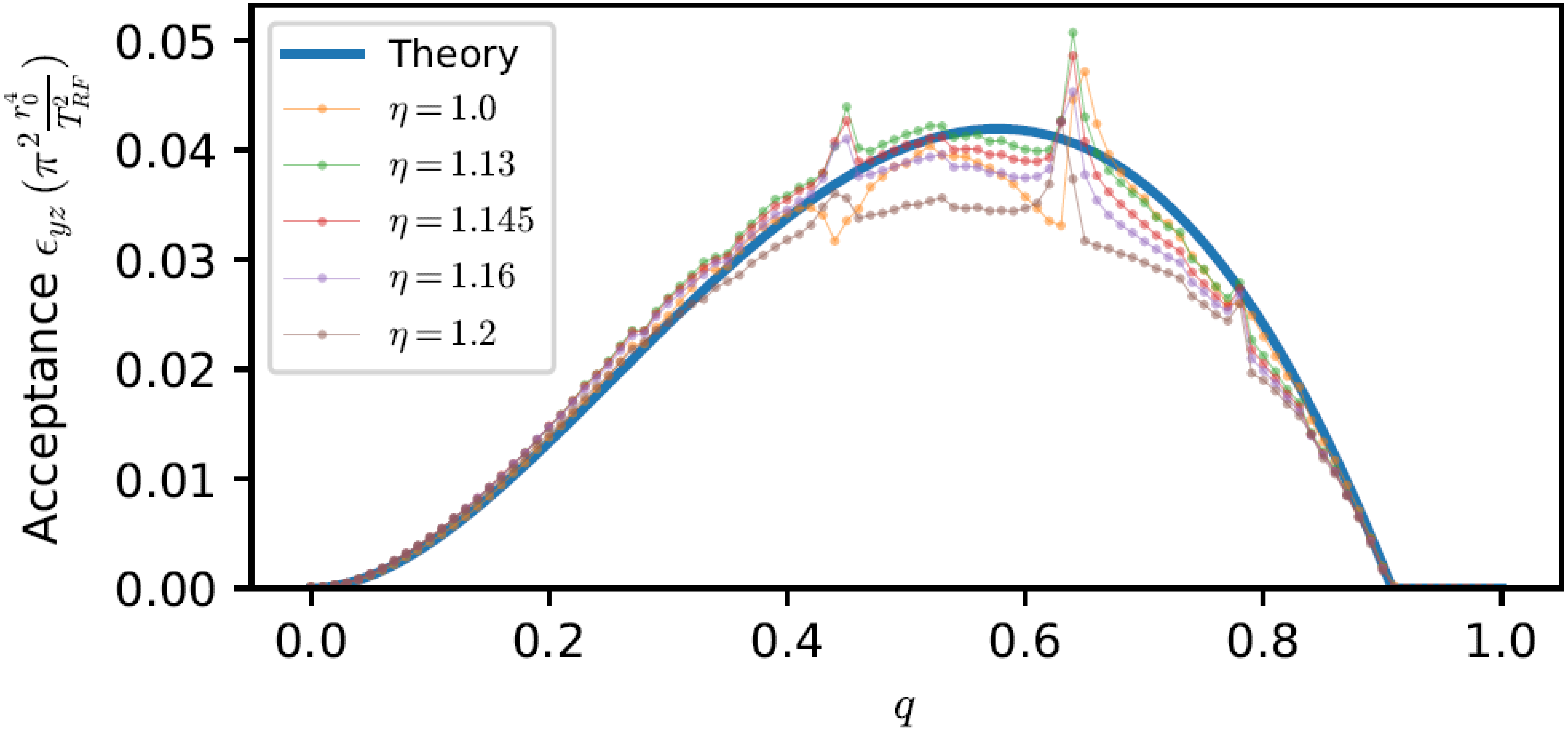
- A problem in assembly:



- Performance of QMF2.2 limited by the mechanical problem
- Best achievable mass resolving power $R_{max} \approx 140$ ✓ (>80)

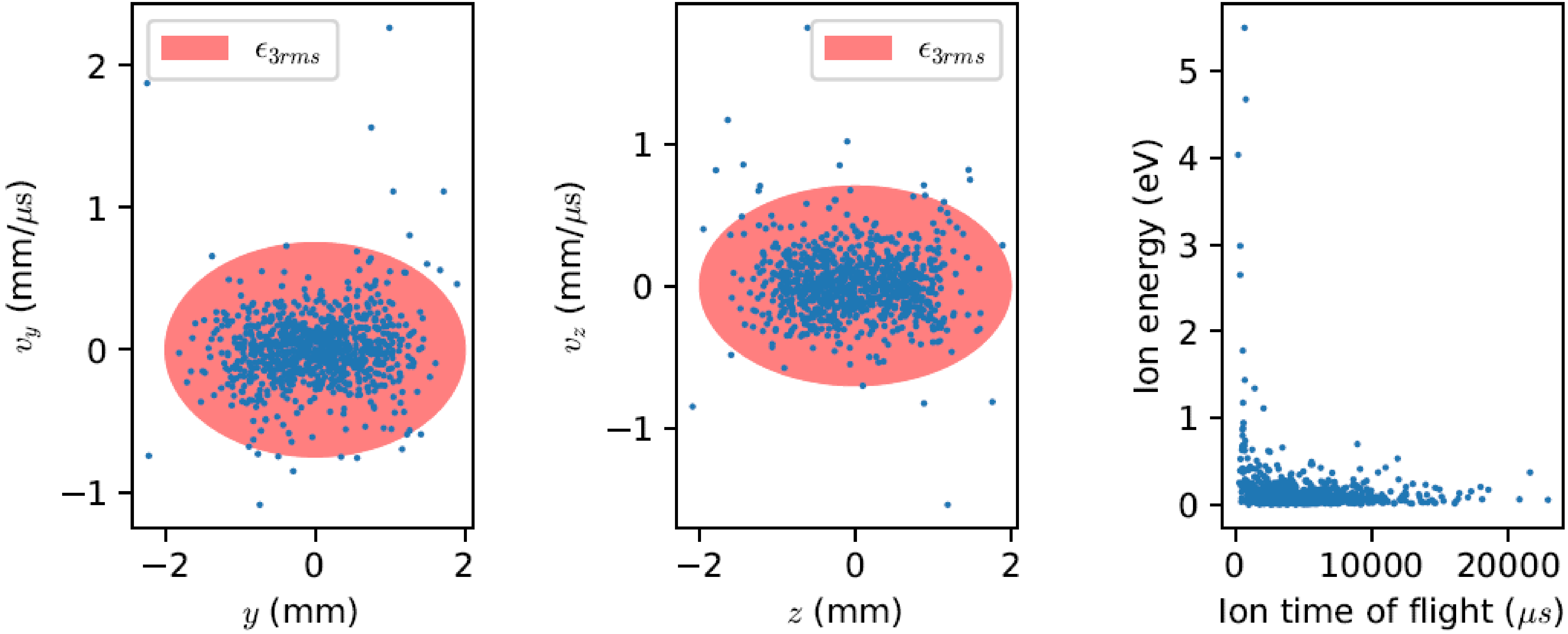
RFQ ion guide acceptance simulation

- r_e/r_0=1.13 is optimum



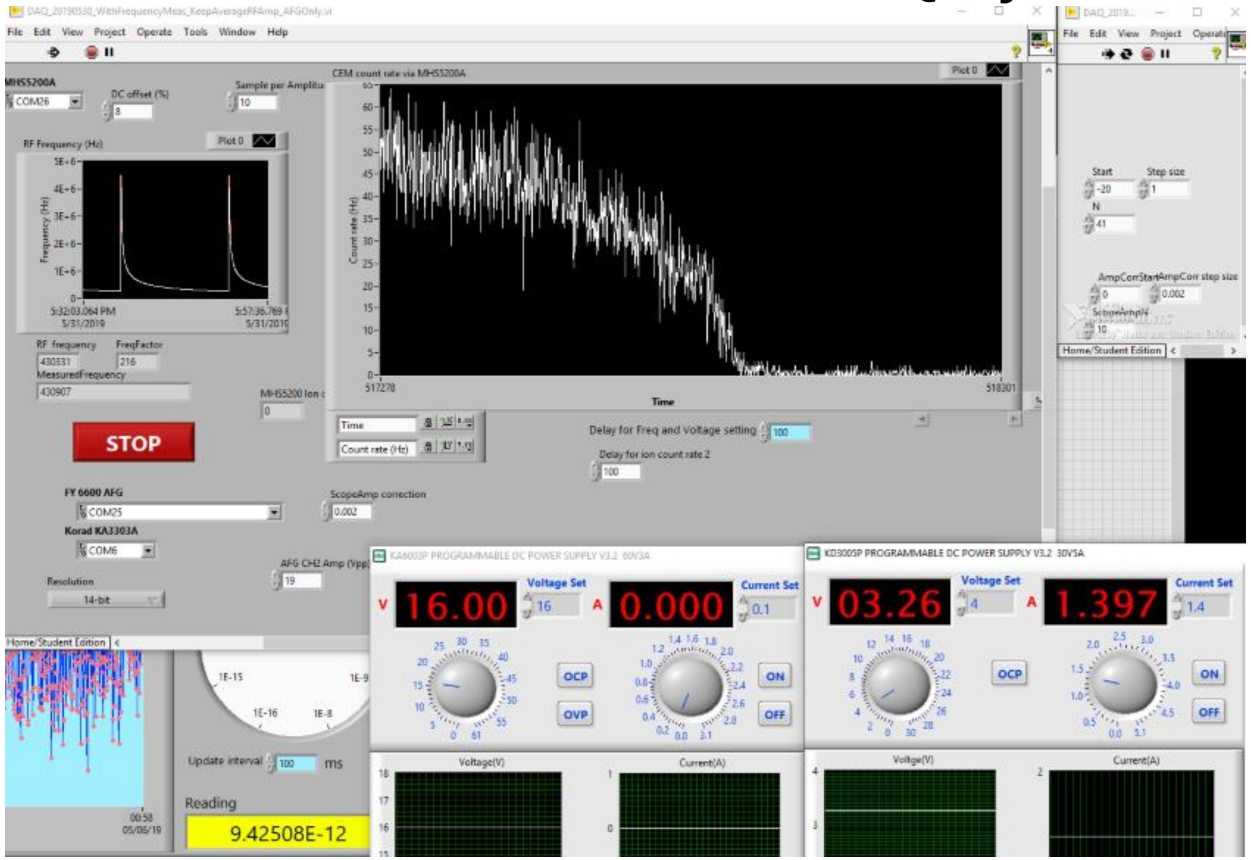
Ion emittance from RF funnel

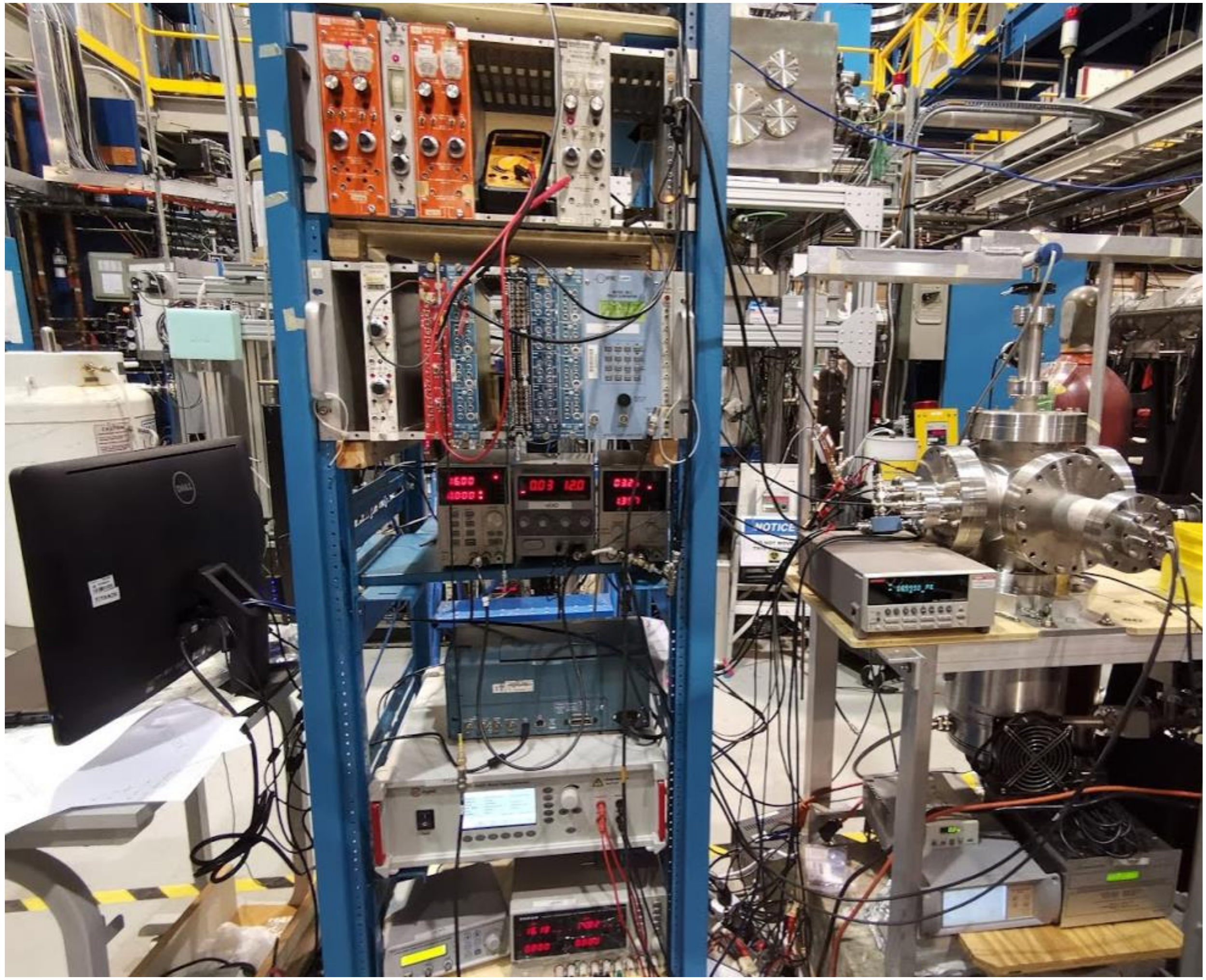
- ϵ_{3rms} = *1.44* mm·mm/μs



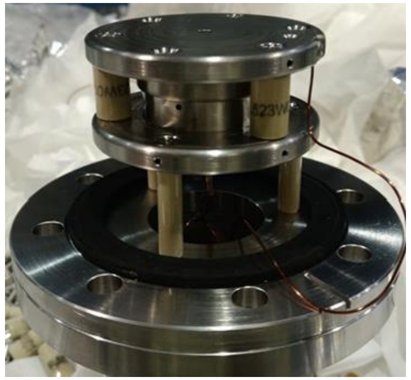
Experimental preparation

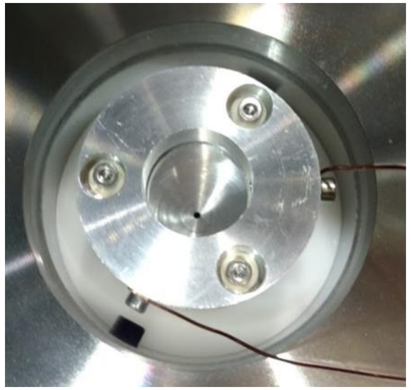
- Electronics, control and DAQ systems





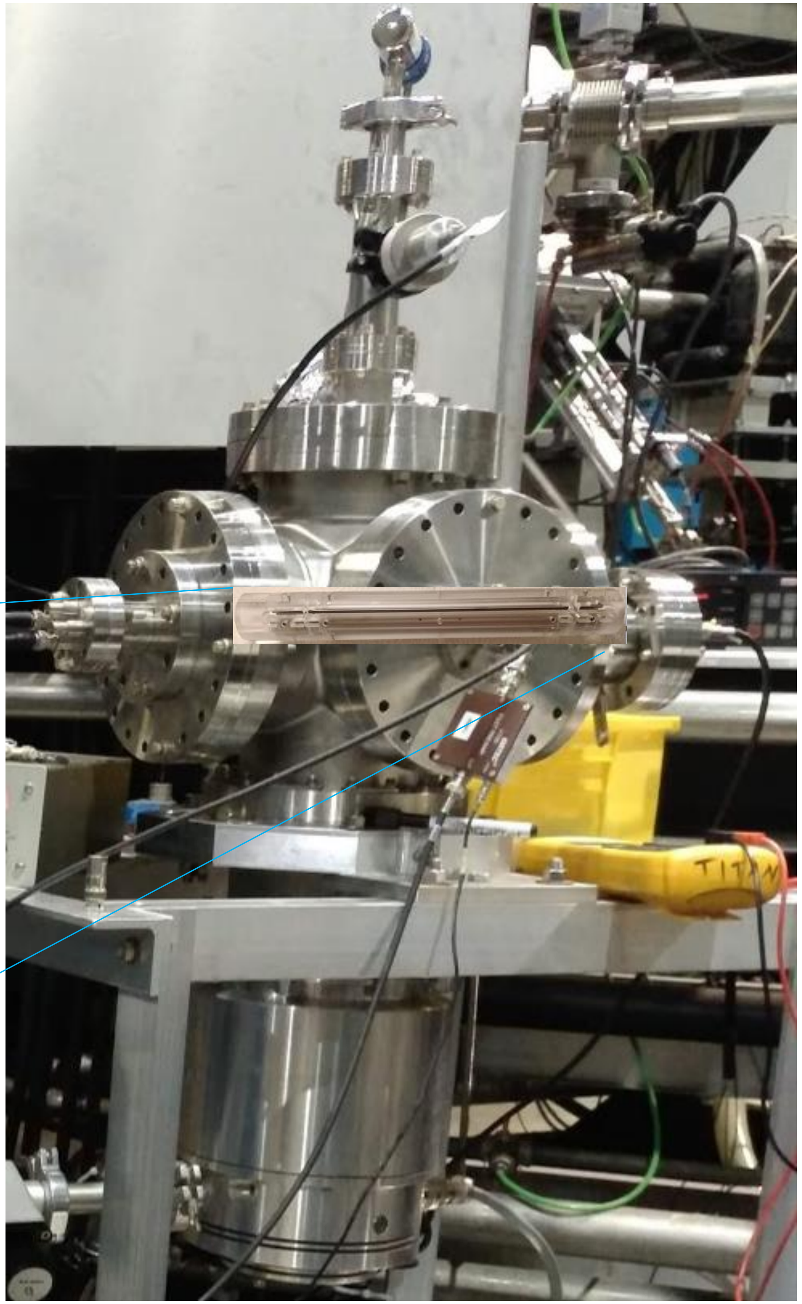
- Vacuum
- Ion source
- ion detector





Quadrupole Mass Filter (QMF) prototypes

- Acrylic QMF (V1.0)
  - Novel design



  - Mechanical tolerance ~ 0.2 mm

0.02 mm (20 μm) tolerance needed

  - Tested as an ion guide
    - Saw optimum ion transmission at 20 Vpp, 530 kHz
    - Things are working: electronics, DAQ, ion source, ion detector …

QMF V2.1

Mechanical tolerance ~ 50 μm (0.002")

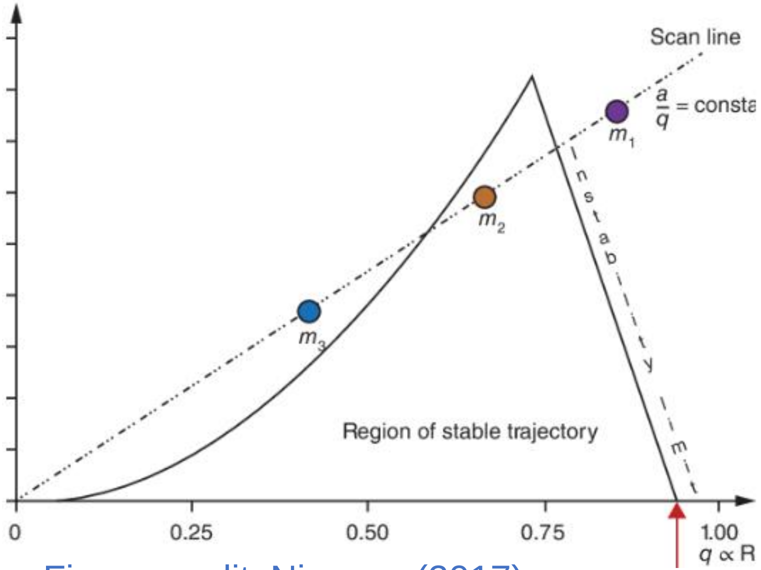
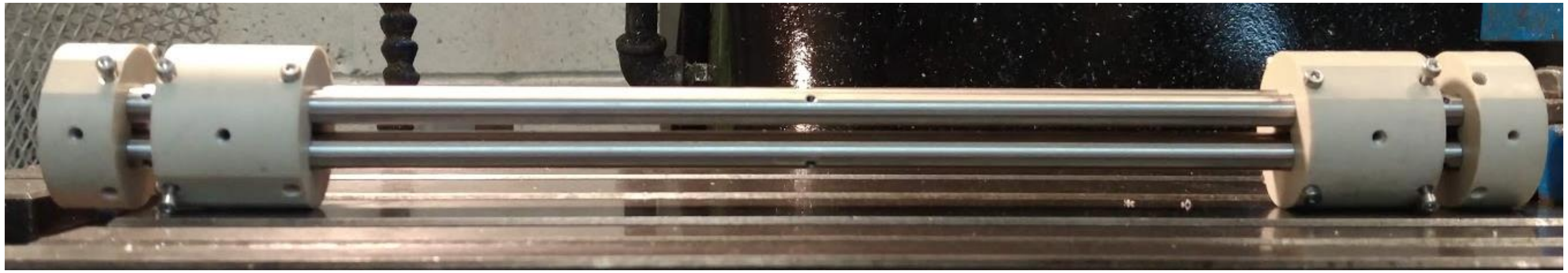
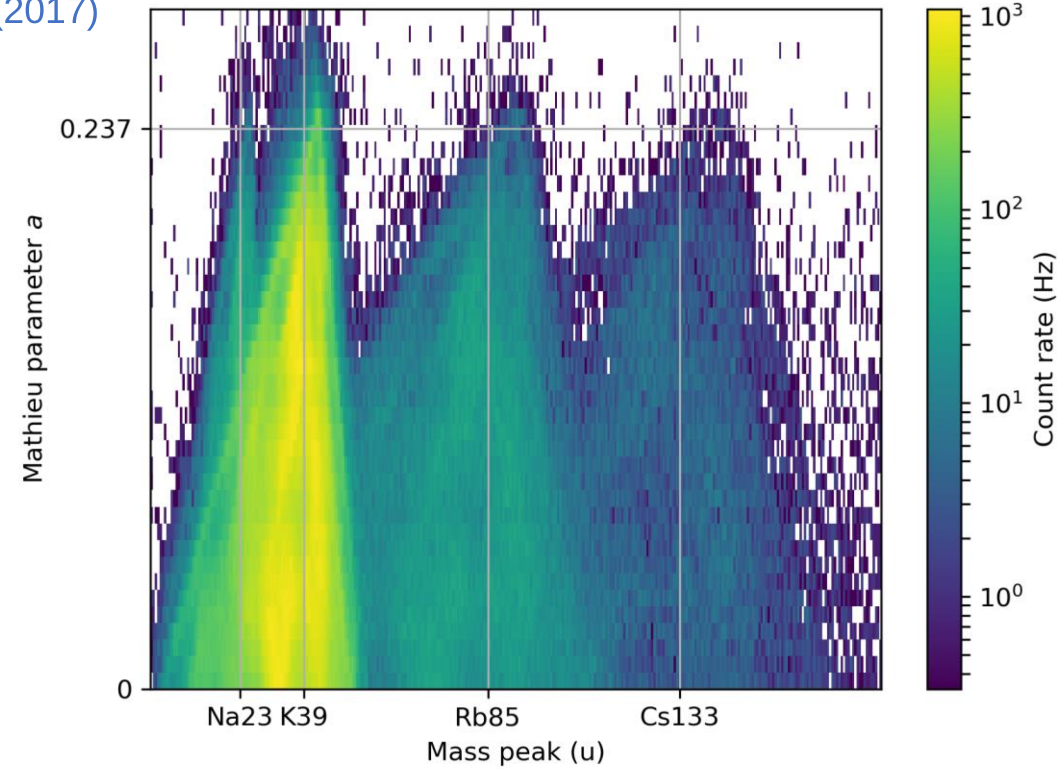
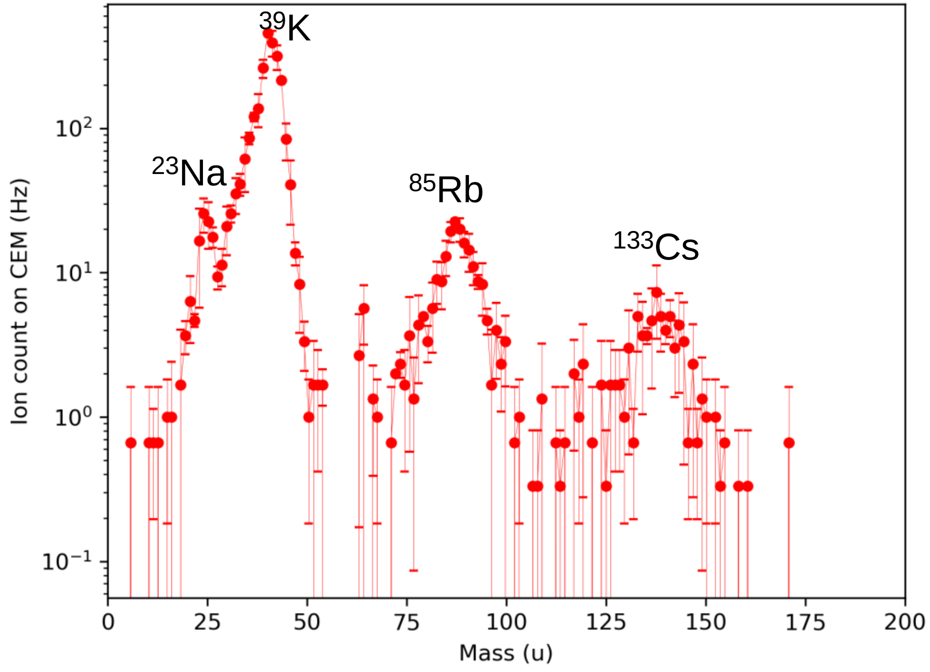


Figure credit: Niessen (2017)



RF amplitude: 20 Vp-p, frequency 0.3 to 0.9 MHz

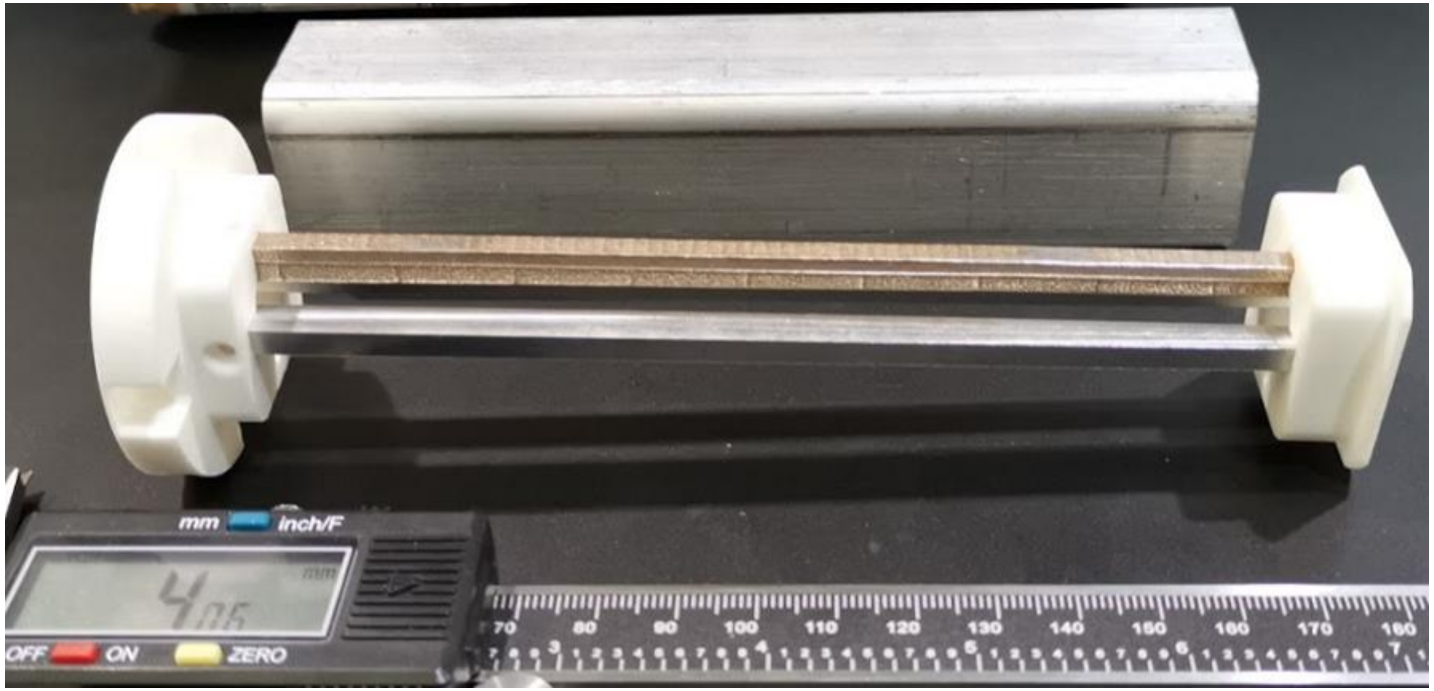




RF cooler prototype

- More complicated geometries
- Less tolerance requirement: 0.3 mm

- Try 3D printing for rapid prototyping
  - Tolerance ~ 0.1 mm ✓

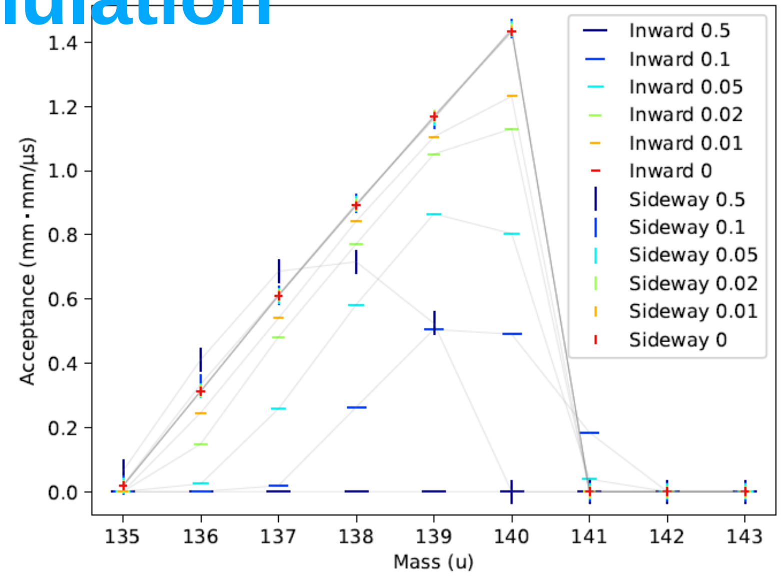


  - Tested vacuum compatibility
    - Below 10^{-6} Torr within 10 hours of pumping ✓

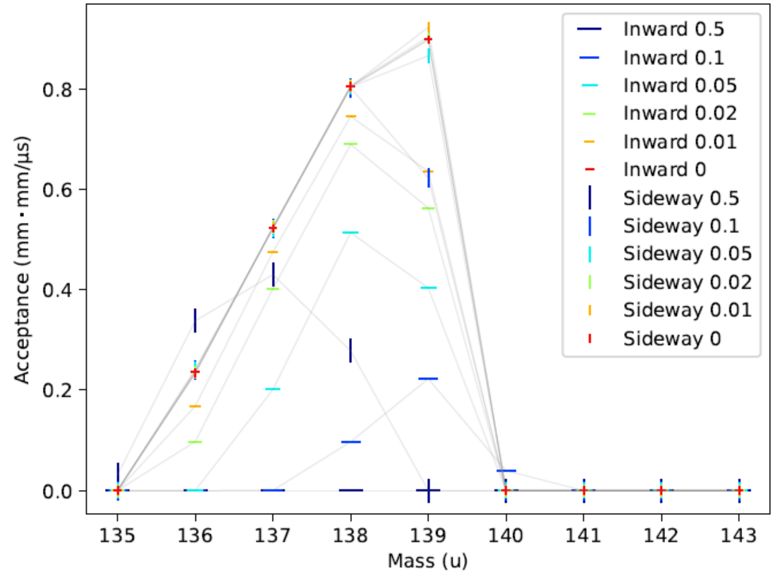
- Ongoing experiment with ion cooler:
  - **Ion trapping and ion ejection**

QMS performance simulation

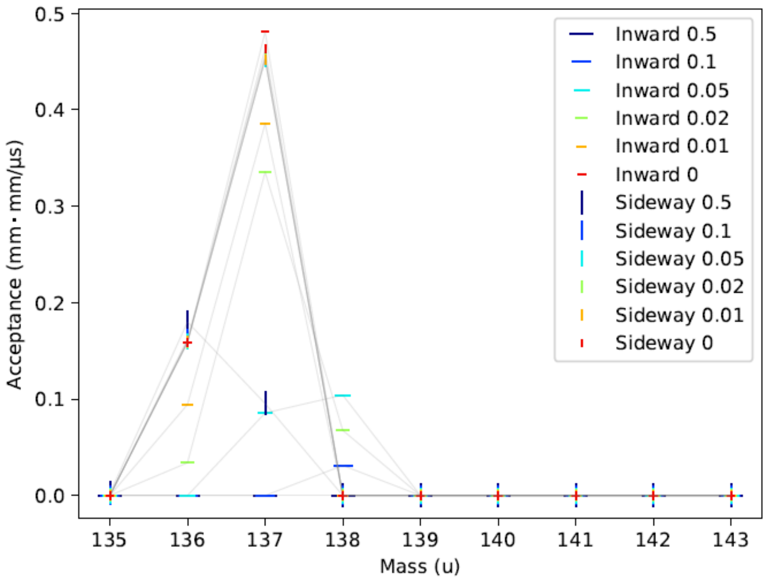
- Transmission efficiency
  - – acceptance
- Mass resolving power
- Validate mechanical tolerance



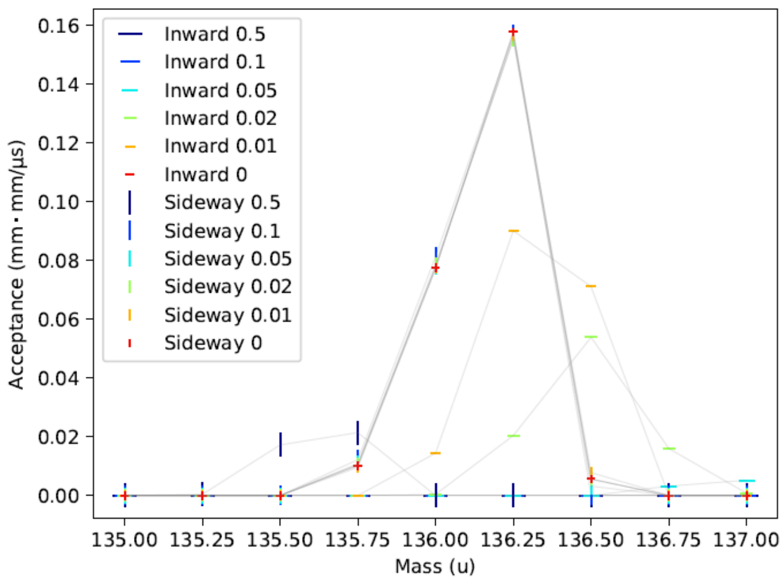
(a) a=0.23, $R = 25$



(b) a=0.232, $R = 36$



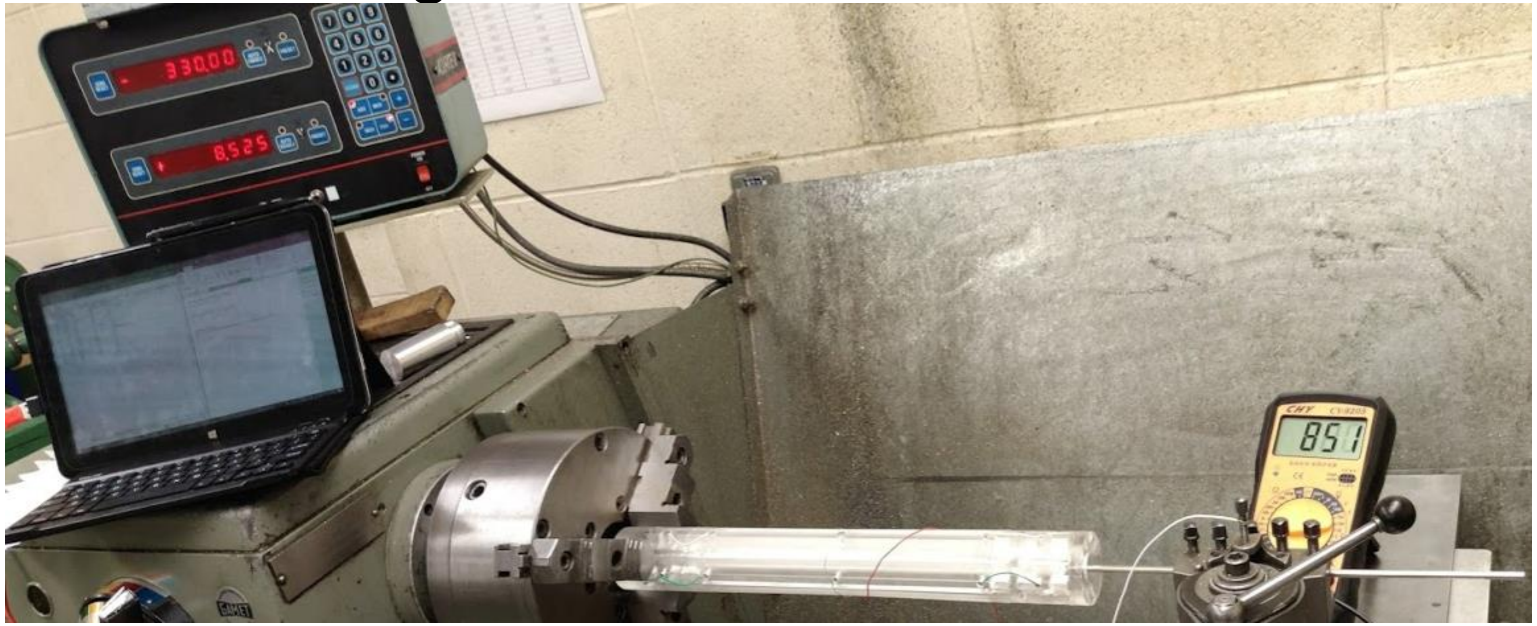
(c) a=0.234, $R = 60$

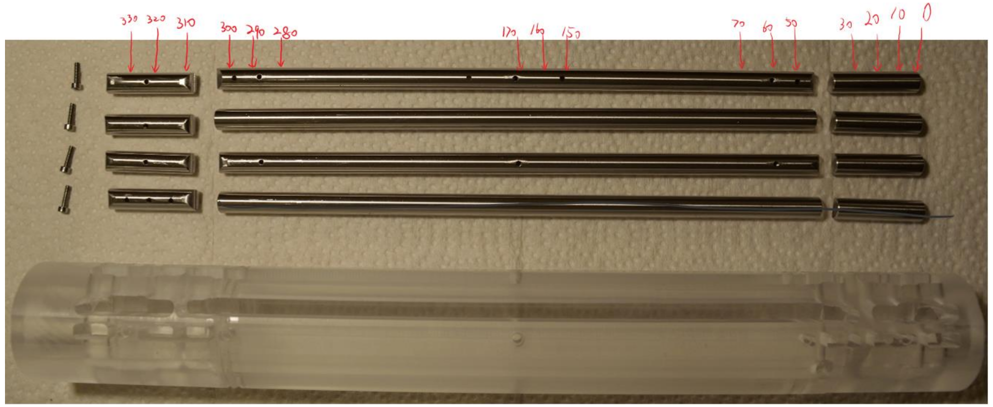


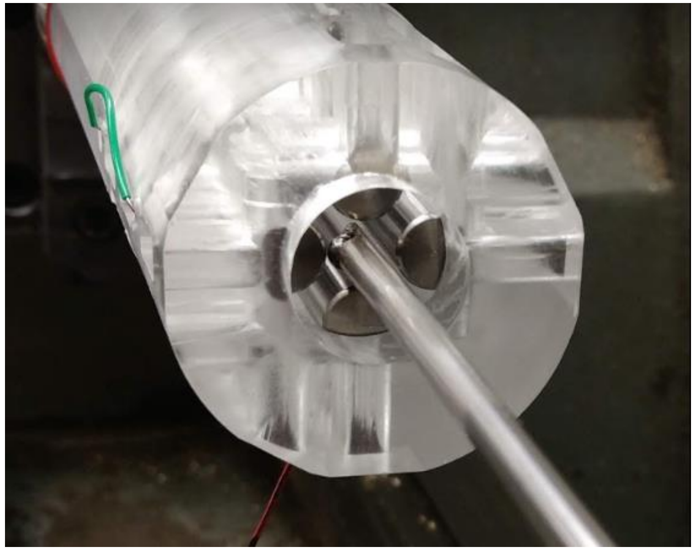
(d) a=0.236, $R = 180$

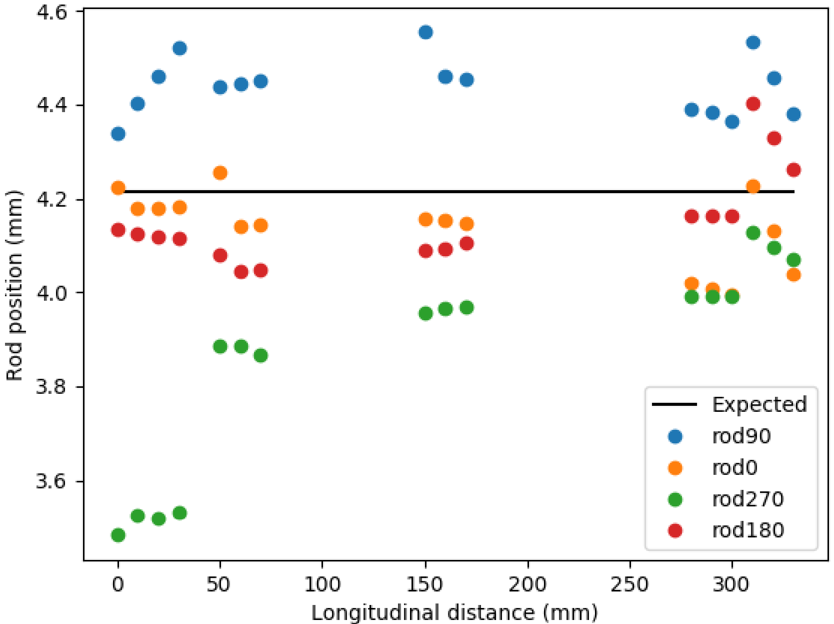
Measure QMS electrode tolerance

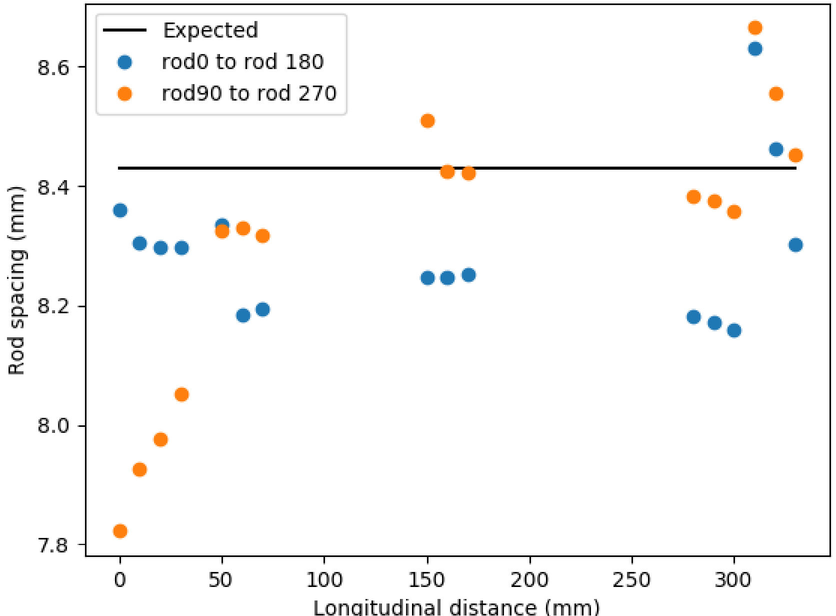
- Use the digital readout on a lathe



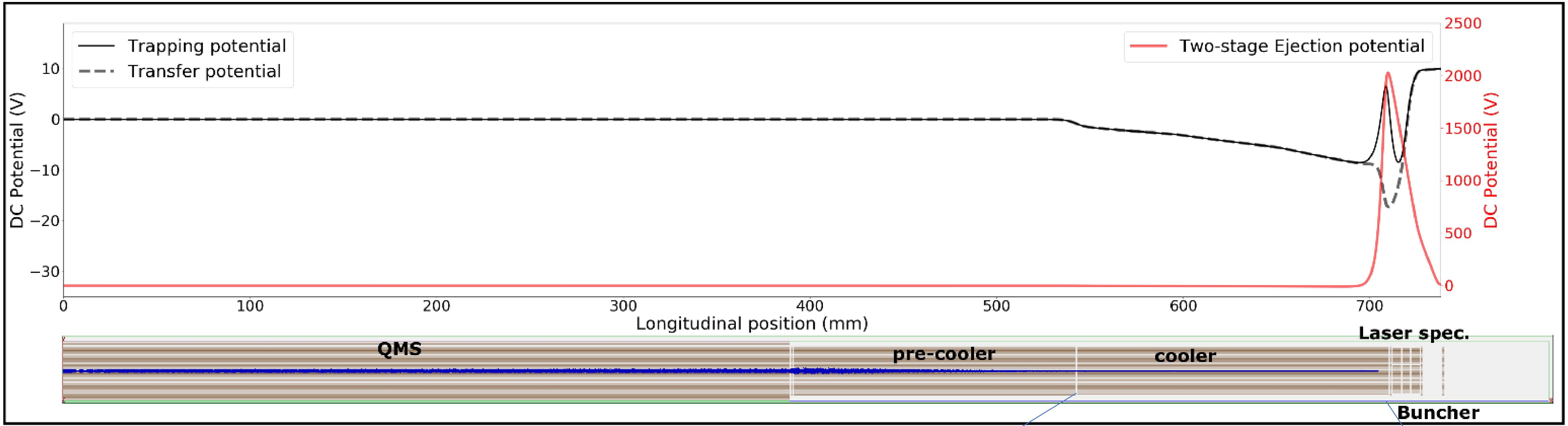


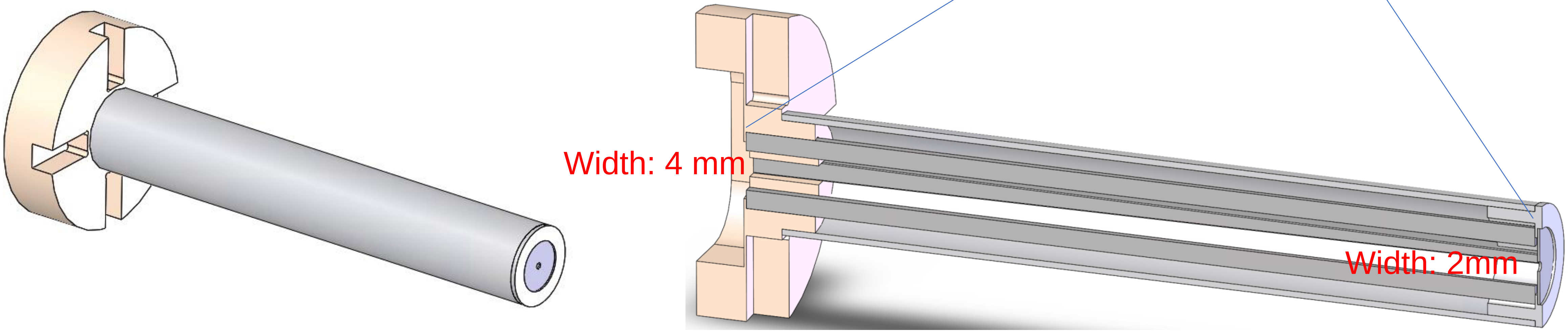






Novel rectangular electrode for cooler





Laser spectroscopy

- Initial study at Stanford (~2005)
- now at Carleton University