Production, formation, and manipulation of radioactive ion beams at SPIRAL-GANIL and S^3-SPIRAL2

SPIRAL is the existing radioactive ion beam (RIB) facility at GANIL (Grand Accélérateur National d'Ions Lourds), recognized as one of the world-leading centers for nuclear research. The exotic nuclei are produced by nuclear target fragmentation using accelerated stable ion beams and a thick carbon target. The RIB are then formed at the target-source assembly and transported to the post-accelerating Cyclotron for Ions of Medium Energy (CIME) delivering high energy beams of outstanding quality and very high intensity for the experiments.

The ongoing upgrade of SPIRAL includes new production targets and ion sources which will add more than 20 new elements to the existing beams. A major part of the upgrade is the installation of an ECR charge-breeder in the existing transfer line between the ion source and CIME. This will allow reaching higher charge states, and thus higher energies after post-acceleration. The installation of the charge-breeder requires verification of the beam transport with optical calculations due to changes in the lattice and the limits imposed by the existing beam line. **The first part of this presentation focuses on the optical simulations including topics such as transport efficiency, dispersion matching, and emittance blow-up.**

From the very beginning of the SPIRAL project, an upgrade – SPIRAL2 – was envisaged to increase both the range and the mass of exotic nuclei produced by SPIRAL. The SPIRAL2 project employs a superconducting linear accelerator (LINAG) which will provide extreme intensities of light/heavy-ion beams for RIB production both by low-energy in-flight and ISOL methods. The in-flight production will be made at the target station of the S3 spectrometer. The latter is designed as a momentum achromat combined with a m/q separator. It will allow to produce pure samples of exotic nuclei either for delayed spectroscopy studies at the focal plane of S3 or for gas stopping, laser ionization, and subsequent extraction of low energy RIB towards a decay station and/or the future DESIR facility. **The second part of the presentation will focus on the operation modes of the S3 spectrometer and the formation and manipulation of the low energy radioactive beams using a complex system of Radio Frequency Quadrupoles (REGLIS3 ANR).**

Outlook

SPIRAL (Système de Production d'Ions Radioactifs Accélérés en Ligne)

Radioactive ion beams at SPIRAL-GANIL and S3-SPIRAL2

SPIRAL upgrade project

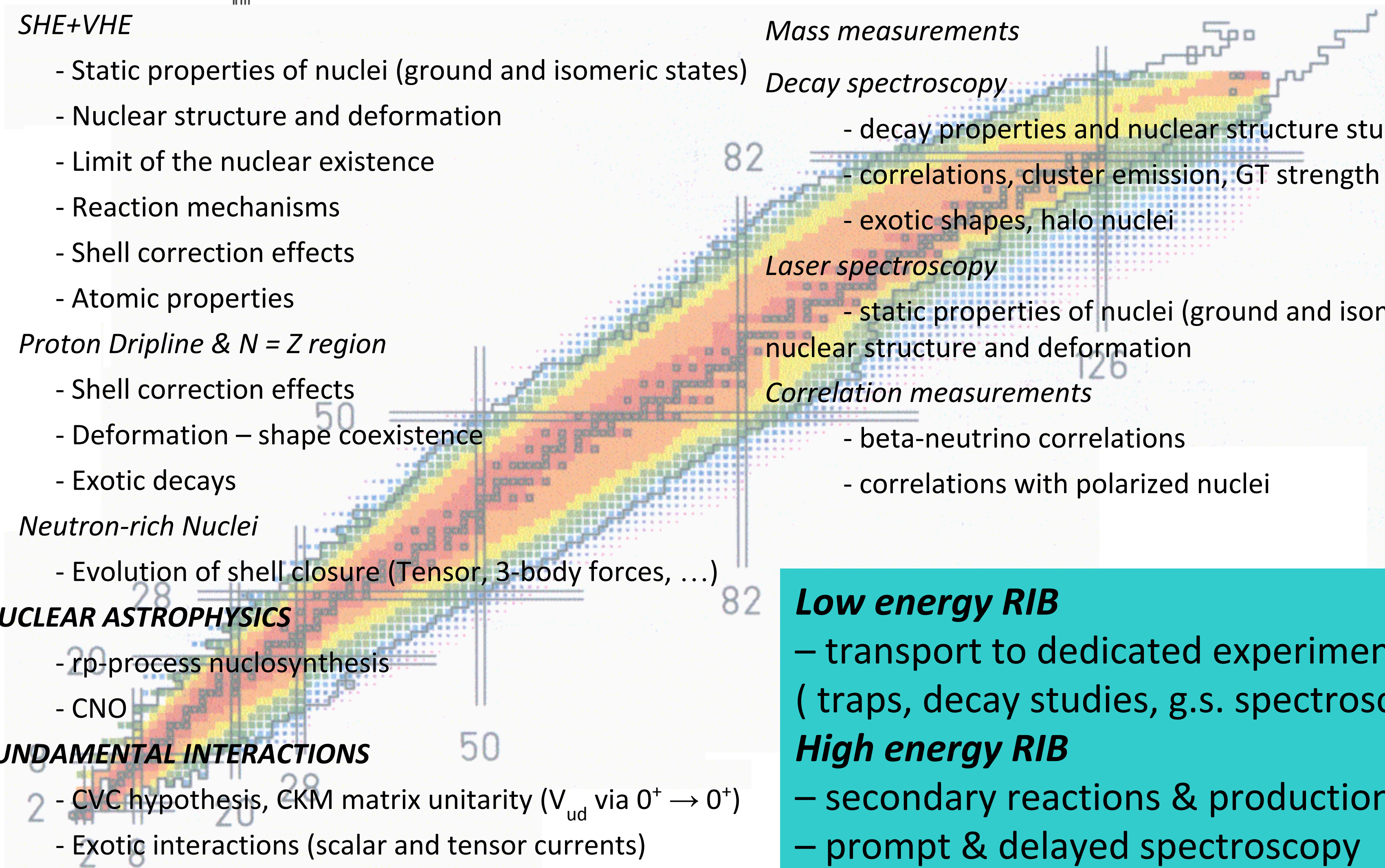
- Production target/ion sources and the TBE beam line
- Installation of a PHOENIX Charge Booster in TBE
- TBE beam line modifications
- Operations modes of TBE
- Optical calculations
- Conclusion

S^3 spectrometer and LEB branch

- Main operation modes
- Delayed spectroscopy
- In-gas laser ionization and spectroscopy (IGLIS)
- S^3 LEB line
- Simulations for $REGLIS^3$
    - Gas jet atoms interaction with ions
    - S-shaped Radio Frequency Quadrupole cooler
    - Quadrupole mass filter
    - Novel techniques for mass selection
- Conclusion

Physics motivation for RIB at SPIRAL-GANIL and S^3-SPIRAL2

SPIRAL (Système de Production d'Ions Radioactifs Accélérés en Ligne)



NUCLEAR STRUCTURE

SHE+VHE

- Static properties of nuclei (ground and isomeric states)
- Nuclear structure and deformation
- Limit of the nuclear existence
- Reaction mechanisms
- Shell correction effects
- Atomic properties

Proton Dripline & N = Z region

- Shell correction effects
- Deformation – shape coexistence
- Exotic decays

Neutron-rich Nuclei

- Evolution of shell closure (Tensor, 3-body forces, …)

NUCLEAR ASTROPHYSICS

- rp-process nuclosynthesis
- CNO

FUNDAMENTAL INTERACTIONS

- CVC hypothesis, CKM matrix unitarity (V_{ud} via $0^+ \rightarrow 0^+$)
- Exotic interactions (scalar and tensor currents)
- CP and T violation

EXPERIMENTAL METHODS AND TECHNIQUES

Mass measurements

Decay spectroscopy

- decay properties and nuclear structure studies
- correlations, cluster emission, GT strength
- exotic shapes, halo nuclei

Laser spectroscopy

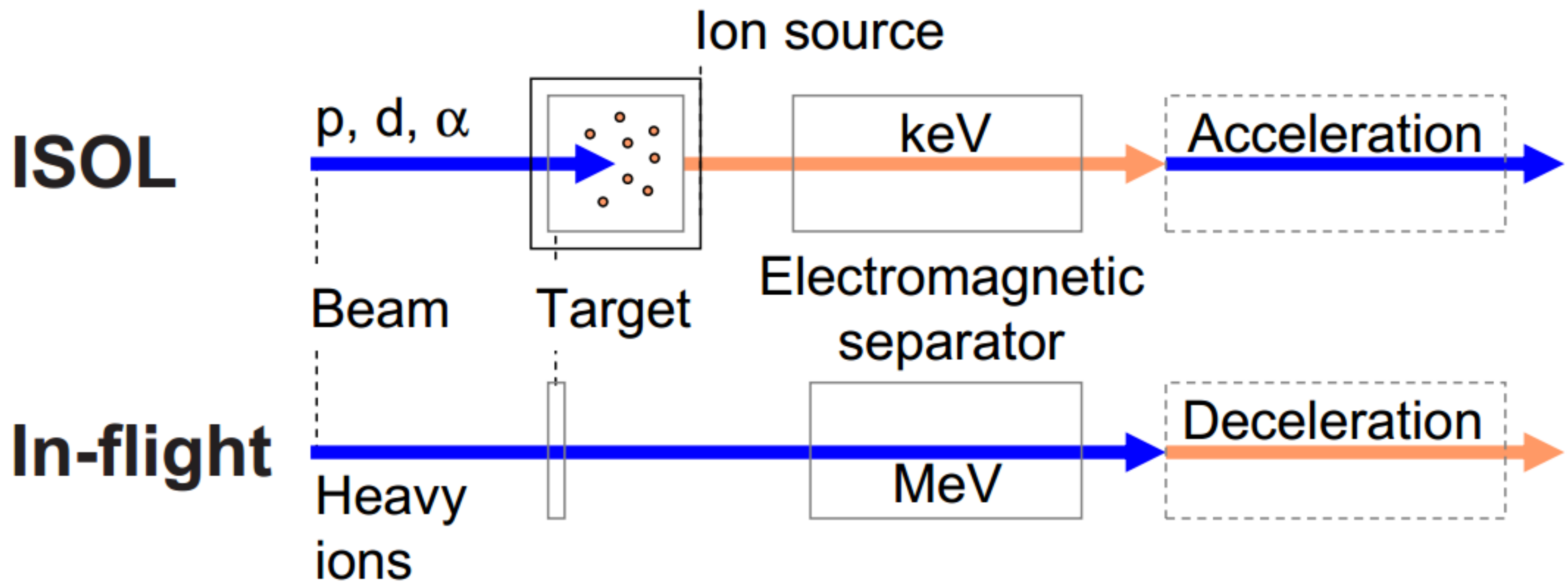
- static properties of nuclei (ground and isomeric) - nuclear structure and deformation

Correlation measurements

- beta-neutrino correlations
- correlations with polarized nuclei

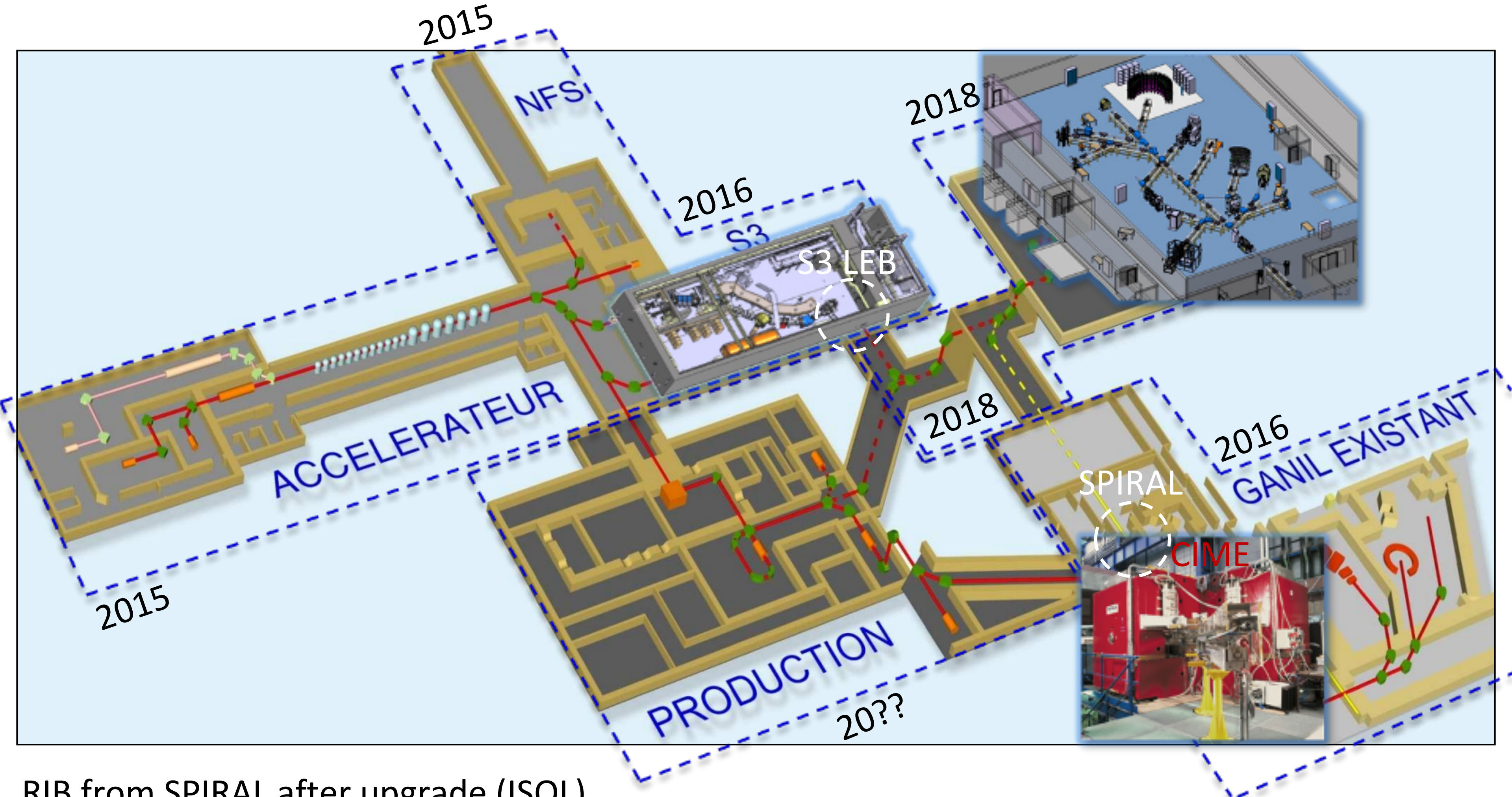
Low energy RIB
– transport to dedicated experiments
(traps, decay studies, g.s. spectroscopy)
High energy RIB
– secondary reactions & production,
– prompt & delayed spectroscopy

Radioactive ion beam production methods



$$Yield = \left(I_{\mathrm{beam}}\sigma_{\mathrm{reaction}}d_{\mathrm{target}}\right)\varepsilon_1\varepsilon_2\varepsilon_3\ldots\varepsilon_n$$

Radioactive ion beams at GANIL/SPIRAL2



RIB from SPIRAL after upgrade (ISOL)

- ➪ CIME cyclotron ➪ existing GANIL experimental area (2016)
- ➪ DESIR experimental hall – LIRAT beam line + new LEB line (2018)

RIB from S^3 spectrometer (In-flight + ISOL)

- ➪ DESIR experimental hall – S3 LEB line + new LEB line (2018)

RIB from SPIRAL2-phase2 production (ISOL)

Très Basse Energie (TBE) beam line and SPIRAL upgrade

Beam requirements for

CIME @OIC (PR34)

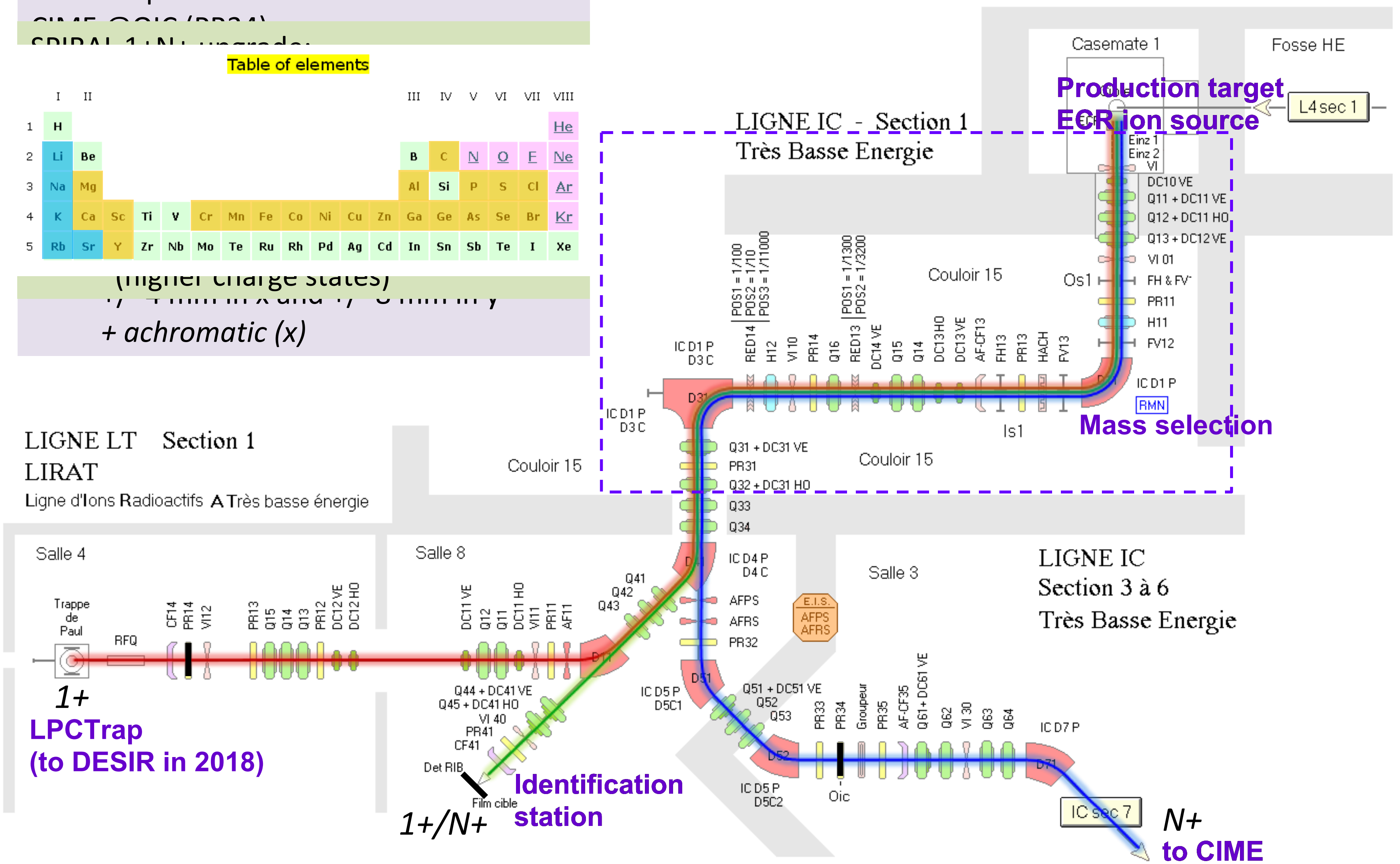
SPIRAL 1+N+ upgrade:

Table of elements

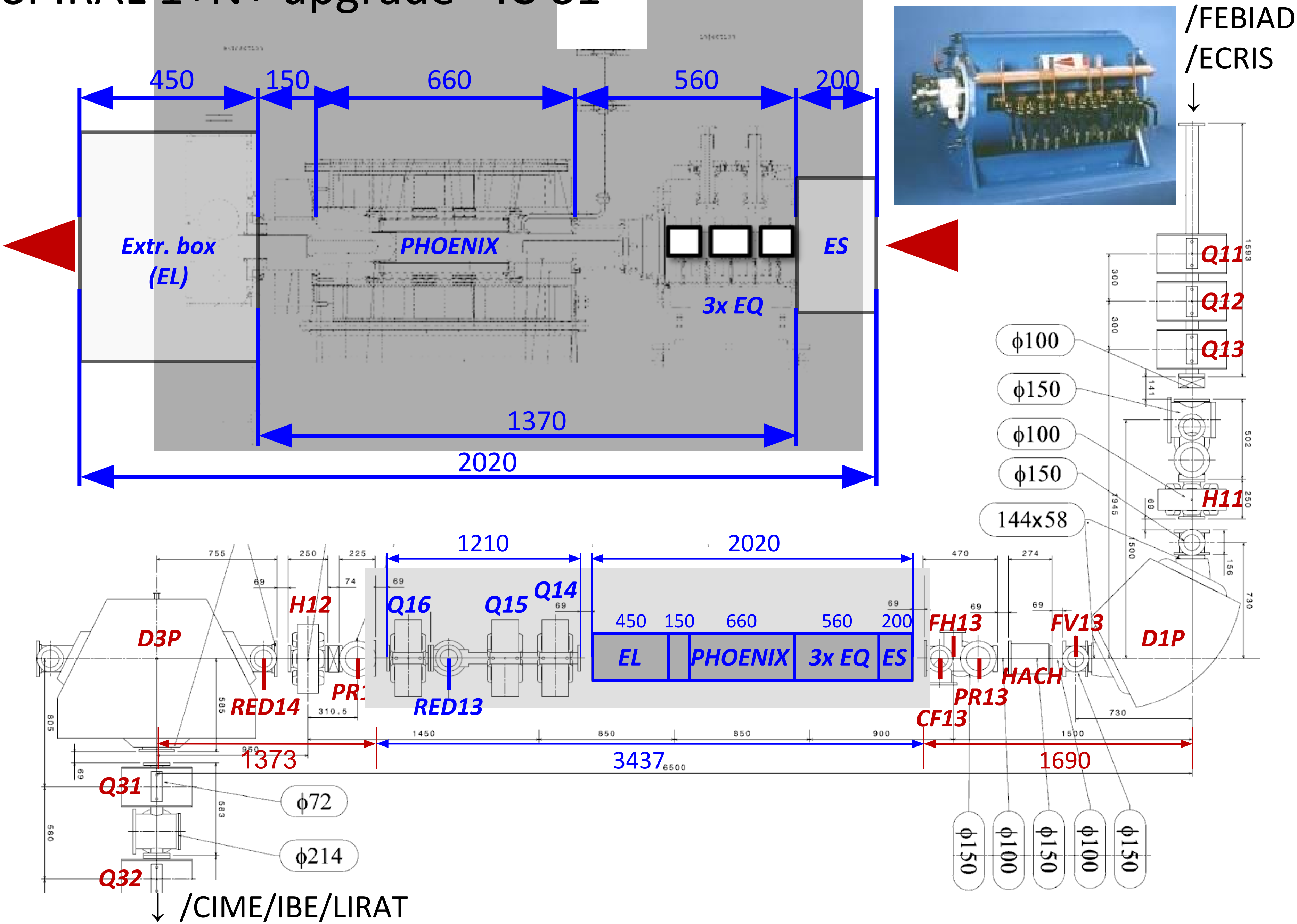
	I	II											III	IV	V	VI	VII	VIII
1	H																	He
2	Li	Be											B	C	N	O	F	Ne
3	Na	Mg											Al	Si	P	S	Cl	Ar
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Te	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe

(higher charge states)

+ achromatic (x)



SPIRAL 1+N+ upgrade - IC-S1



Optical calculations for the 1+/N+ upgrade of SPIRAL

Main goal
Optimal configuration for the installation of a PHOENIX CB in the TBE beam line

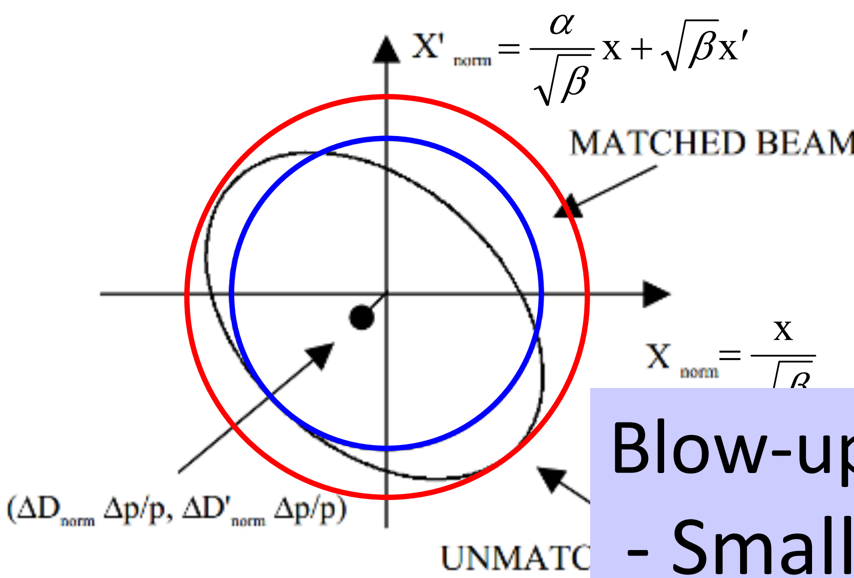
Requirements
- Match beam properties to the requirements for object points of CIME, IBE and LIRAT
- Preserve achromaticity conditions (if/where possible)
- Maximize transmission in the desired magnetic rigidity range
- Provide sufficient resolving power for isotope selection before and after the booster

Operation modes

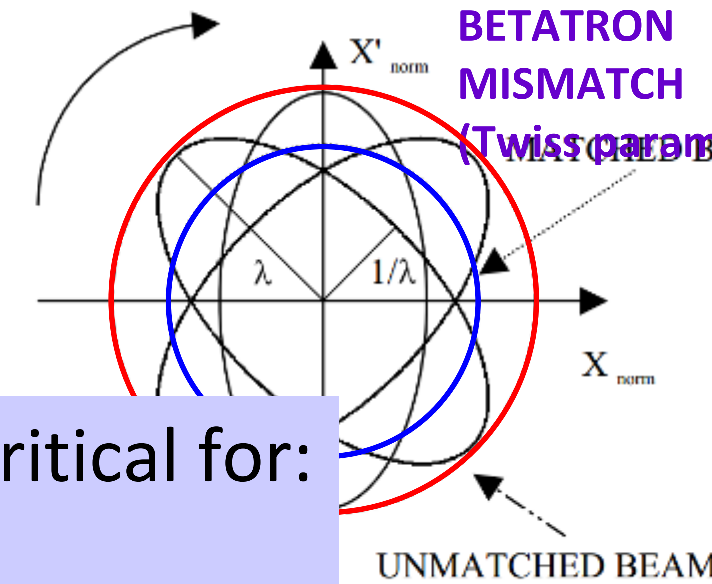
1. Charge booster ***ON*** (*1+N+* mode)
   - **1A. Loading of *1+* ions from ECR/FEBIAD into PHOENIX (B$\rho \leq$ 0.22 T.m, A $\leq$ 90))**
   - **1B. Extraction of from *N+* ions from PHOENIX to CIME/IBE/(*LIRAT) (B$\rho \leq$ 0.075 T.m, A $\leq$ 90)**
2. Charge breeding ***OFF*** (only coils of PHOENIX ECRIS in use)
   - **2A. Transport 1+ ions from FEBIAD/ECR through PHOENIX to LIRAT/IBE (B$\rho \leq$ 0.137 T.m, A $\leq$ 90)**
   - 2B. Transport of N+ ions from ECR through PHOENIX to CIME/IBE (lower Bρ, not very critical)

Beam properties used in the calculations:
- FEBIAD: 25 π.mm.mrad at 20 kV, $\Delta E/E$ = 0.5 ‰, HT = 10 – 34 kV
- ECR/PHOENIX: 80 π.mm.mrad at 20 kV, $\Delta E/E$ = 0.5 ‰, HT = 10 – 34 kV

Dispersion matching and emittance blow-up

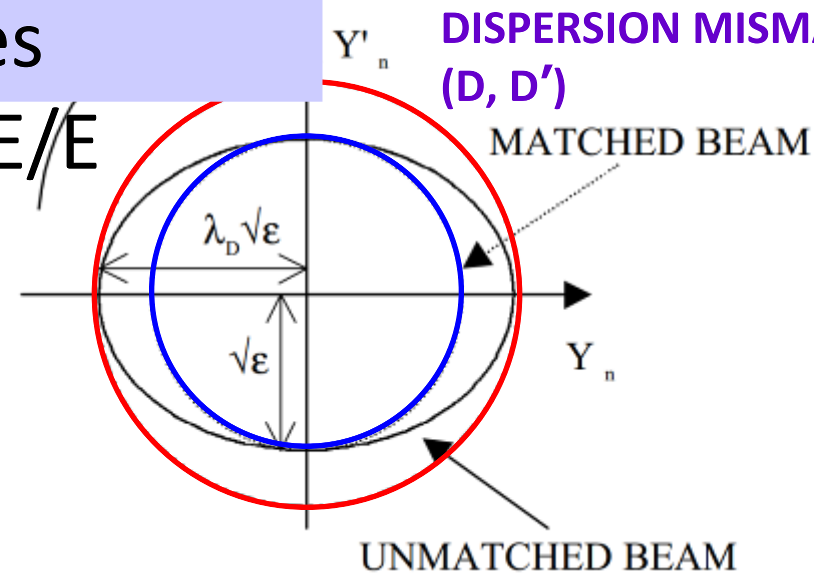


BETATRON MISMATCH (Twiss parameters)



Blow-up critical for:
- Small emittances
- Large ΔE/E

DISPERSION MISMATCH (D, D')



Normalized phase space:

$$x_{norm} = \frac{x}{\sqrt{\beta}} \qquad x'_{norm} = \frac{\alpha}{\sqrt{\beta}} x + \sqrt{\beta} x'$$

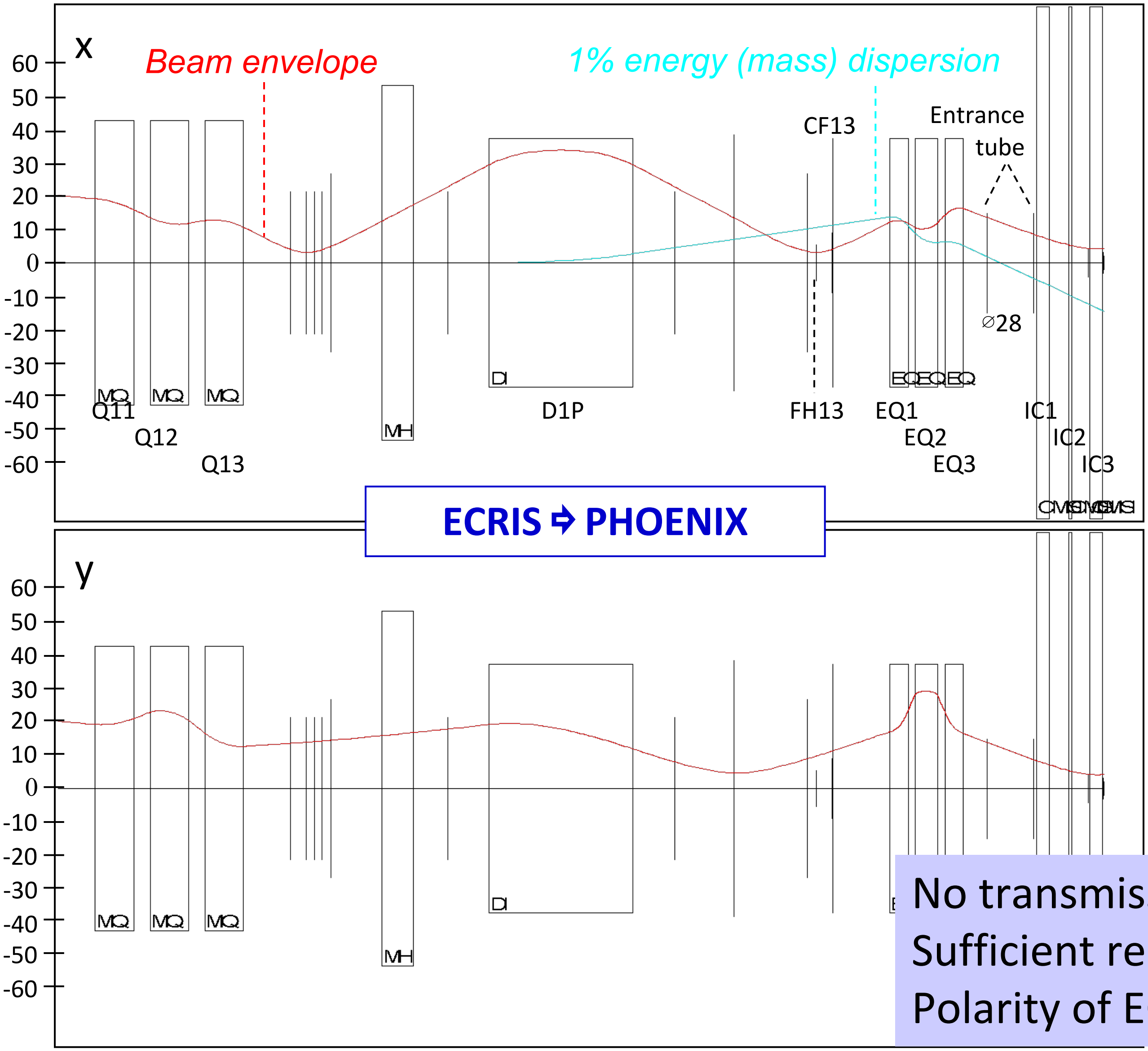
$$D_{norm} = \frac{D}{\sqrt{\beta}} \qquad D'_{norm} = \frac{\alpha D}{\sqrt{\beta}} + \sqrt{\beta} D'$$

Geometrical emittance blow-up due to dispersion mismatch

$\varepsilon_G = \varepsilon_0(1 + 1/2(\gamma D^2 + \beta D'^2 + 2\alpha D D')\delta_E^2/\varepsilon_0)$

Figures from G. Arduini, CERN

Loading of 1$^+$ beams into the PHOENIX charge-breeder



$B\rho$ = 0.22 T.m
A = 117, Q = 1
E = 20 keV
ε_t = 80.0 π mm.mrad
$\Delta E_{init.}$ = 0.5‰

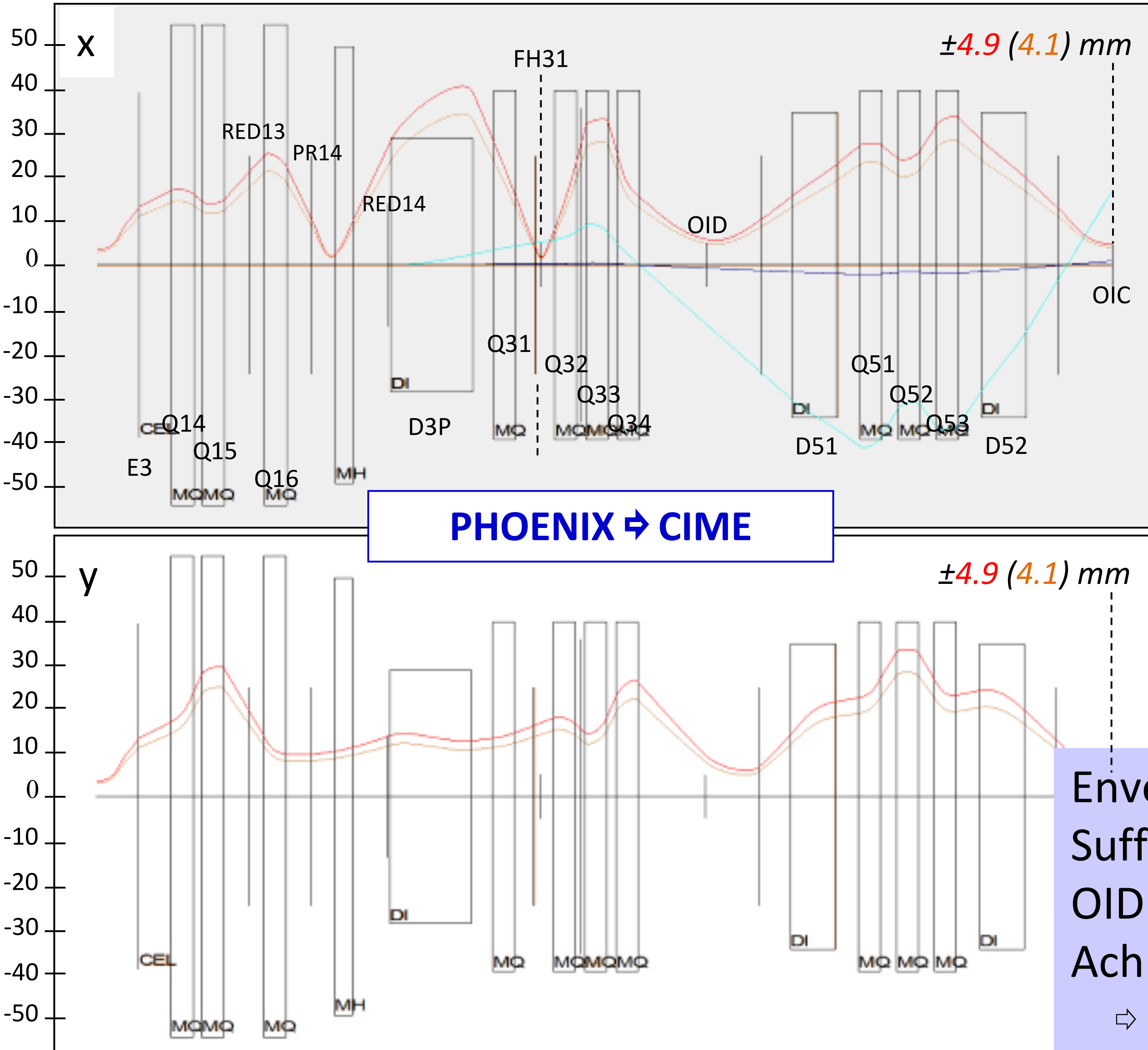
Q11 = 0.0530 [T]
Q12 = -0.119 [T]
Q13 = 0.1336 [T]

EQ1 = 1.250 [kV]
EQ2 = -1.697 [kV]
EQ3 = 1.263 [kV]

R_1 (FH13) = 170

No transmission losses
Sufficient resolving power
Polarity of EQ triplet can be reversed

Extraction of N+ beams from PHOENIX to CIME



$B\rho_{max}$ [T.m] = *0.075 T.m*
HV_{min} = *10 kV*
HV_{max} = *34 kV*
A/Q ≤ 27
$\Delta E_{init.}$ = 0.5‰

HV_1 =*20 kV*
ε_{t1} = *80 π.mm.mrad*
HV_2 =*10 kV*
ε_{t2} = 113 *π.mm.mrad*

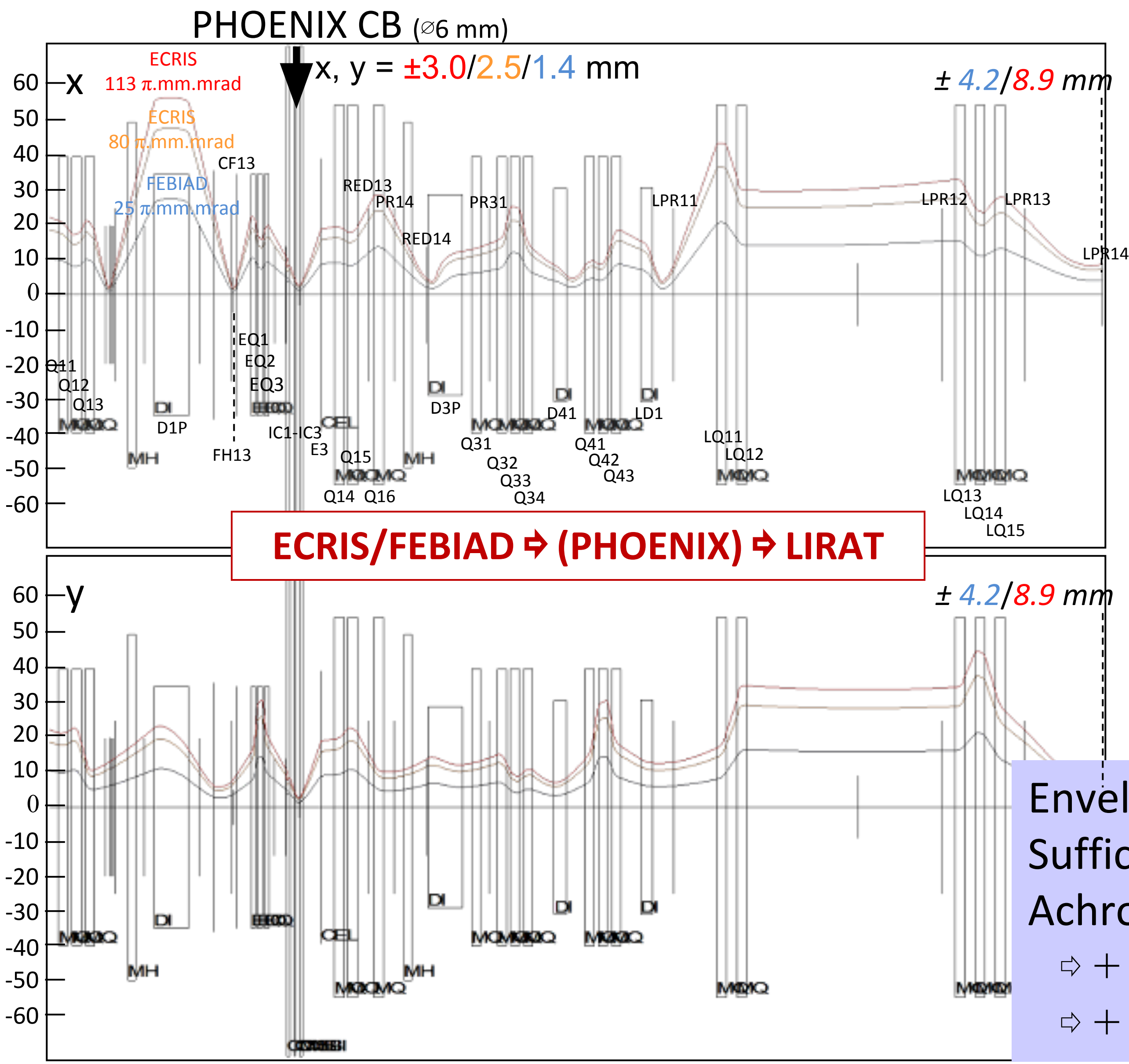
R_2 *(FH31)* = 178/149

Emittance blow-up

$\varepsilon_G = \varepsilon_t +$ *2.5 π.mm.mrad*

Envelope within boundaries
Sufficient resolving power
OID conditions not matched
Achromaticity not preserved
⇨ + 2.5 *π.mm.mrad*

FEBIAD/ECRIS beams through PHOENIX towards LIRAT (DESIR)



Bρ = 0.1366 T.m

A = 81, Q = 1

HV = 10 kV

$\Delta E_{init.}$ = 0.5‰

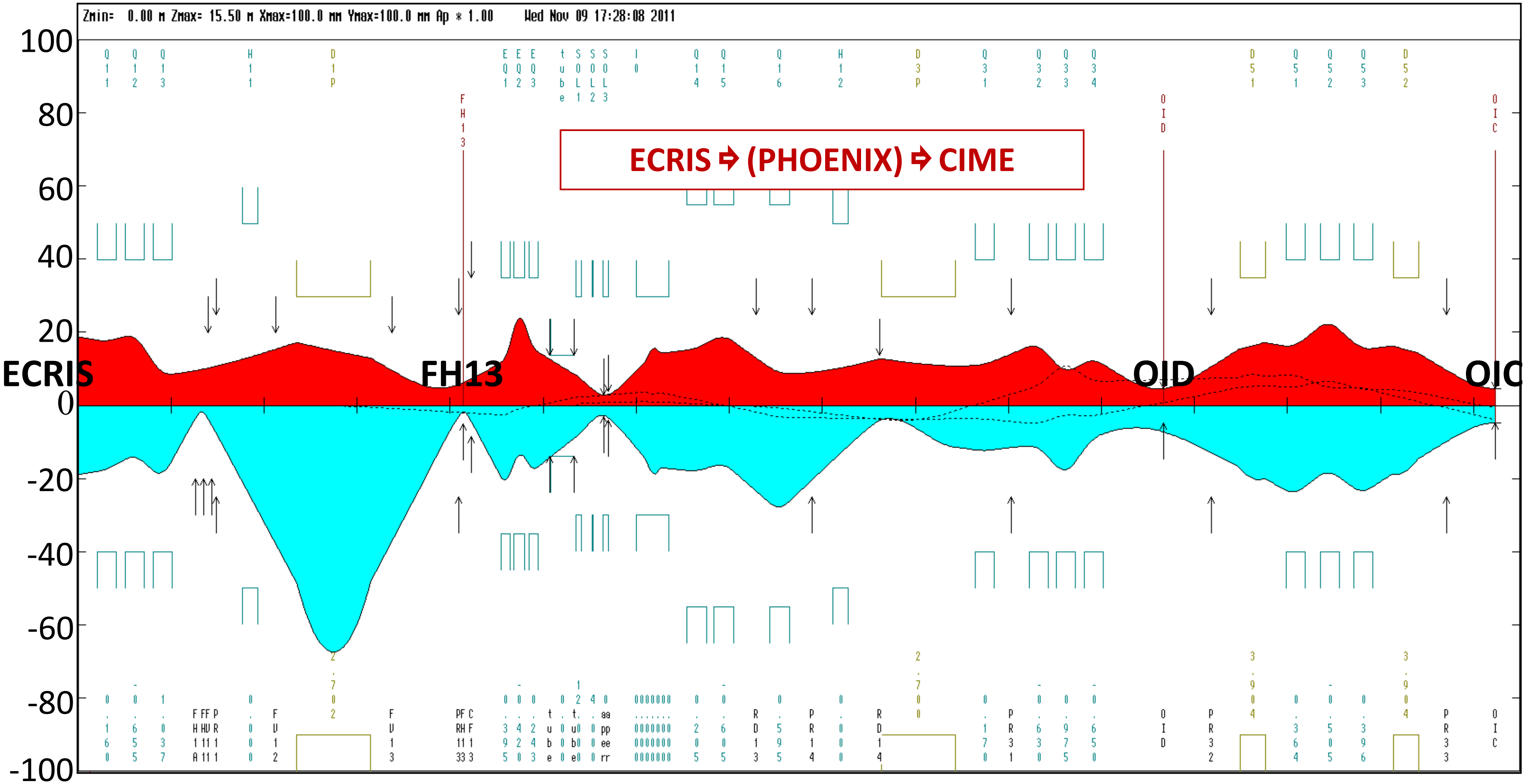
R_1 (FH13) = 242/288/511

±4.2 ÷ ±8.9 mm

PHOENIX coils at 1200 A and 400 A (third coil off)

Envelope within boundaries
Sufficient resolving power
Achromaticity not preserved
➪ + 1.4 *π.mm.mrad in x*
➪ + 1.1 *π.mm.mrad in y*

ECRIS ➪ PHOENIX ➪ CIME: COSY Infinity vs. TRANSPORT



	Q11	Q12	Q13	R_1	Q14	Q15	Q16	Q31	Q32	Q33	Q34	Q51	Q52	Q53
Program\Units	[T]	[T]	[T]	M/ΔM	[T]	[T]	[T]	[T]	[T]	[T]	[T]	[T]	[T]	[T]
COSY	0.0160	-0.0655	0.1037	**288**	0.0215	-0.0605	0.0605	0.0180	-0.0623	0.0992	-0.0667	0.0337	-0.0506	0.0392
TRANSPORT	0.0160	-0.0655	0.1037	**289**	0.0205	-0.0605	0.0595	0.0170	-0.0630	0.0975	-0.0650	0.0364	-0.0505	0.0396

Optical calculations for the SPIRAL upgrade - summary

- Maximal transmission for the whole mass and rigidity range
- Estimation of emittance blow-up due to dispersion mismatch
- Minor modifications of existing elements (ES steerers, Q32, einzel lenses, apertures)
- In several calculations quadrupoles (Q13, Q15, Q33) operate at their maximal power

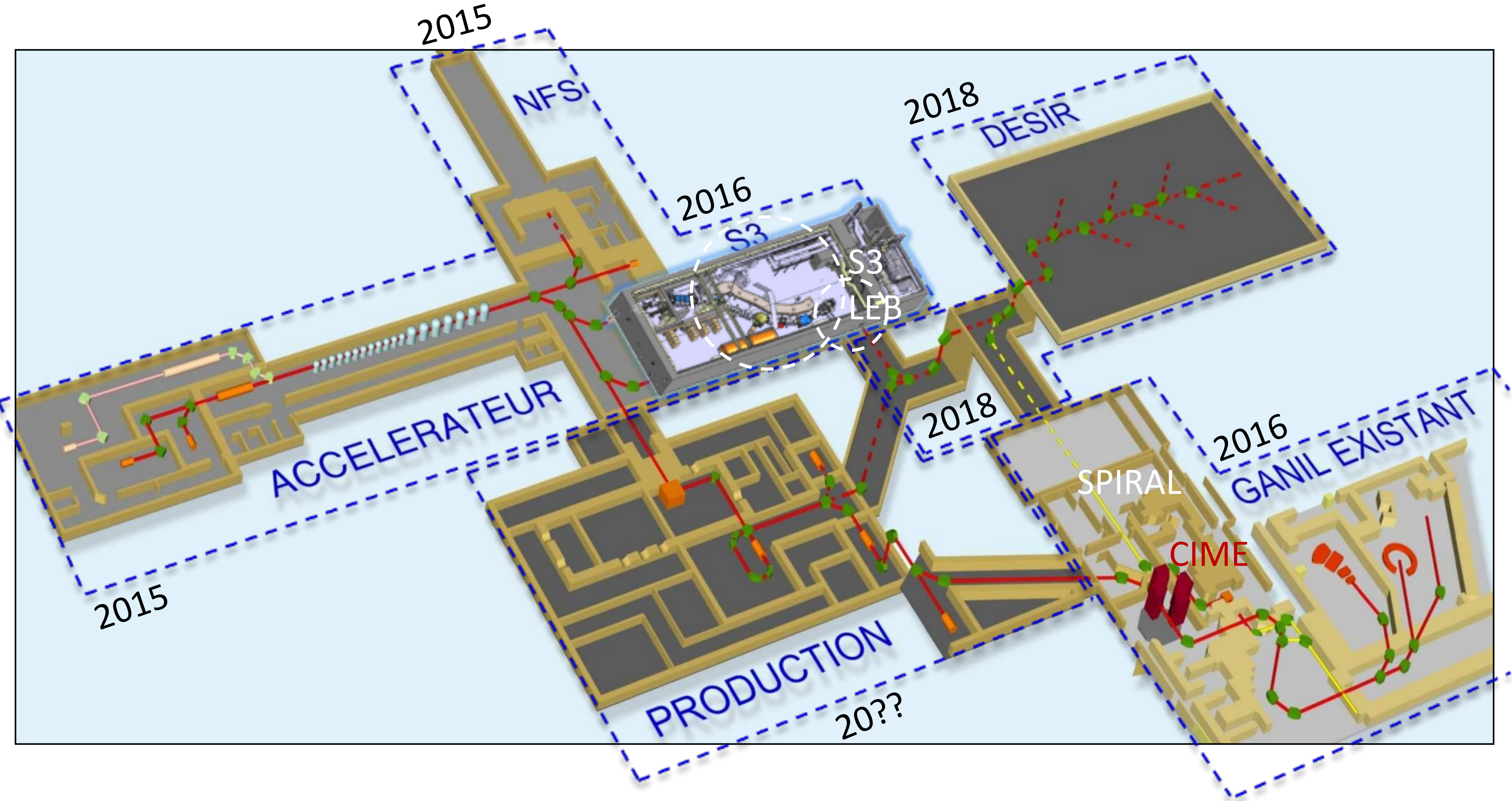
Source	Mode	Max.Bρ [T.m]	A/Q	$U_{acc.}$ [kV]	ε_0 [mm.mrad]	Resolving power
ECRIS	1	0.22	117	20	80	**170**
ECRIS	1	0.22	230	10.2	112.3	**143**
FEBIAD	1	0.22	69	33.8	15.1	**409**
PHOENIX	2 → CIME	0.075	27 (13.5)	10 (20)	113 (80)	**149 (178)**
PHOENIX	2 → IBE	0.075	27 (13.5)	10 (20)	113 (80)	**149 (178)**
PHOENIX	2 → LIRAT	0.075	27	10	113	**149**
ECRIS/FEBIAD	3 → PHOENIX	0.1366	90	10	113 ÷ 25	**242 ÷ 511**
ECRIS/FEBIAD	3 → LIRAT	0.1366	90	10	113 ÷ 25	**242 ÷ 511**
ECRIS/FEBIAD	3 → CIME	0.075	90	10	113 ÷ 25	**242 ÷ 511**

A summary of all beams and the achieved mass resolving powers for each case.

Mode 1 is for loading of ECRIS/FEBIAD 1+ beams into PHOENIX charge booster
Mode 2 is for extraction of N+ beams from PHOENIX to CIME, IBE or LIRAT
Mode 3 is for transport of 1+/n+ beams from ECRIS/FEBIAD (through PHOENIX) to CIME, IBE or LIRAT

SPIRAL upgrade is in progress and first RIB are expected in 2016

S3 spectrometer and production of radioactive ion beams

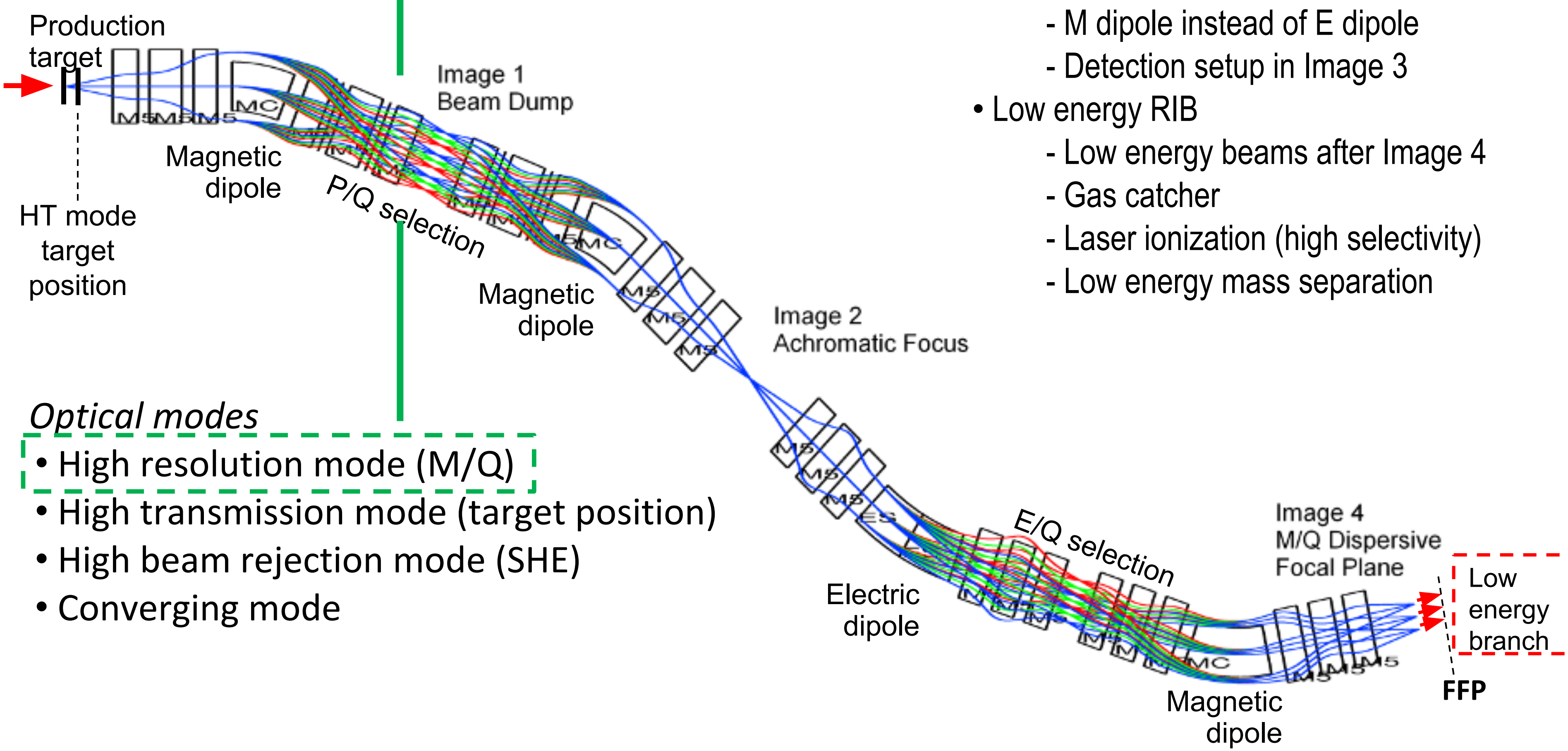


Operation and optical modes of S^3 spectrometer

Standard operation

Operation modes

- Momentum achromat (P/Q)
    - up to Image 2
- Mass separator (M/Q)
    - from Image 2 to Image 4
- Spectrograph (alt. configuration)
    - M dipole instead of E dipole
    - Detection setup in Image 3
- Low energy RIB
    - Low energy beams after Image 4
    - Gas catcher
    - Laser ionization (high selectivity)
    - Low energy mass separation



Optical modes

- High resolution mode (M/Q)
- High transmission mode (target position)
- High beam rejection mode (SHE)
- Converging mode

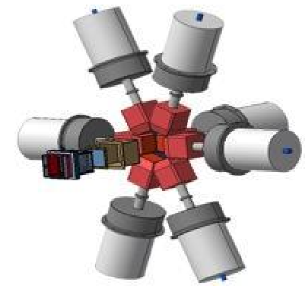
Spectroscopy at S3

In-beam spectroscopy (Two step reactions)
EXOGAM2, PARIS, AGATA, MUST2/GASPARD

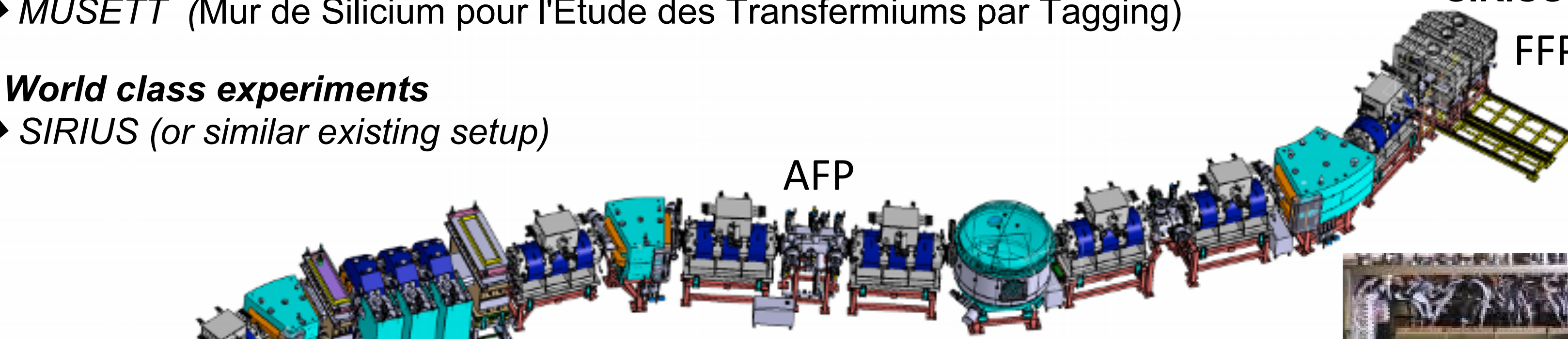
Delayed spectroscopy (VHE-SHE, N=Z)
p, *α*, *γ*, *e*- decay
Implantation-decay station at the M/Q dispersive plane

Commissioning & first experiments
➔ *MUSETT* (Mur de Silicium pour l'Etude des Transfermiums par Tagging)

World class experiments
➔ *SIRIUS (or similar existing setup)*

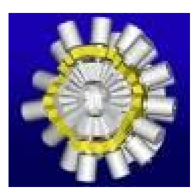


SIRIUS

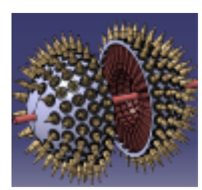


MUSETT

EXOGAM2



AGATA

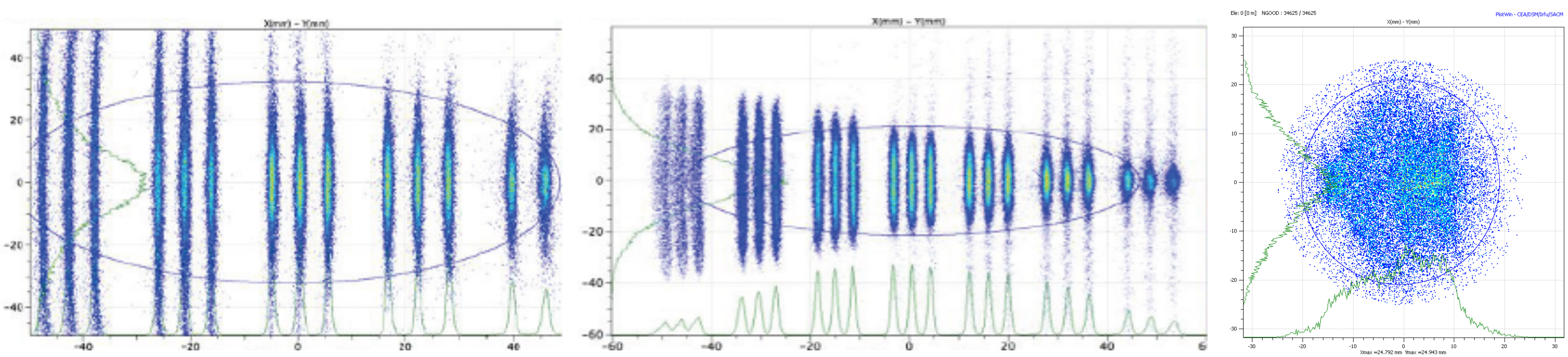


PARIS

Production target

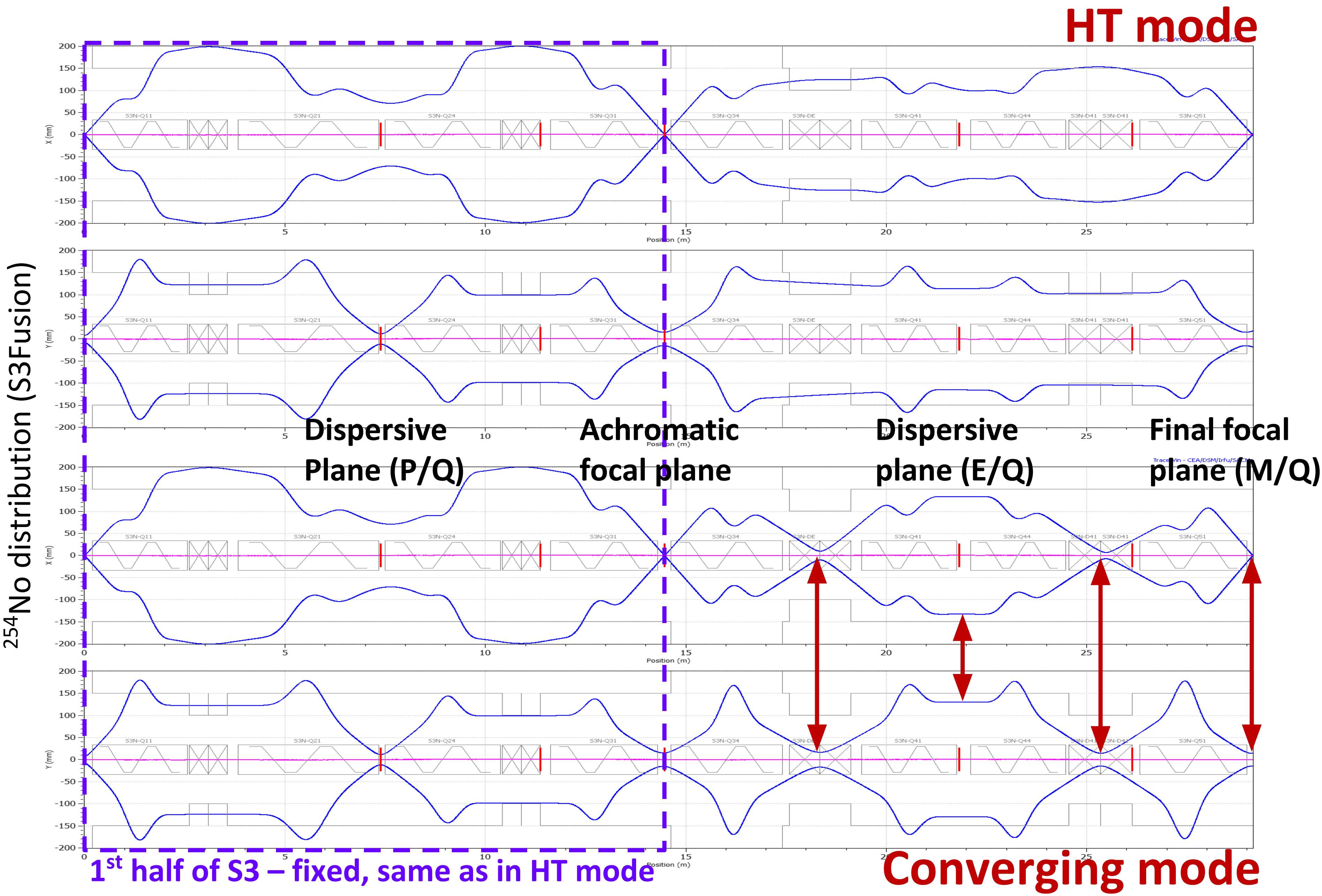
Optical modes of S^3 spectrometer

1. **High Resolution mode**
   - Designed for maximum selection
   - Weighted mass resolution: **M/ΔM = 460**
   - Folded transmission: 50% for ^{58}Ni + ^{46}Ti ⇨ ^{100}Sn^{24+} + 4n
2. **High Transmission mode**
   - Designed for very asymmetric reactions (large emittances)
   - Weighted mass resolution: **M/ΔM = 260**
   - Folded transmission: 15-20% for ^{22}Ne + ^{238}U ⇨ ^{255}No + 5n
3. **Converging mode**
   - Designed for gas cell – Laser spectroscopy
   - Folded transmission: 68% for ^{58}Ni + ^{40}Ca ⇨ ^{94}Ag + p3n
   - Folded transmission: 56% for ^{48}Ca + ^{208}Pb ⇨ ^{254}No + 2n



Distributions at the Final Focal Plane for different operating modes

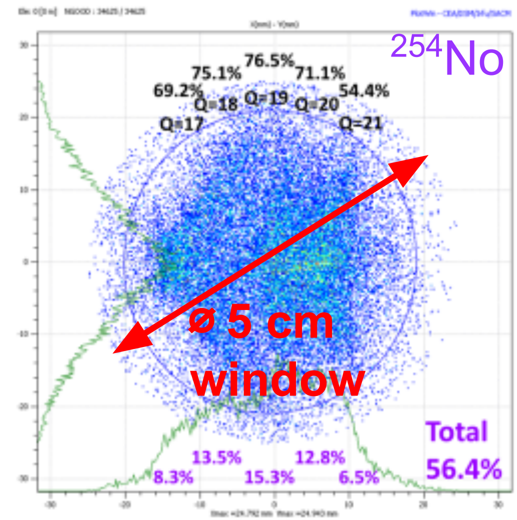
Converging mode based on HT mode for ^{254}No distribution



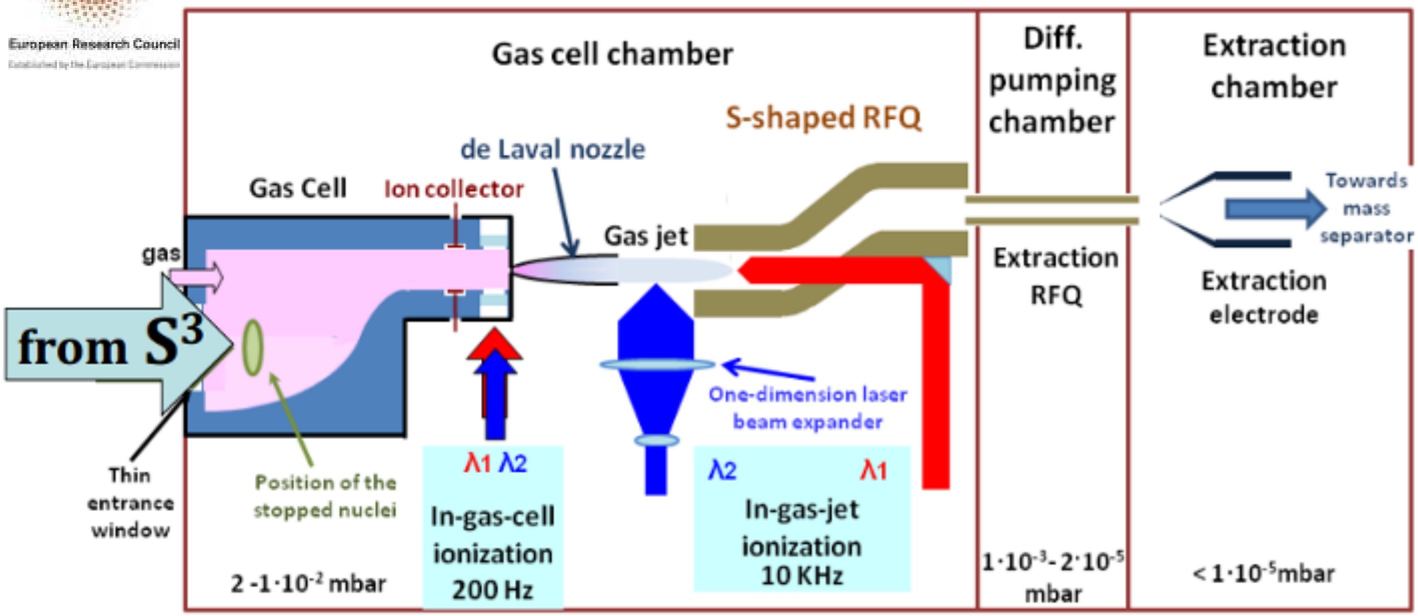
Gas stopping, neutralization, and selective laser ionization

REGLIS^3: In-gas cell laser ionization and spectroscopy

- Pre-selection by S^3 in-flight separator
- Thermalization and neutralization in gas (Ar, He)
- Selective re-ionization of stopped reaction products
- HR laser spectroscopy in gas jet ($^{94\text{-}96}$Ag, $^{101\text{-}105}$Sn, trans-actinides)
- Decay spectroscopy and mass measurements
- Laser ion source RIB production DESIR



A generic IGLIS setup to be commissioned and tested at the HELIOS (Heavy Element Laser Ionization Spectroscopy) laboratory @ KU Leuven



Gas-cell + Laser ionization

⇩

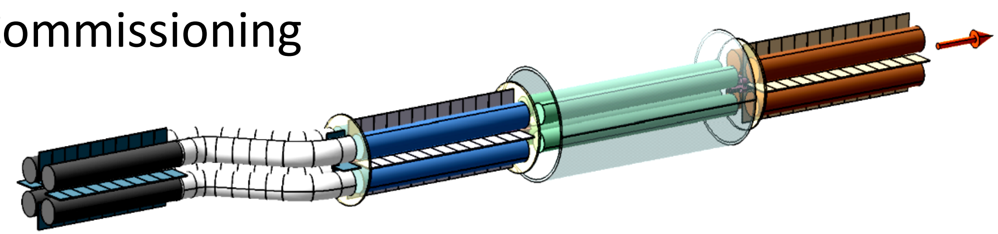
Testing, Optimization, Installation at S^3 LEB

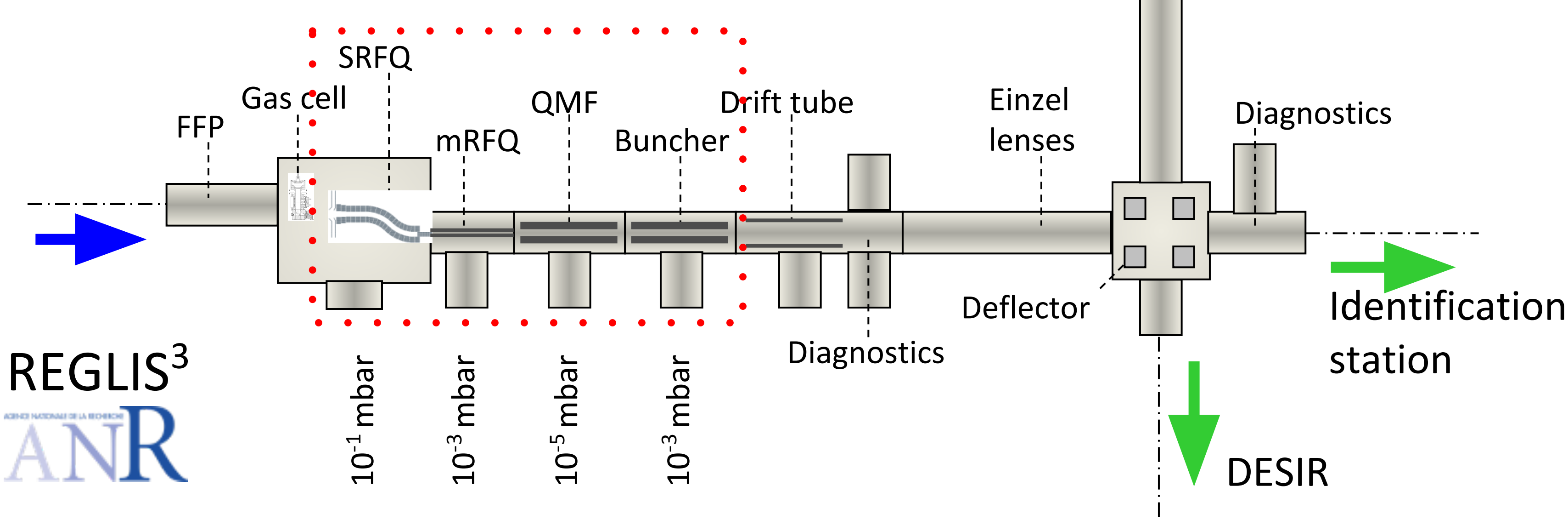
The in-gas-jet laser ion source: Resonance ionization spectroscopy of radioactive atoms in supersonic gas jets, Yu. Kudryavtsev, *et al.*,Nucl. Instrum. Meth. B 297 (2013) 7–22

Low energy beam line of S^3 spectrometer

Main steps

- Ion transport simulations
    - Dimensions and distances
    - DC and RF electronics
    - Vacuum and gas systems
- Design
- Construction
- Commissioning





REGLIS³

ANR

Free gas expansion jet definition and injection into RFQ

$$M_z = x^{\frac{2}{3}}\left(3.232 - \frac{0.7563}{x} + \frac{0.3937}{x^2} - \frac{0.0729}{x^3}\right)$$

$$\rho_z = \left(1 + \frac{1}{3}M_z^{\ 2}\right)^{-\frac{3}{2}}$$

$$\theta = \operatorname{atan2}(\sqrt{y^2 + z^2}, x)$$

$$\varphi = \operatorname{atan2}(y, z)$$

$$\boxed{\rho_{\text{int}} = \rho_z \cos^2(\theta)\cos^2\left(\frac{\theta\pi}{2\cdot 1.365}\right)}$$

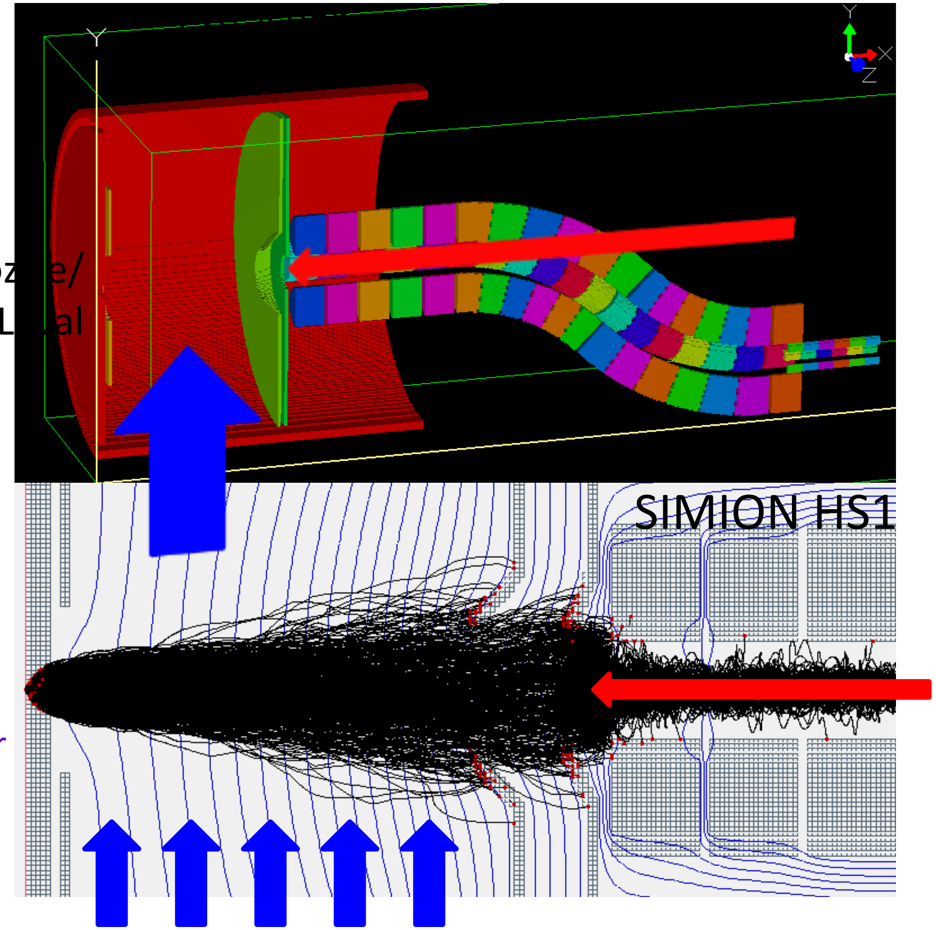
$$M_t = \sqrt{3\cdot\left(\rho_{\text{int}}^{-\frac{2}{3}} - 1\right)}$$

$$\boxed{\begin{aligned} p &= p_0\left(1 + \frac{1}{3}M_t^2\right)^{-\frac{5}{2}} \\ T &= T_0\left(1 + \frac{1}{3}M_t^2\right)^{-1} \end{aligned}}$$

Jet-ions interaction

P_{cell}

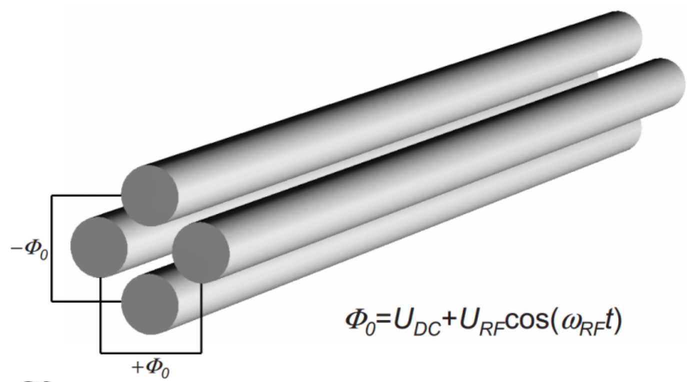
$d_{aperture}$

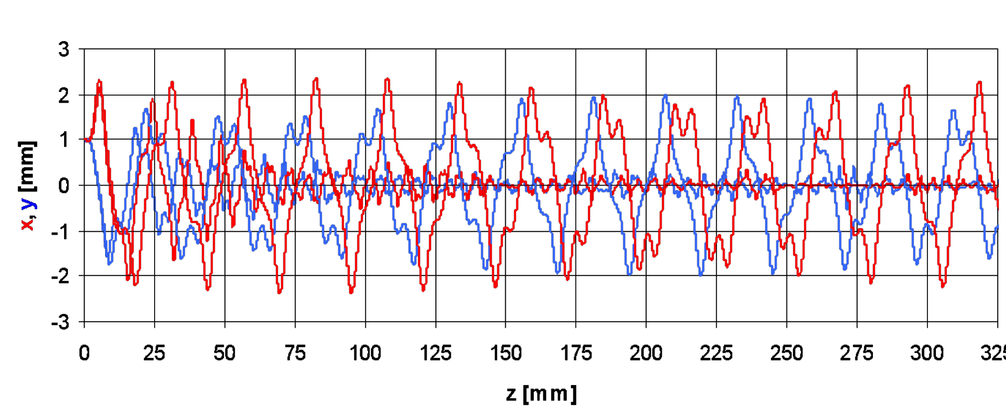


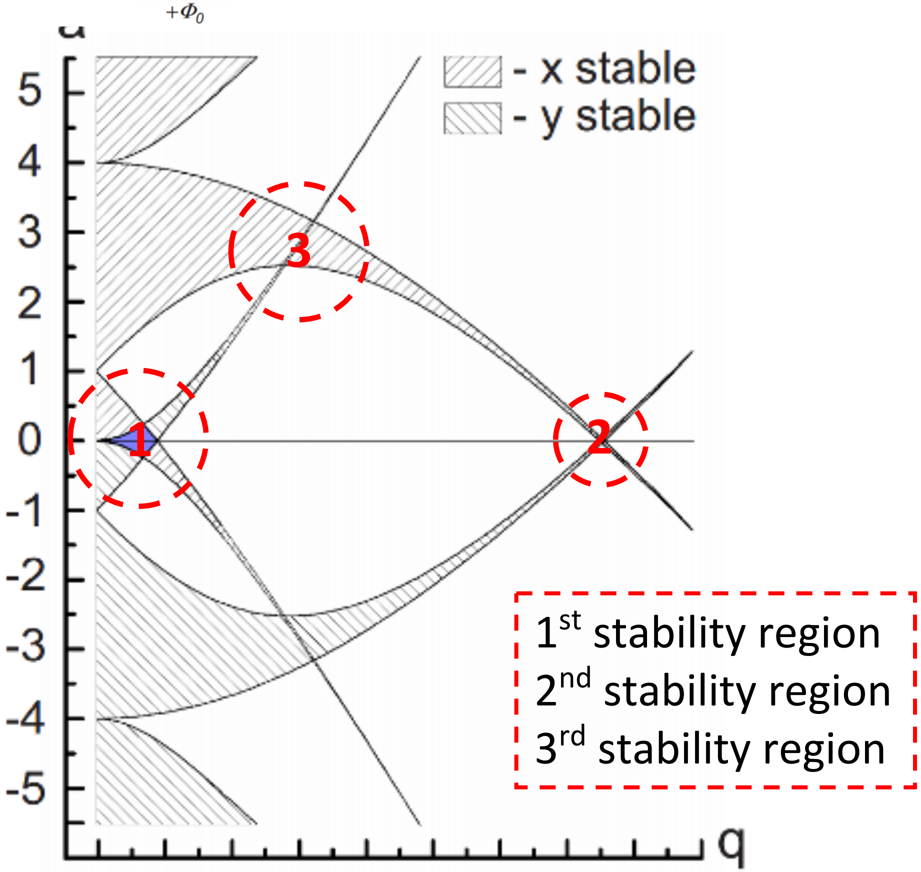
$$\boxed{V_f = \sqrt{\frac{5}{3}\frac{kT_0}{m}}\frac{M_t}{\sqrt{1 + \frac{1}{3}M_t^2}}} \Rightarrow \begin{aligned} V_x &= V_f \cos\theta \\ V_y &= V_f \sin\theta \sin\varphi \\ V_z &= V_f \sin\theta \sin\varphi \end{aligned}$$

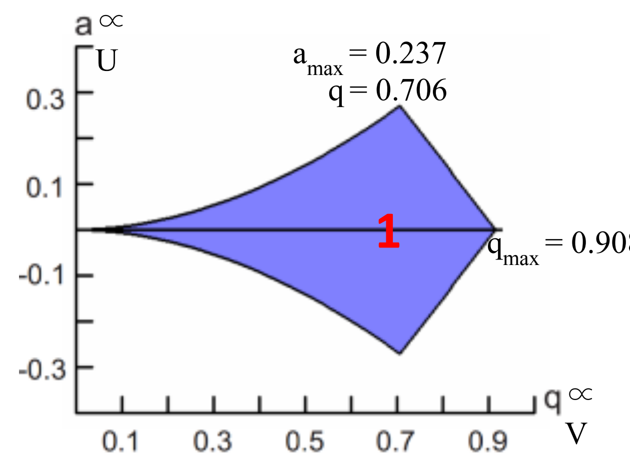
Yu. Kudryavtsev, *et al.,* Nucl. Instrum. Meth. B 297 (2013) 7

Linear RFQ: ion stable motion – operating modes







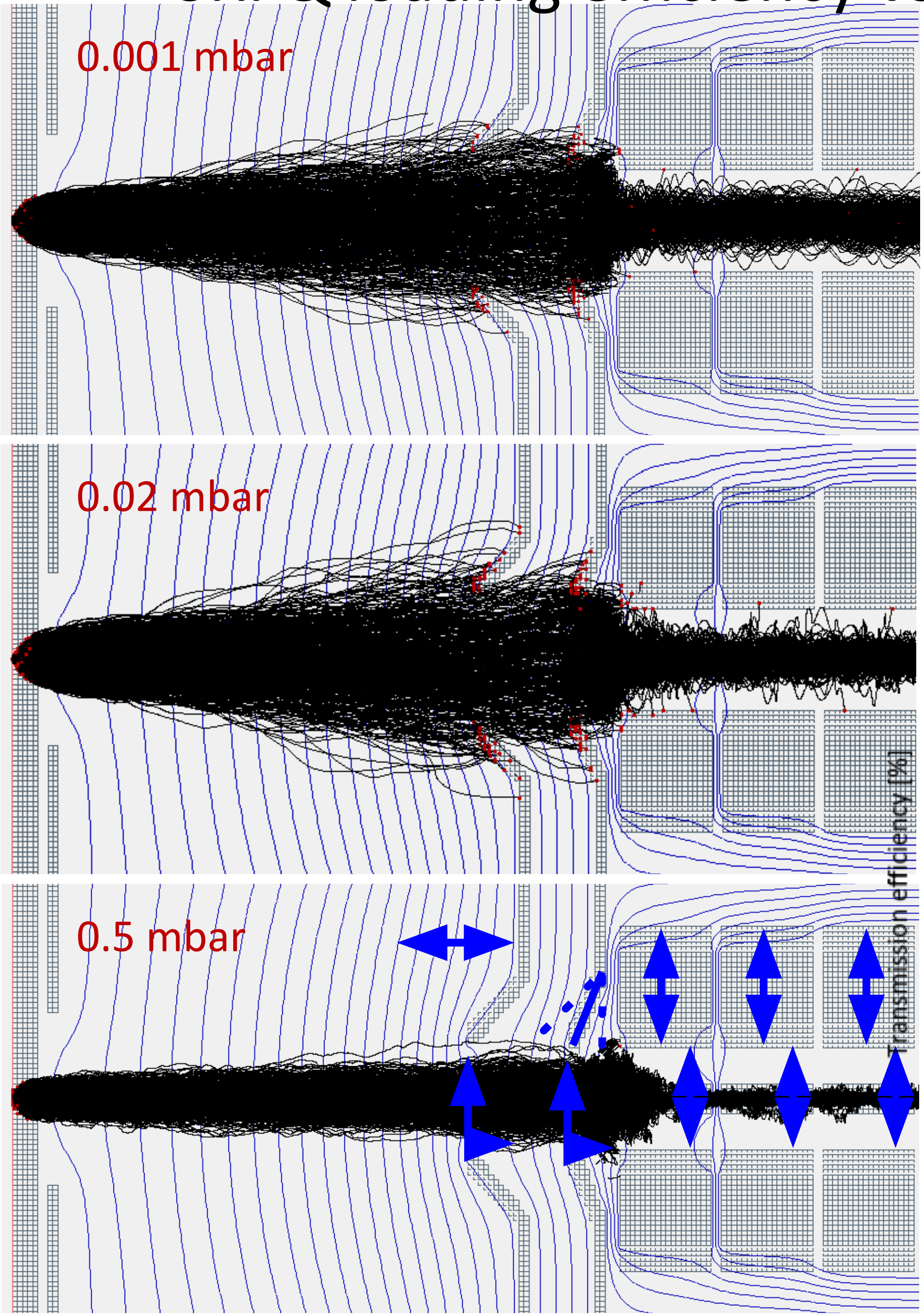


Mathieu equation:

$$\frac{d^2u}{d\xi^2} + \left(a_u - 2q_u\cos(2\xi)\right)u = 0 \qquad \xi \equiv \frac{\Omega t}{2}$$

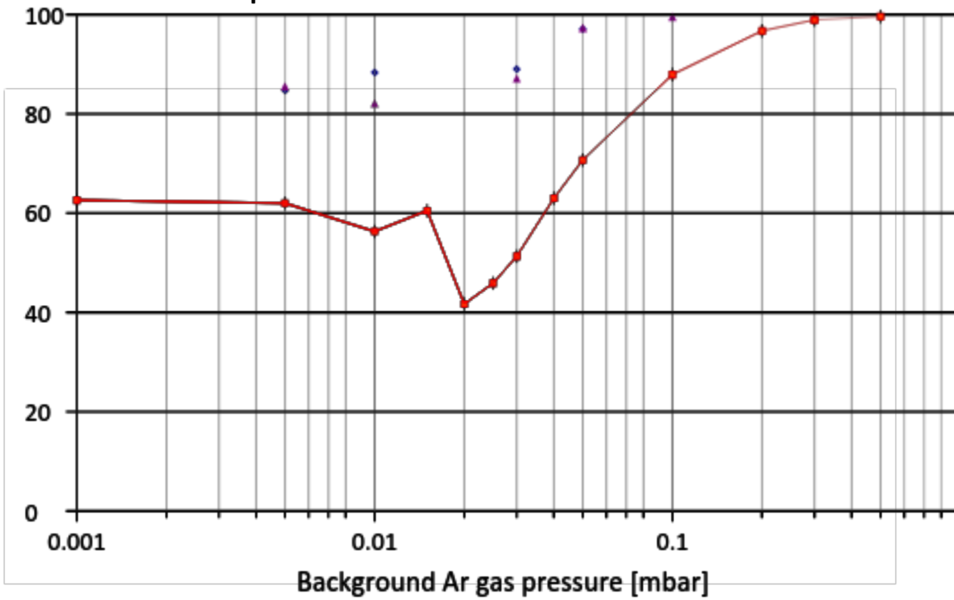
$$q_u = \frac{4zV}{mr_0^2\Omega^2} \qquad a_u = \frac{8zU}{mr_0^2\Omega^2} = 0$$

SRFQ loading efficiency vs. Ar background pressure

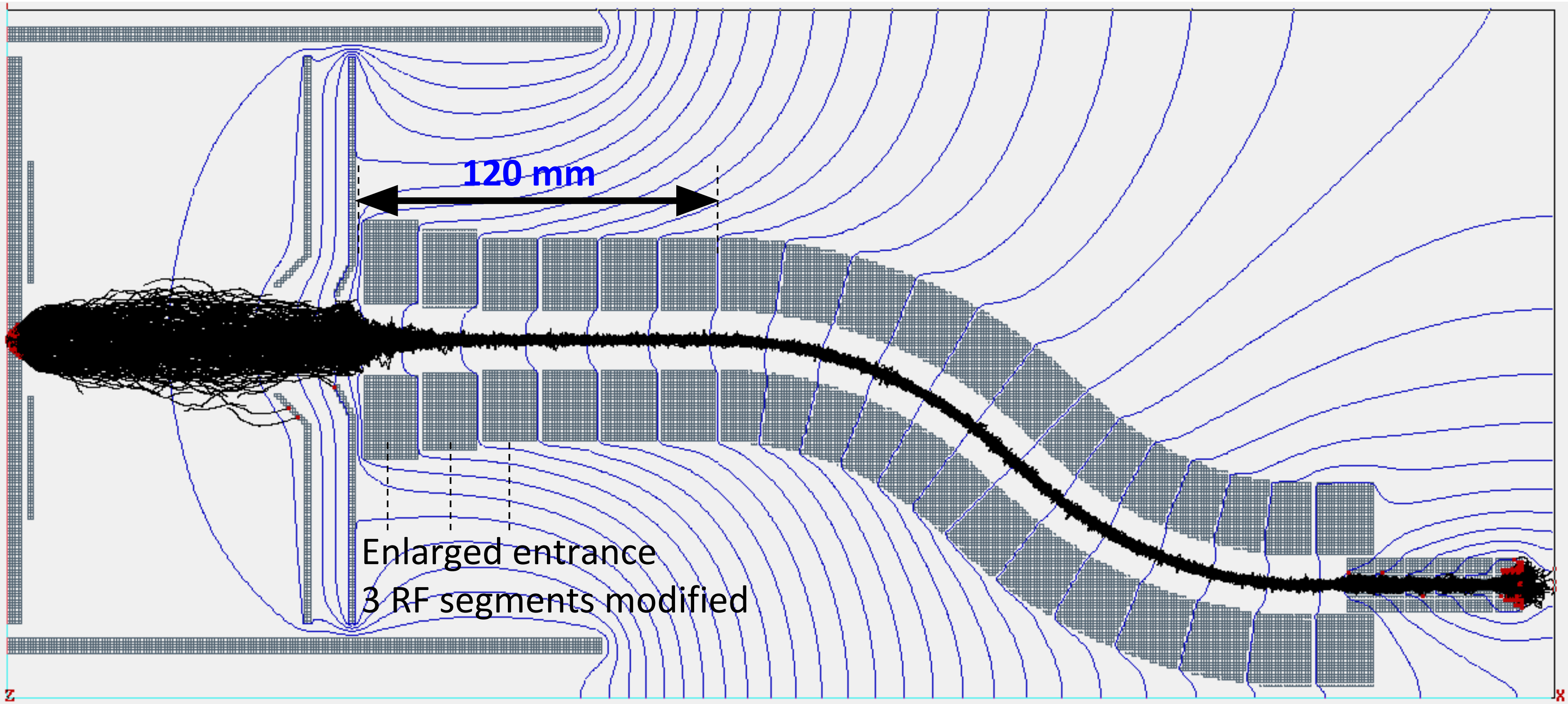


<u>Optimization of parameters vs. pressure</u>

- Position of injection electrodes
- Angle of second injection electrode
- Apertures of injection electrodes
- Position and size of entrance RF segments
- DC and RF potentials



Optimal design for injection electrodes and SRFQ



Quadrupole Mass Filter

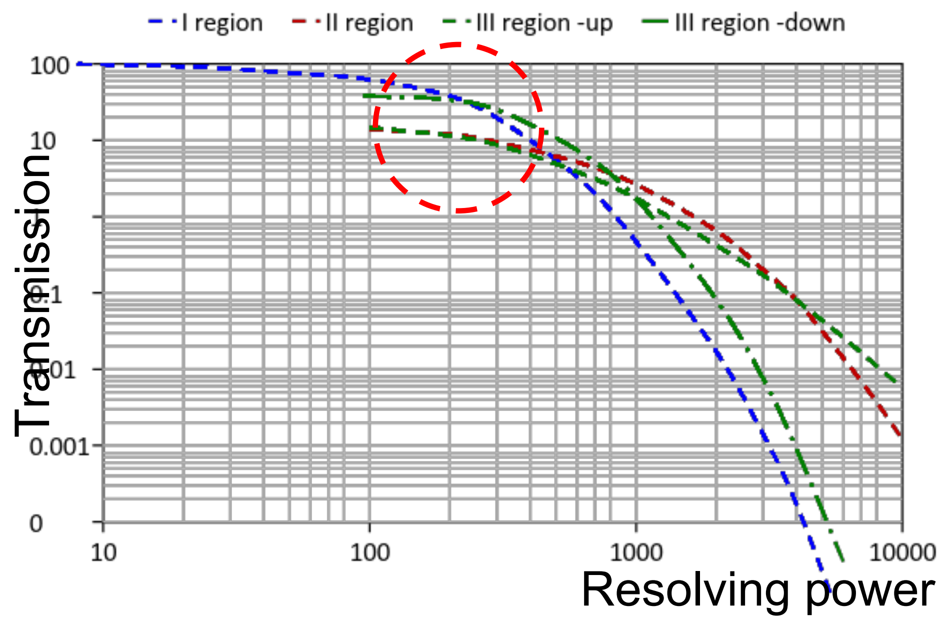
Detailed Study of the Quadrupole Mass Analyzer Operating Within the First, Second, and Third (Intermediate) Stability Regions.
II. Transmission and Resolution
V. Titov, J. Am. Soc. Mass Spectrom. 1998, 9, 50-69

L = 20.3 cm, r_0 = 0.35 cm, f_{RF} = 2 MHz, KE = 5 eV

L = 27.5 cm, r_0 = 0.72 cm, f_{RF} = 1 MHz, KE = 60 eV

L = 15.0 cm, r_0 = 0.35 cm, f_{RF} = 1 MHz, KE = 34 eV

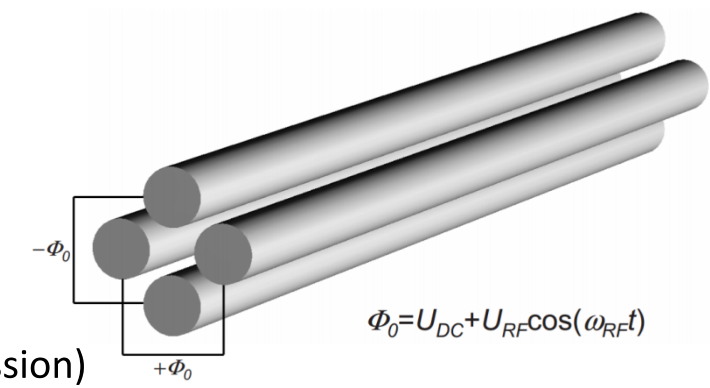
L = 27.5 cm, r_0 = 0.72 cm, f_{RF} = 1.55 MHz, KE = 18 eV



1st stability region is preferable for the purpose of high transmission and R ≤ 250

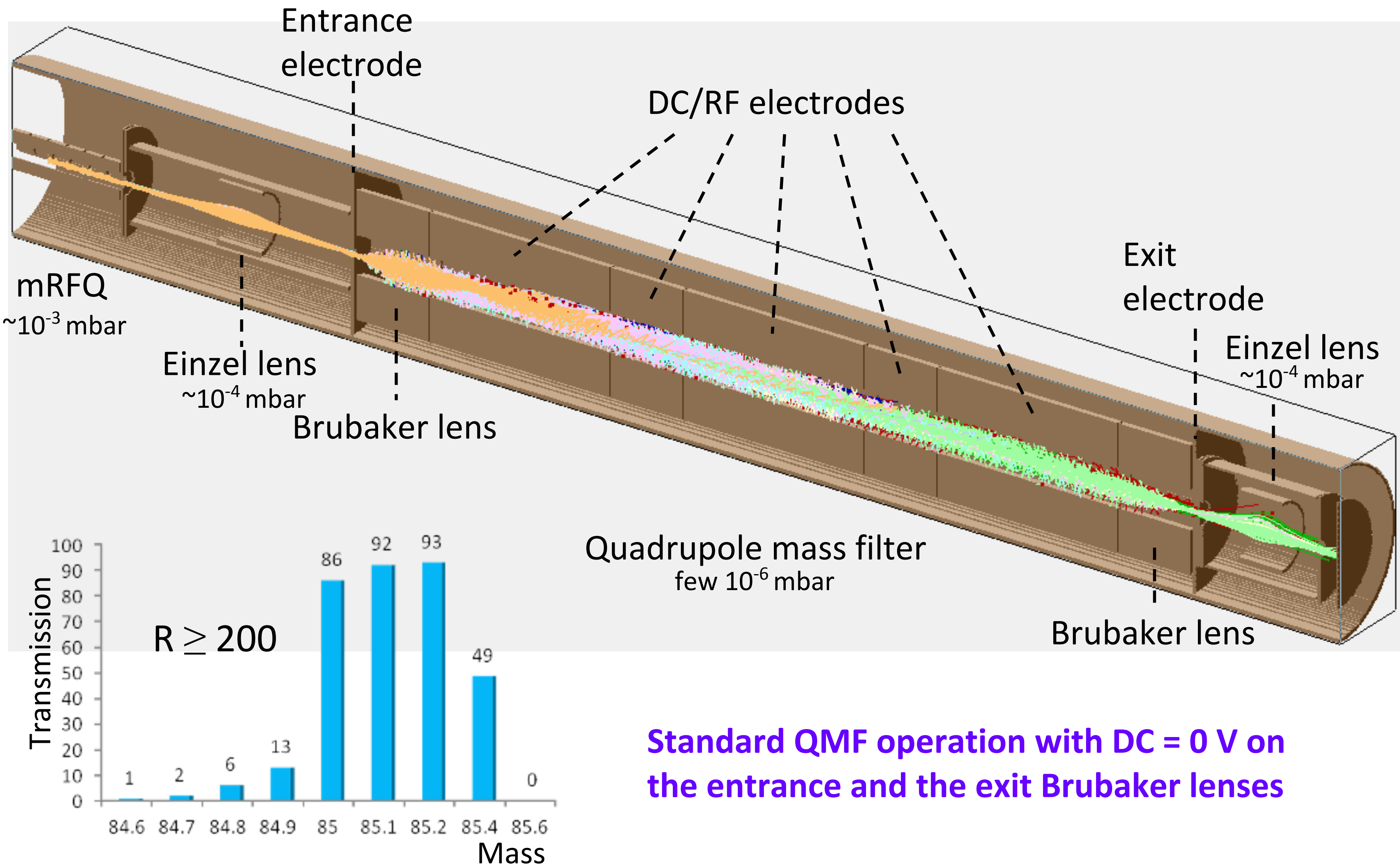
Operation modes of Linear Quadrupole Mass Filters

- RF only
  - Fringe field acceleration (at $q \approx 0.908$)
  - Notch filter (resonances in target ions for removal)
- RF+DC
  - First stability region
  - Second and third stability regions (higher R, lower transmission)
  - Axial focusing at the exit aperture
  - Multiple axial focusing + unstable regions



⇨ **Novel techniques for enhanced QMF operation**

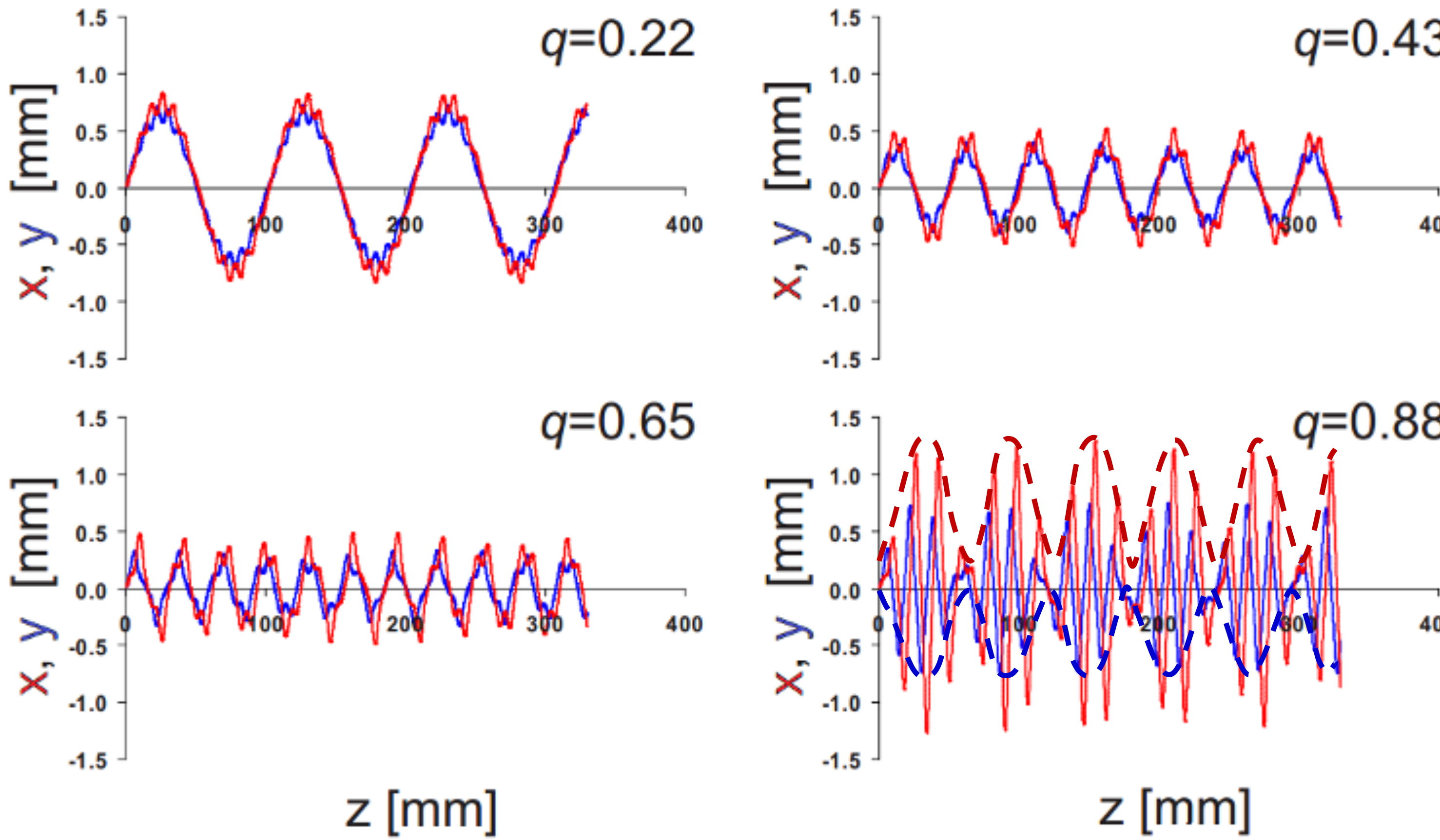
mRFQ and Quadrupole Mass Filter design



Standard QMF operation with DC = 0 V on the entrance and the exit Brubaker lenses

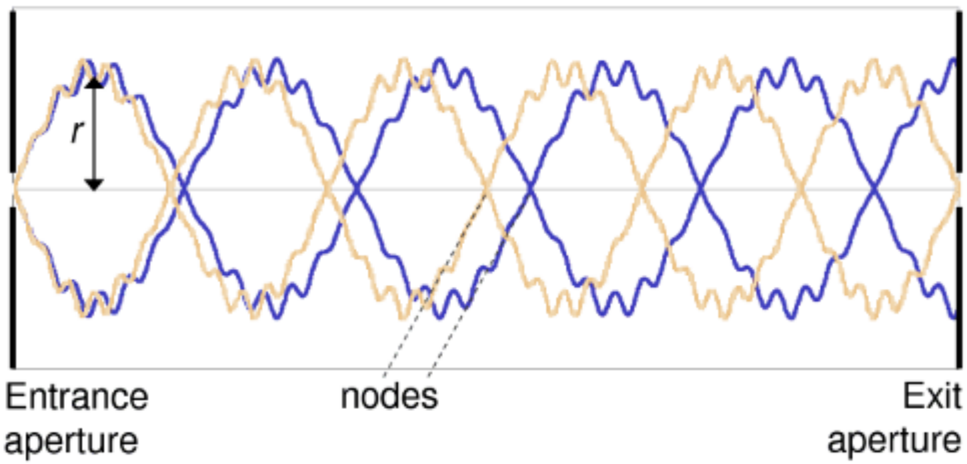
Axial focusing of cooled ion beams in an RFQ

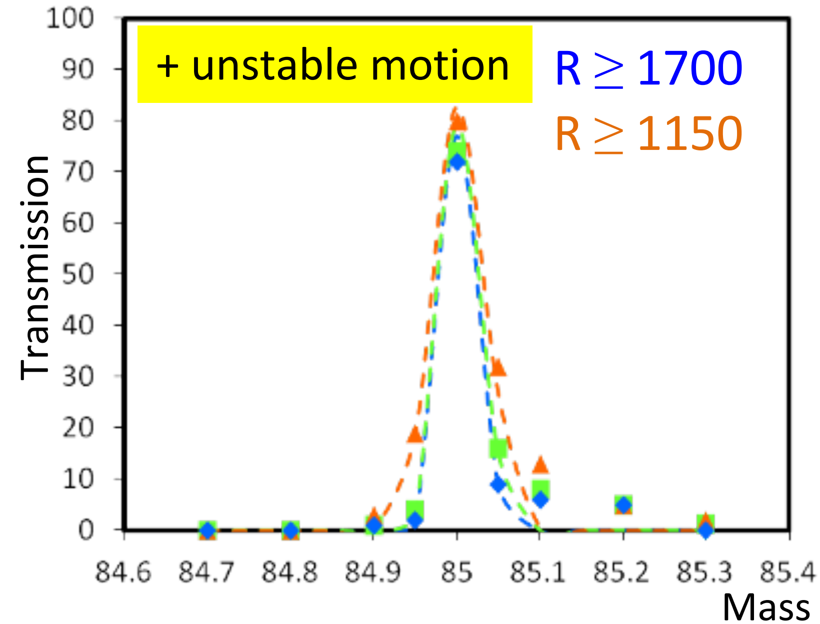
Single ion motion in a confining RF field



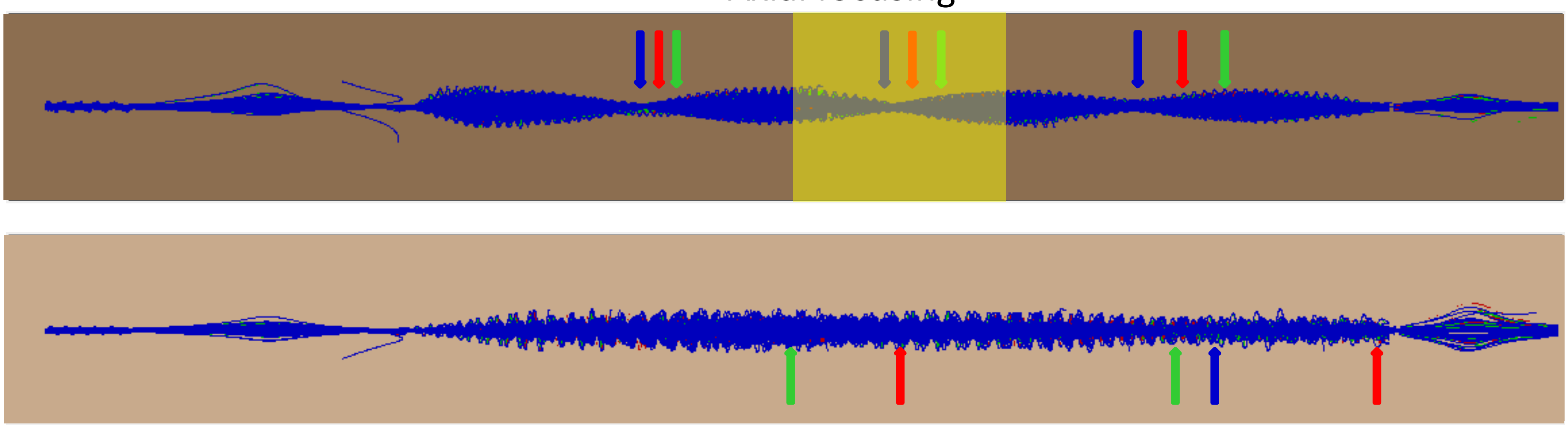
Cooled ion beam – particles have similar initial properties after mRFQ

Axial focusing + unstable motion (electronic aperture)





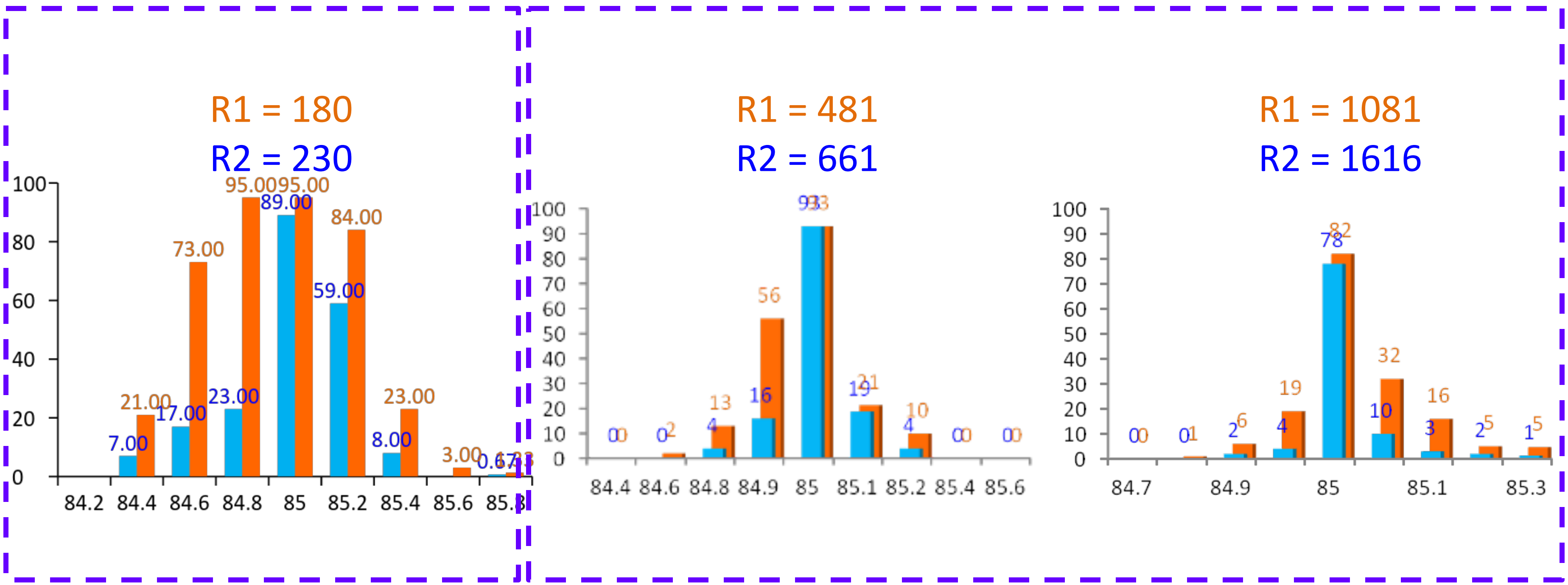
Axial focusing



M_1 = 85 **M_3 = 84.95** **M_2 = 85.05**

Standard operation vs. axial focusing

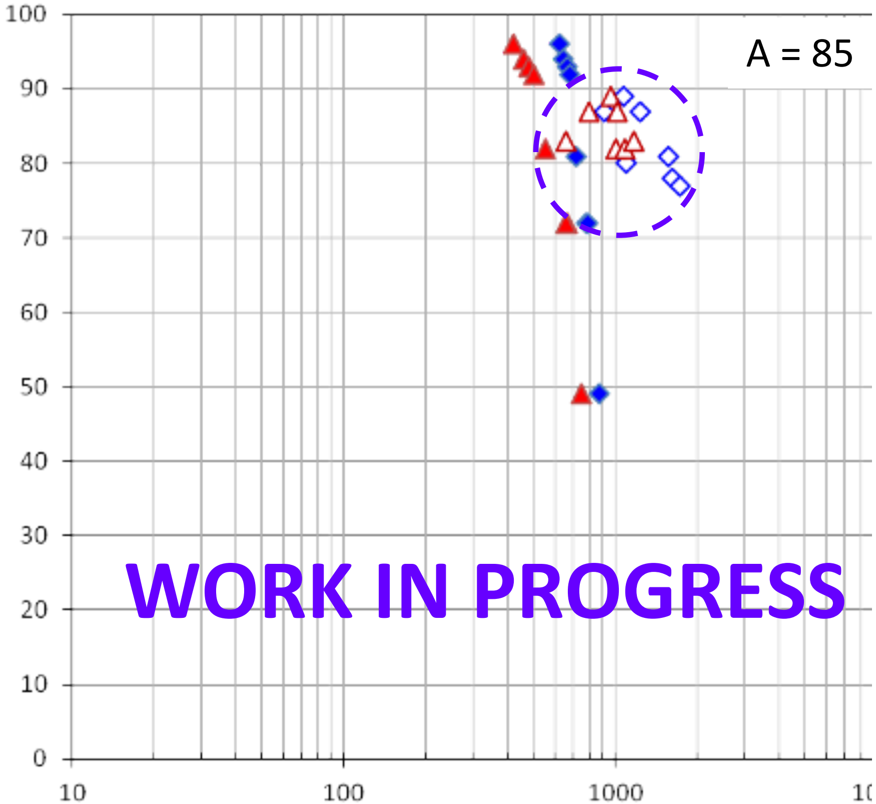
Standard QMF operation
with Brubaker lenses

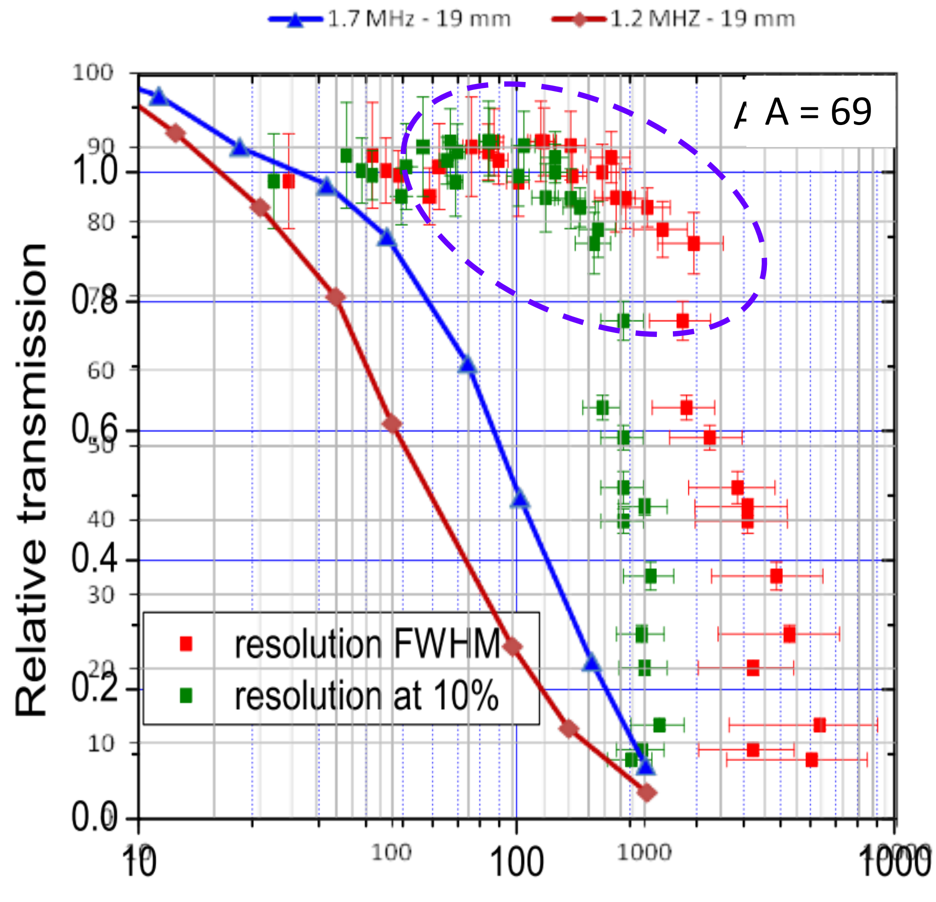


QMF operation with
Axial focusing

QMF operation with
Axial focusing
+ unstable regions

QMF operation modes: resolving power vs. transmission





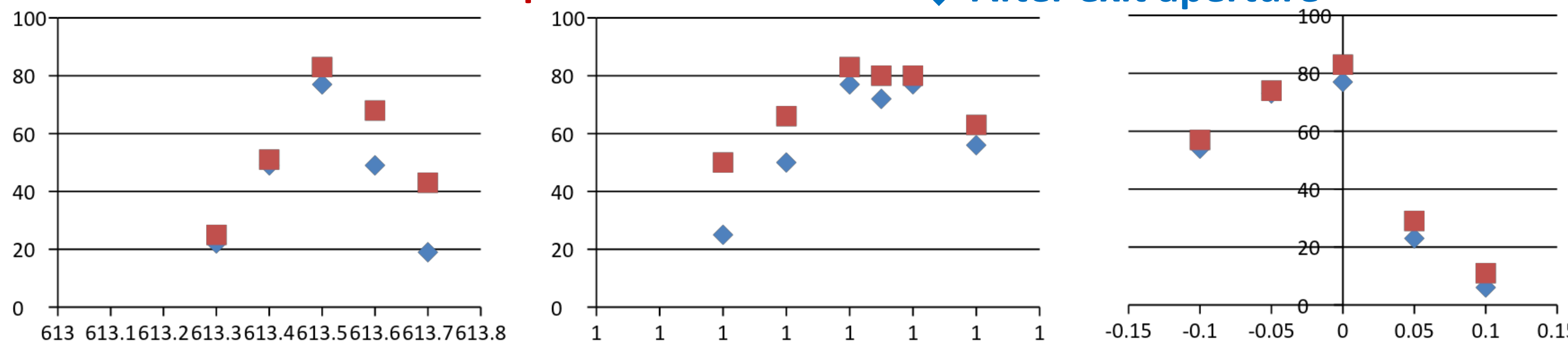
Data from Excel Application Note GT-310D

E. Haettner, *et al.*, GSI SCIENTIFIC REPORT 2010

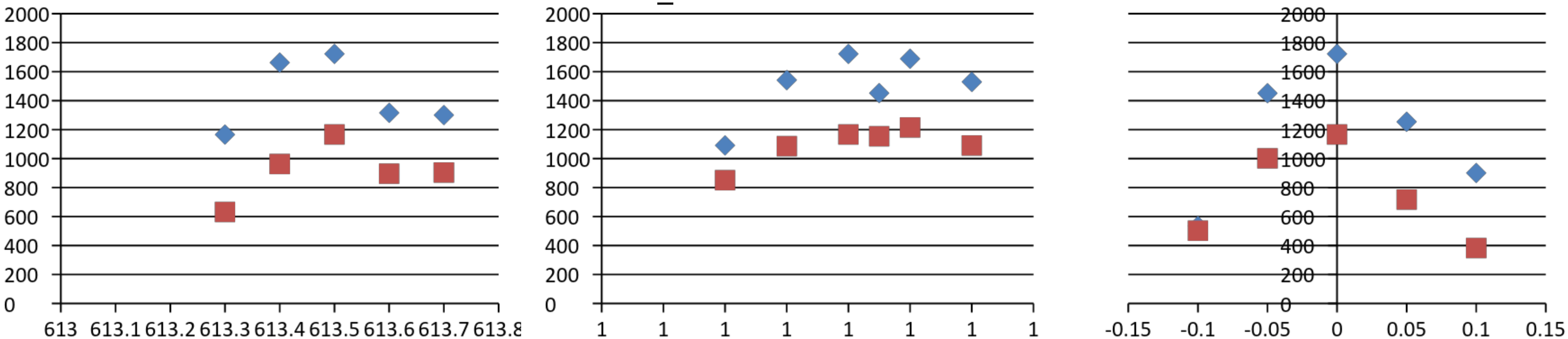
Parametrization of the QMF performance

QMF operation in axial focusing (+ unstable motion)

■ **Before exit aperture** ◆ **After exit aperture**



V_{RFref} = 613.5 V f_{RF_ref} = 1.00000 MHz U_{DCref} = 102.6 V



Very demanding on precision of RF amplitude!

S3-LEB conclusion

Optical modes of S3 – studied by simulations
Converging mode for low energy RIB
HELIOS lab – gas stopping and ionization
REGLIS3 – simulations and design of the S3-LEB

- **Loading into SRFQ**
- **Transmission through a mRFQ**
- **Operation modes of QMF**
- **Novel separation techniques**
- **Final design and electronics (2015)**
- **Commissioning**