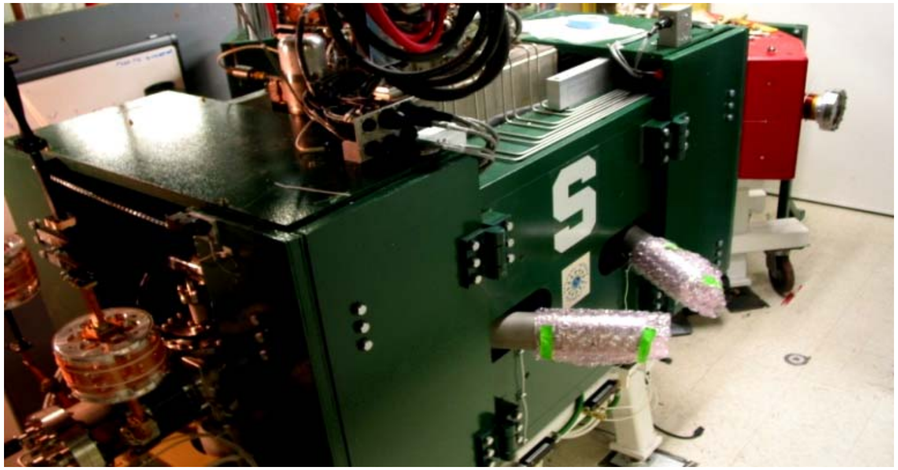
Transverse collimation with the Superconducting ECR ion source SuSI at the Coupled Cyclotron Facility (CCF)



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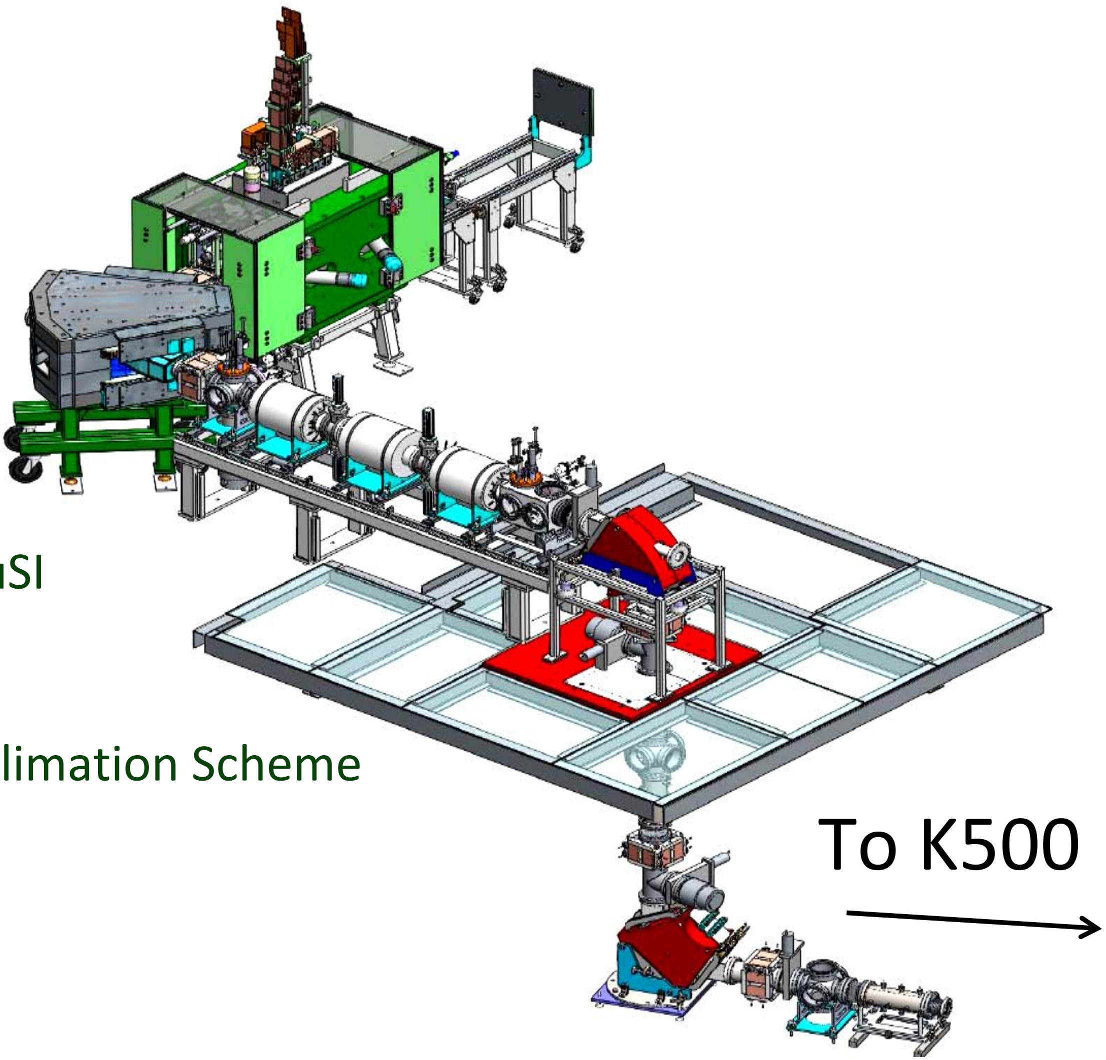
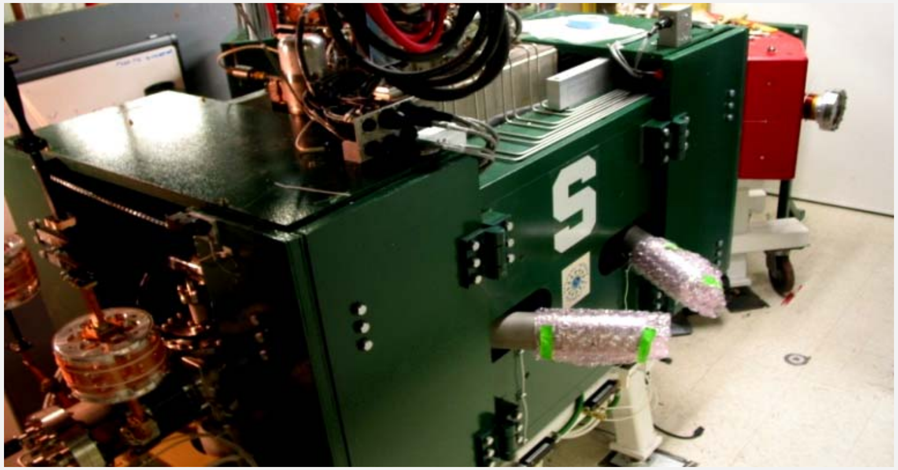
Outline

- CCF / Motivations to build SuSI
- Features of SuSI
- Intensity Performances
- Installation and Operation of SuSI for CCF
- Transport of ECR beams and Collimation Scheme



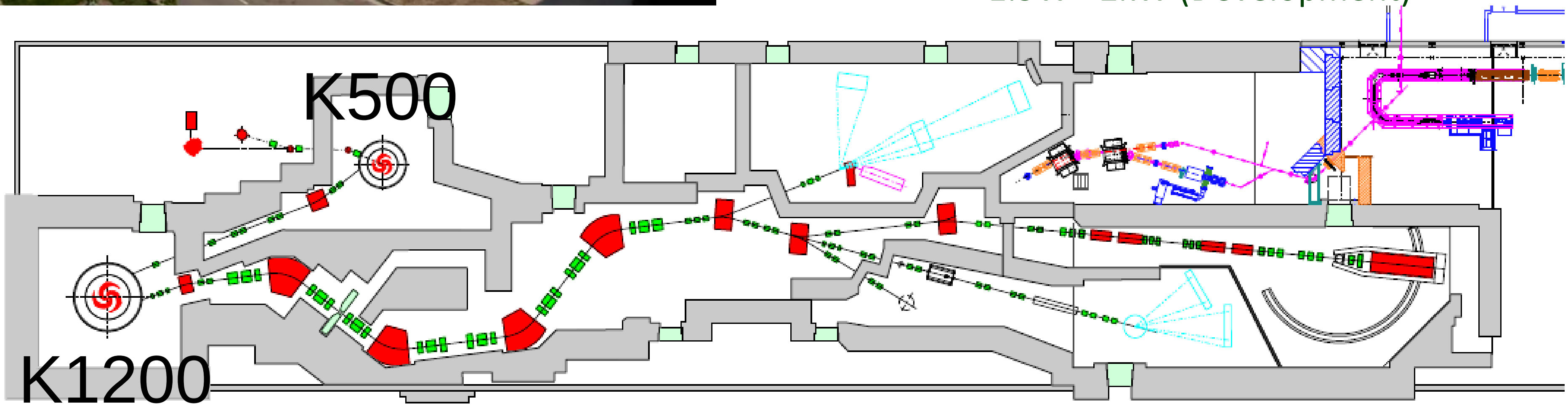
Coupled Cyclotron Facility (CCF)

Motivations



NSCL (MSU) Laboratory

- US user facility for Rare Isotope research
- Isotope production by fast-beam fragmentation and in-flight separation
- Education in nuclear science, nuclear astrophysics and accelerator physics
- Primary beam output :
  - Energy: 140 – 160 MeV /u
  - Power: 0.5kW -1kW (Experiments)
    1.5W - 2kW (Development)



Coupled Cyclotron Facility - CCF

- Broad range of elements for light to heavy are used for CCF
- 2 ECR ion sources (redundancy)

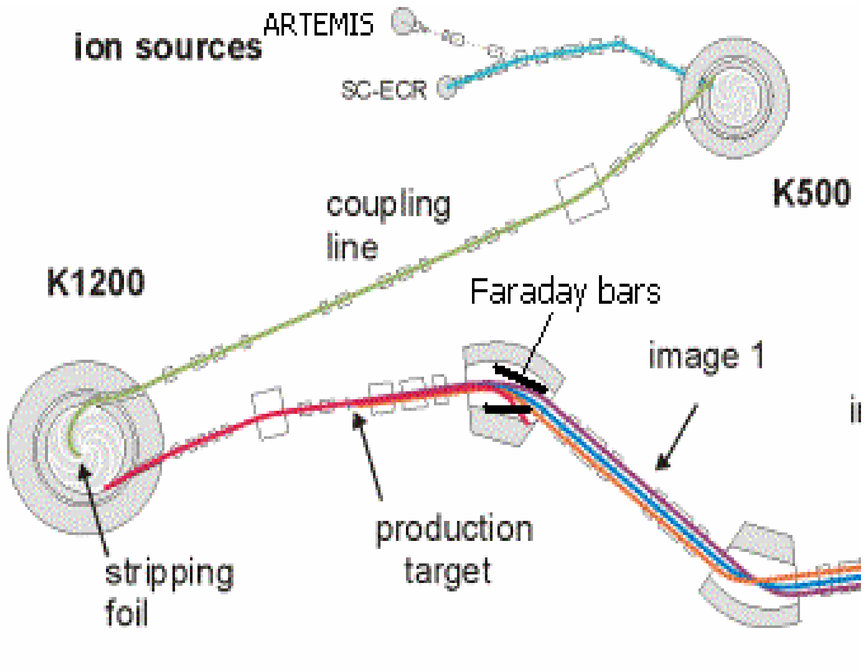
ARTEMIS -14.5GHz ~~SC-ECR-6.4 GHz~~

SuSI-18GHz

K500 Injection

Ion	Charge State	Current (euA)
^{18}O	3^{+}	35
^{40}Ar	7^{+}	40
^{48}Ca	8^{+}	10
^{58}Ni	11^{+}	8
^{76}Ge	12^{+}	5
^{78}Kr	14^{+}	15
^{136}Xe	21^{+}	11

Medium charge states



K500 Injection challenges & developments

- Challenges
  - Improve beam brightness and Improve beam matching into K500
    - Theoretical acceptance:75π.mm.mrad but best performance obtained with lower emittance(<25 π.mm.mrad)
  - Minimize beam losses on deflectors
  - Improve stripper foil lifetime

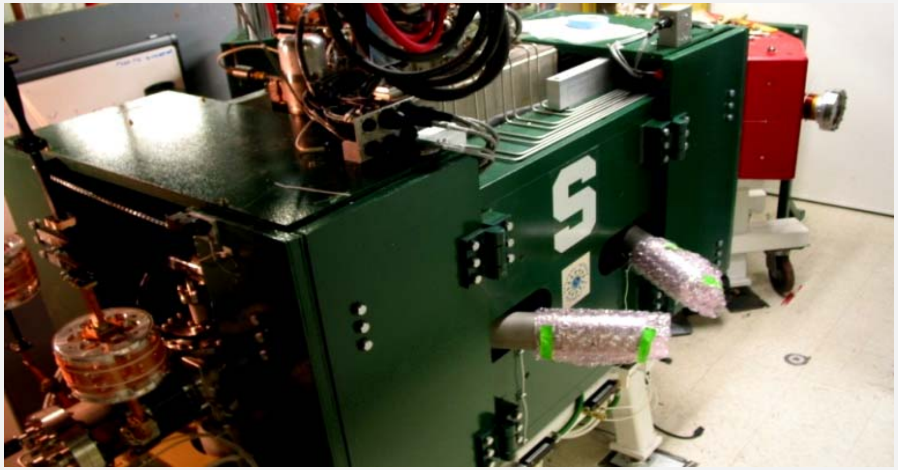
- Developments in K500 injection line
  - Electrostatic focusing (DDS) replace solenoid
  - Offline ECR ion source and diagnostics
  - New dipole magnets (sextupole aberrations)
  - Beam chopper
  - Spherical bender (under K500)

  - **Improve beam intensity from ion source (SUSI)**
  - **Develop collimation scheme**

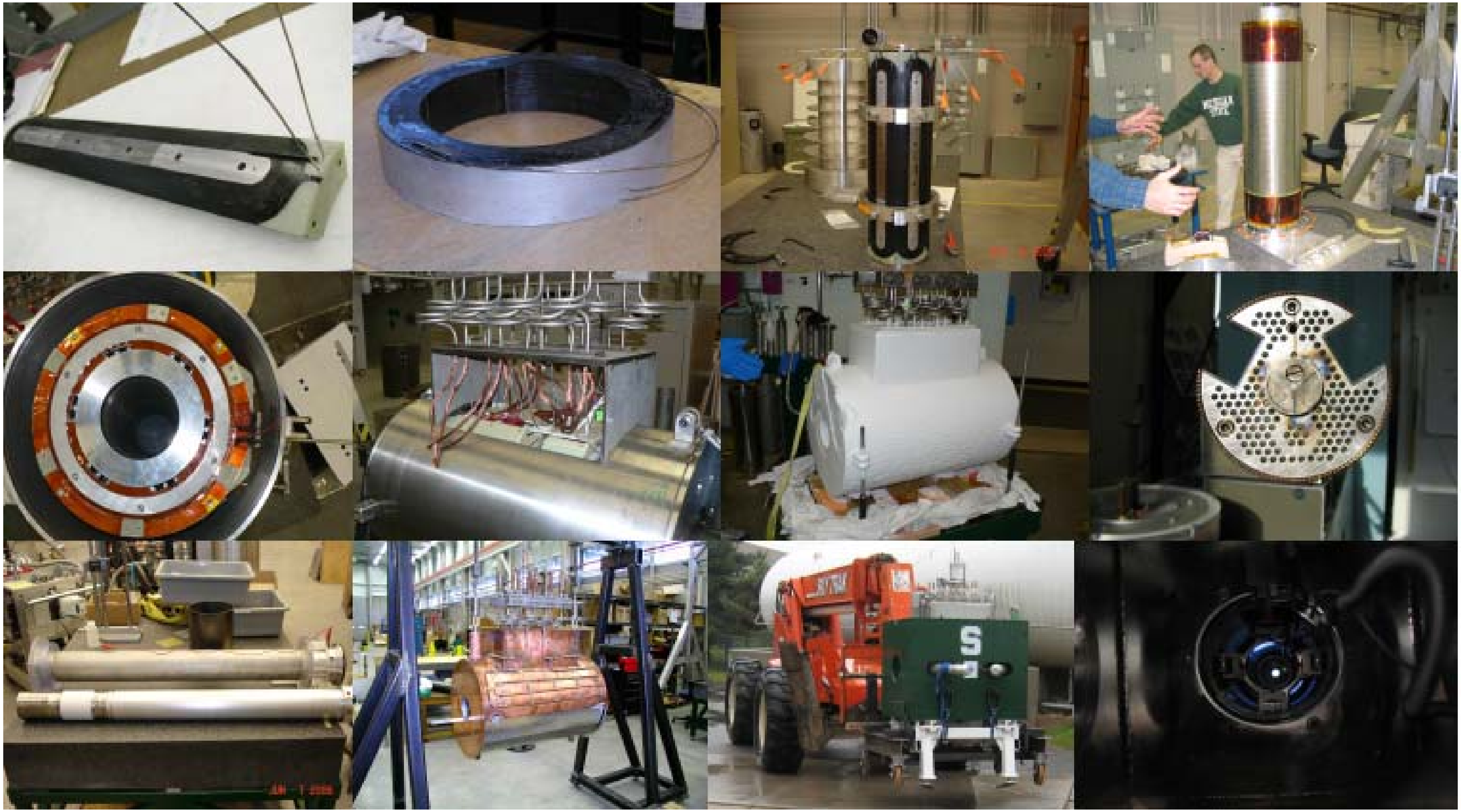
ARTEMIS(14GHz)

CYCLOTRONS 07

Features of SuSI & Performances



Design and Construction of SuSI



Design and Construction of SuSI

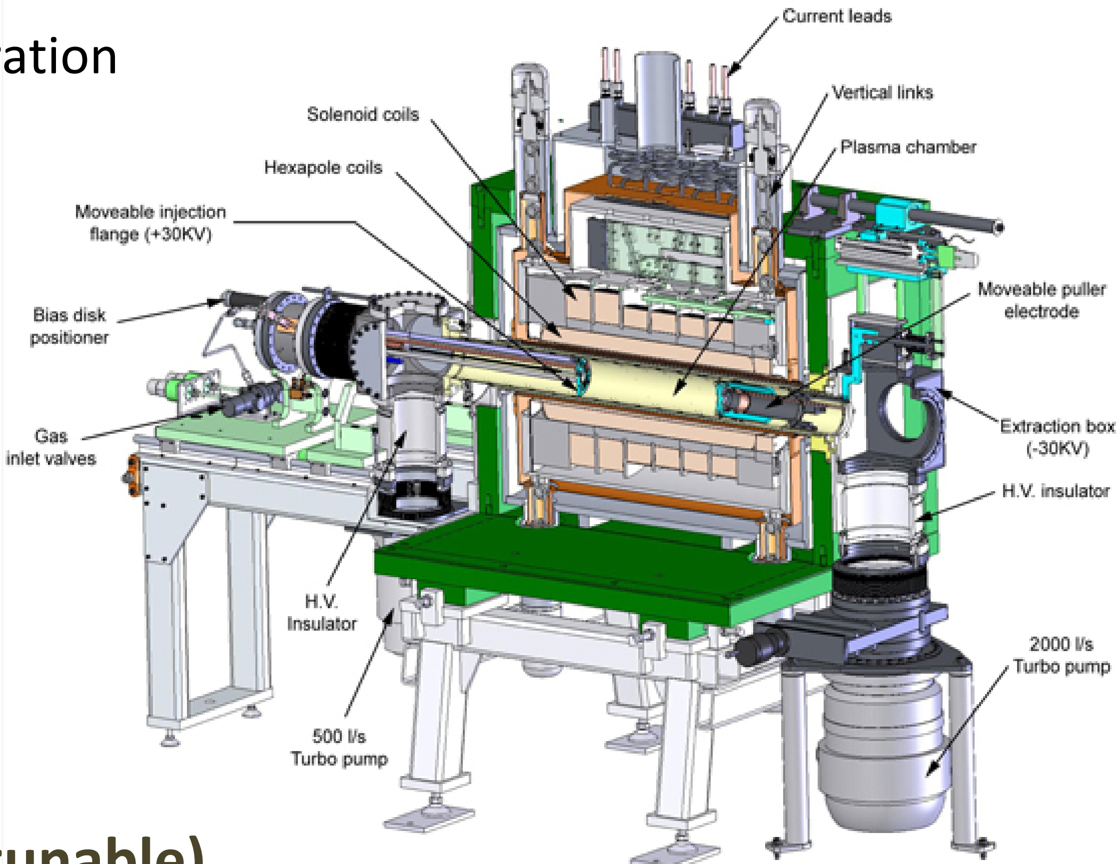
- **Project started in 2003:**
  - Replace 6.4 GHz with high performance fully SC **18 GHz ion source**
  - Develop knowledge and capability to design and build FRIB injector
- **Mechanical design started in early 2004**
  - Engineering greatly inspired by LBNL VENUS ion source
- **Coils winding completed in September 2005**
  - Tested in Dewar/ Produced field for 28 GHz operation
  - Clamping technique using expendables Bladders
- **Cryostat completed in September 2006**
  - Complete assembly done in december 2006
- **Source assembly completed in January 2007**
  - Ion source moved to test development lab
- **First Plasma ignited in March 2007**
- **Period of training (Quenches) until October 2007**
  - Require to ramp Solenoid and Sextupole together
- **Testing and commissioning until Summer 2009**

Features of SuSI

- Fully Superconducting coils
- 18 GHz operating frequency: **B_{inj}=2.6T, B_{ext}=1.4T, B_{min}=0.5T, B_{rad}=1.3T**
- Demonstrated Field for 24 GHz operation

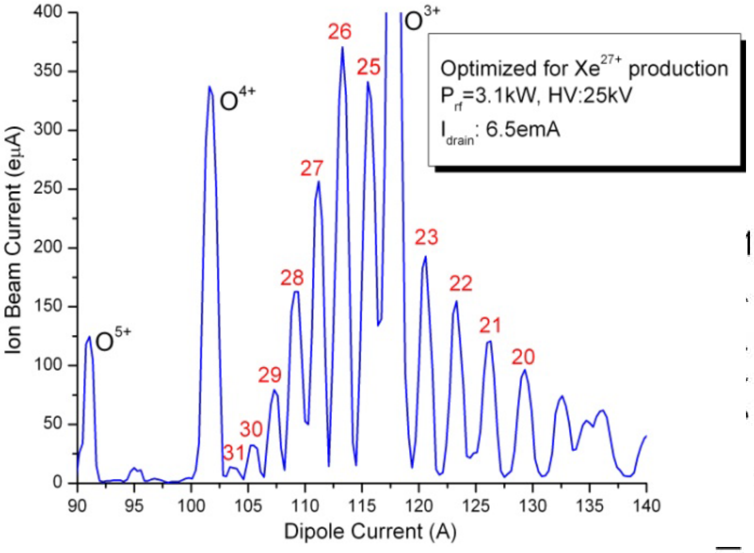
B_{inj}=3.6T, B_{ext}=1.8T, B_{min}=0.75T, B_{rad}=1.6T

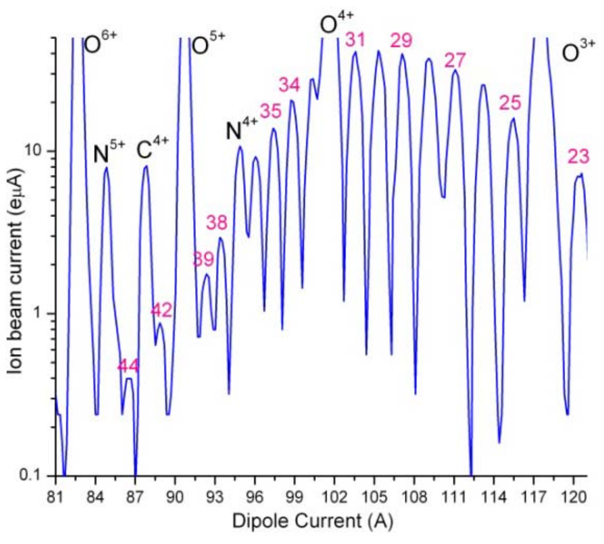
- Al Plasma chamber of ∅101 mm ID
- Extraction HV up to 30kV

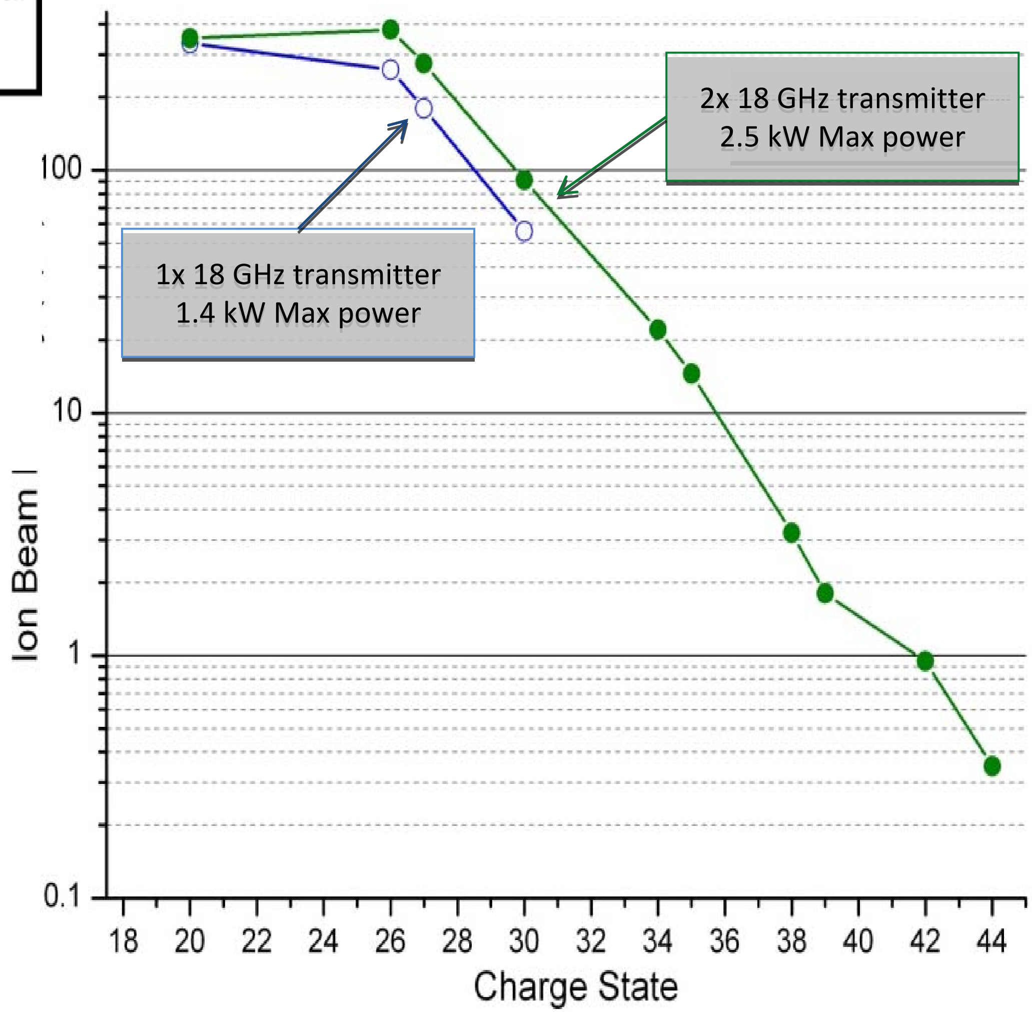


- <u>Specific Design features</u>
  - **6 solenoids coils**
  - **Movable injection baffle (tunable)**

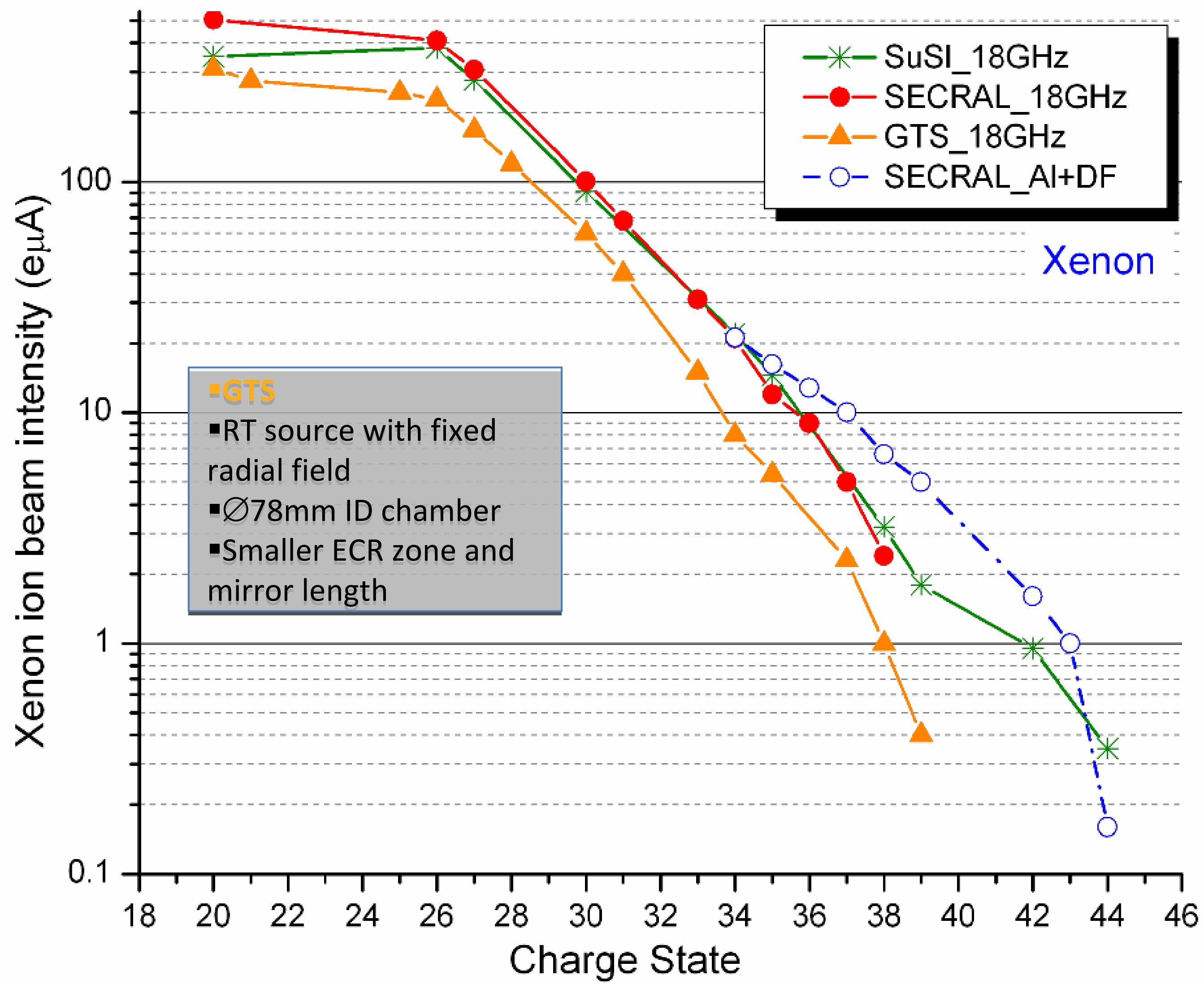
Xenon


Optimized for Xe27+ production
Prf=3.1kW, HV:25kV
Idrain: 6.5emA
Ion Beam Current (eμA)
Dipole Current (A)
O5+
O4+
O3+
26
25
27
28
29
30
31
23
22
21
20

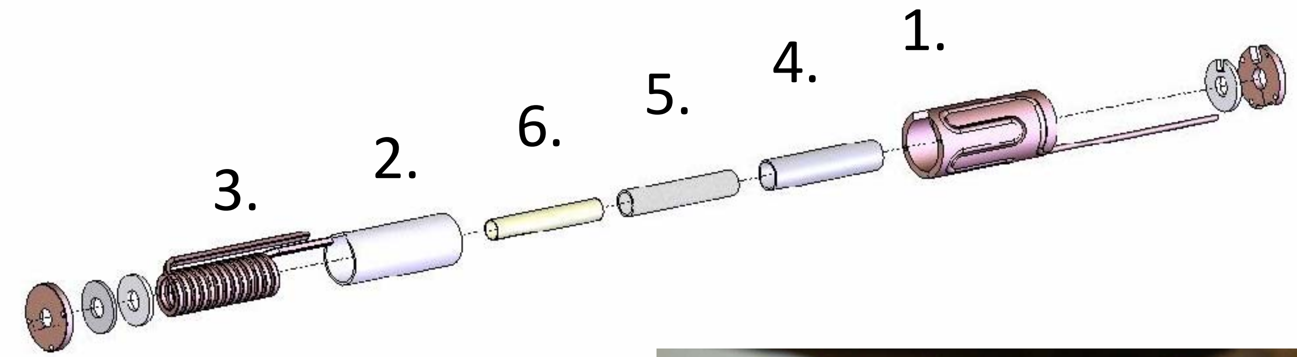

Ion beam current (eμA)
Dipole Current (A)
O6+
O5+
O4+
O3+
N5+
C4+
N4+
31
29
27
25
23
34
35
38
39
42
44


2x 18 GHz transmitter
2.5 kW Max power
1x 18 GHz transmitter
1.4 kW Max power
Ion Beam I
Charge State

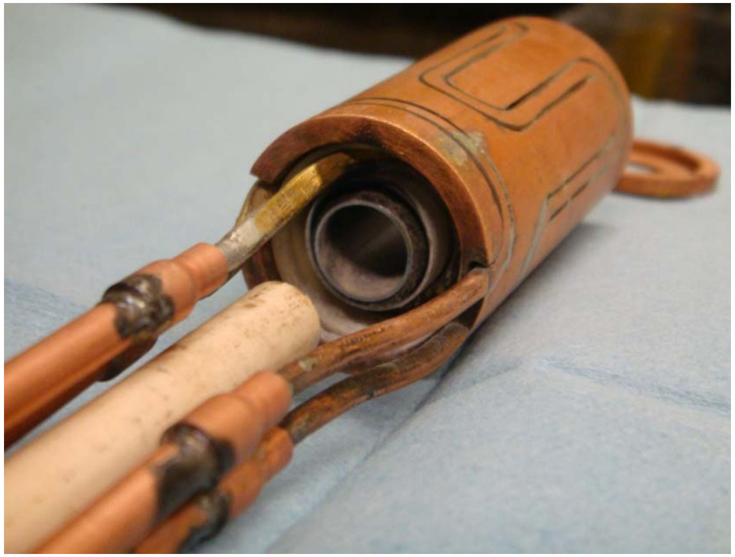
Comparison of SuSI with others 18 GHz ECR ion sources



Inductive Oven



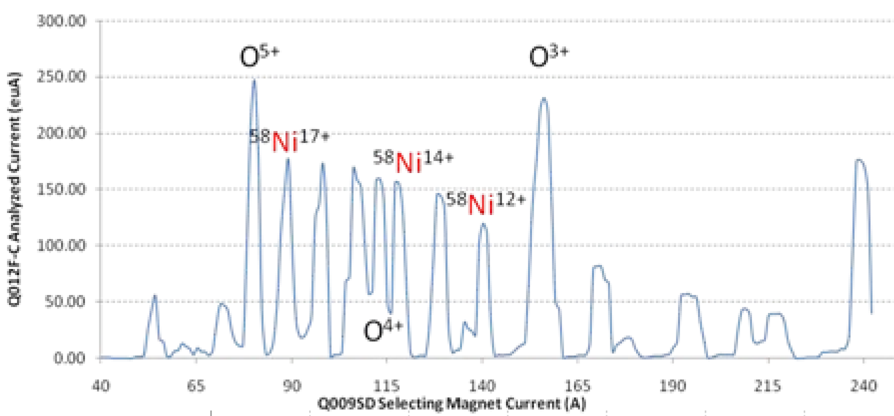
1. Cooling Jacket
2. Alumina ring
3. Work coil
4. Boron Nitride tube
5. Hf02 /Zro2 (Cloth)
6. Susceptor
7. Crucible (Optional)



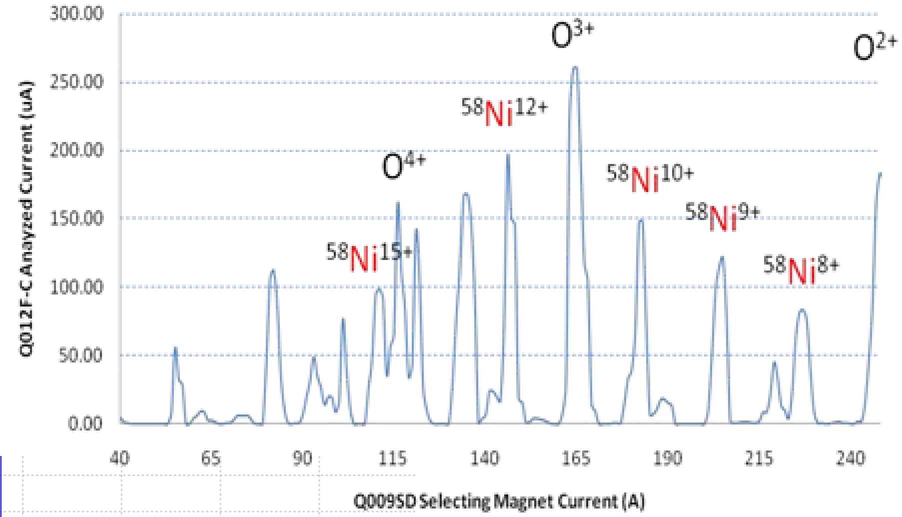
- Can reach beyond 2200 °C

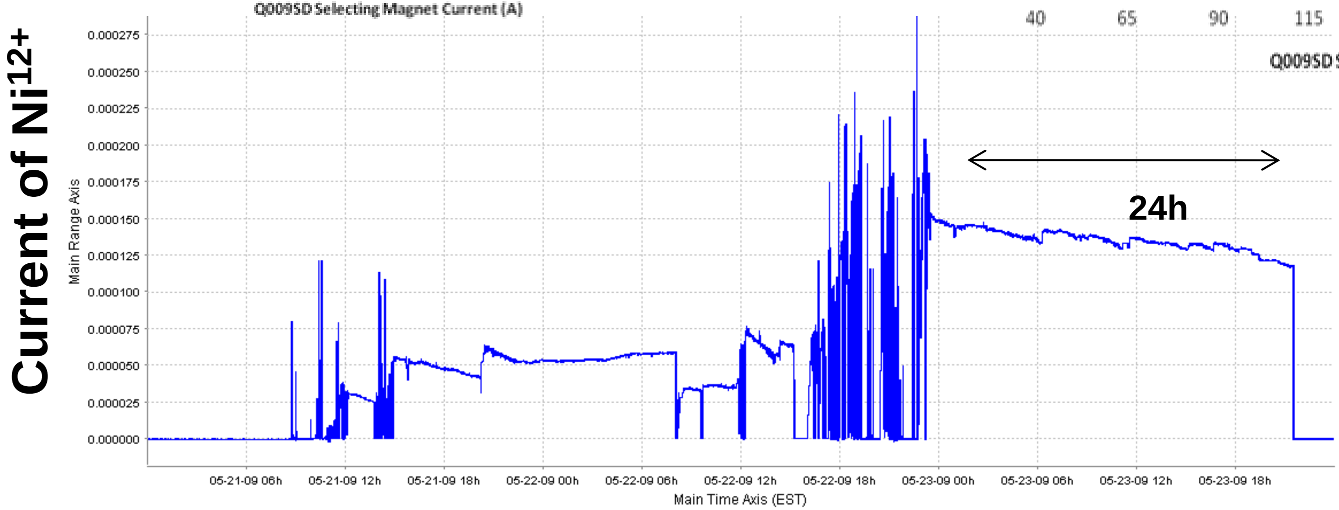
58 Ni development with inductive Oven

180euA of Ni^{17+}



200euA of Ni^{12+}





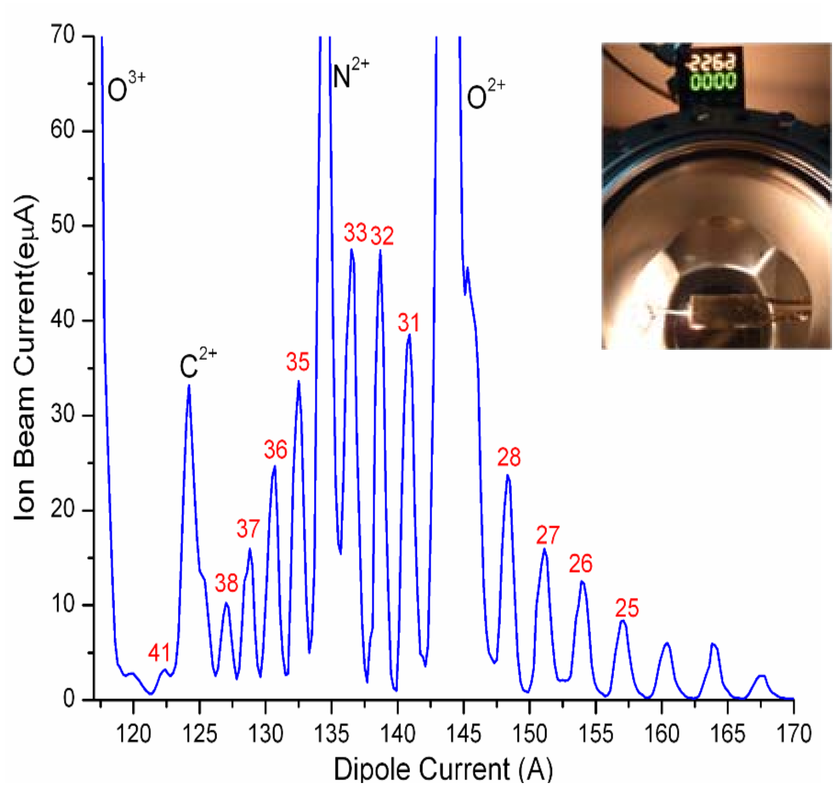
Consumption: 410 mg
60euA 24 hrs
140euA 24 hrs

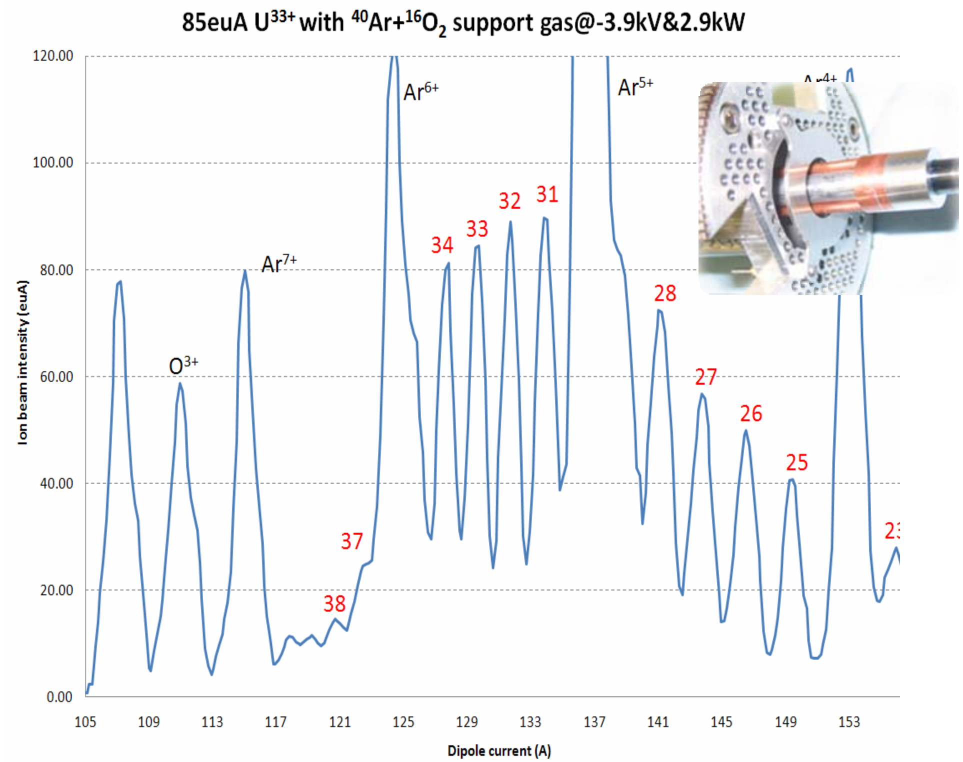
Average: 6.83mg/hr

- **Ni or Ge have been limited by source production for CCF output**

(Existing beam list for 58Ni or 76Ge requires 5 to 10euA from the source)

Uranium beam production with oven and by sputtering





Inductive oven

- UO2
- Rhenium susceptor with Hf02 thermal insulator
- temperature to limit of thermocouple (2300 C)
- 50 euA of U^{33+} (limited by vapor available)

Sputtering

- depleted U target
- Axial positioning
- 1 cm diameter sample
- >80 euA of U^{33+}

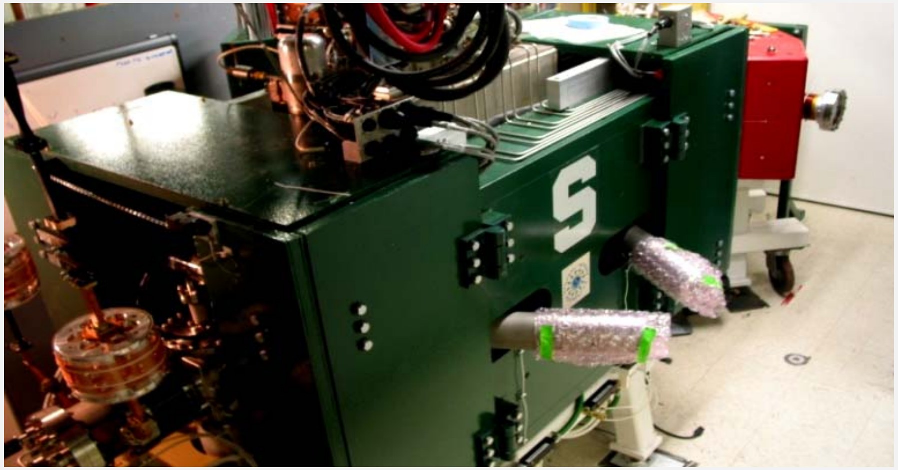
Summary of Performances

SuSI | SECRAL

Element	A	Charge State	SuSI 18 GHz Current (euA)	SECRAL 18GHz Current (euA)	SECRAL 24GHz Current (euA)
Argon	40	8	>1000		
		11	550	510 (12+)	650 (12+)
Krypton	86	14	370		
Nickel	58	17	180		
Xenon	129	20	410	505	
		26	370	400	480
		27	275	306	455
		31	91	101	152
Bismuth	209	29	182	214(28+)	
		30	175	191	
Uranium	238	33	88		
		34	82		

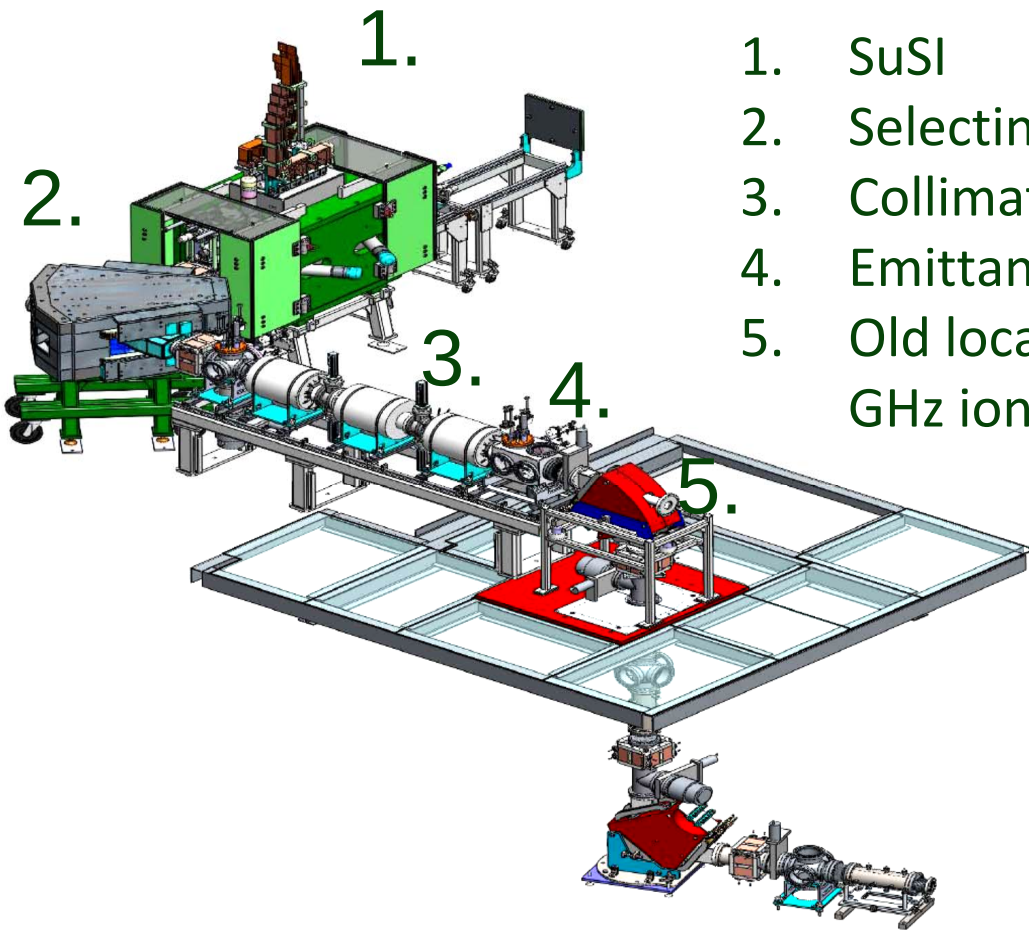
- **Push performances at 18 GHz add 3rd Klystron for test**
- **Upgrade to 24 GHz Operation (Demonstrated field)**

Installation and Operation of SuSI for CCF



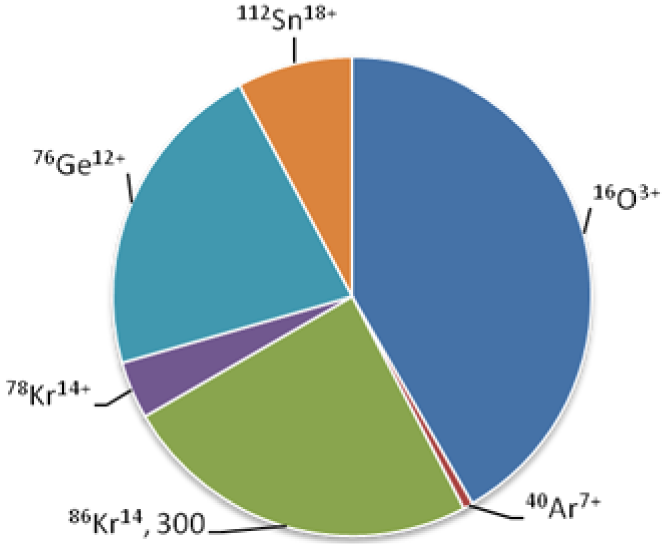
Connection of SuSI to the Coupled Cyclotron

- Summer 2009/10 weeks to complete
- Commissioning of ion source in September 2009
- Testing of collimation channel in early October 2009
- First beam injected into CCF (16 O^{3+}) in November 2009



1. SuSI
2. Selecting Magnet
3. Collimation channel
4. Emittance box
5. Old location of 6.4 GHz ion source

SuSI Operation for CCF



- ✓More than 1200 hrs continuous operation for CCF;
- ✓No quench during operation;
- ✓Good stability and reliability

ECR beams can be difficult to inject

- High Intensity Performance with ECR ion source is good but ECR beam must be matched to the accelerator

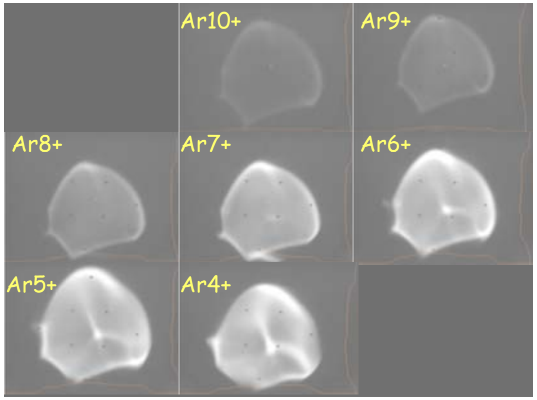
- Extraction of beam from ECR ion source presents many challenges
  - Multispecies & charge states
  - Strong Magnetic field (Angular momentum)
  - Space charge (Neutralization)
  - Initial Beam conditions and distribution

- Observations point to inherent bad properties for ECR beams
  - Inhomogeneous beams (Direct imaging)
  - Distorted Phase space(2D emittances)
  - Charge and mass Dependent

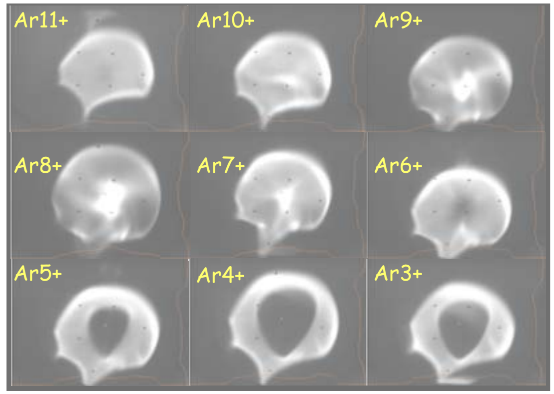
- Blame it on the source:
  - Convolution of (Plasma + Extraction) + (Beam transport elements) ex: Bending Magnet

Space charge issue when using a Solenoid as first focusing element after the ion source

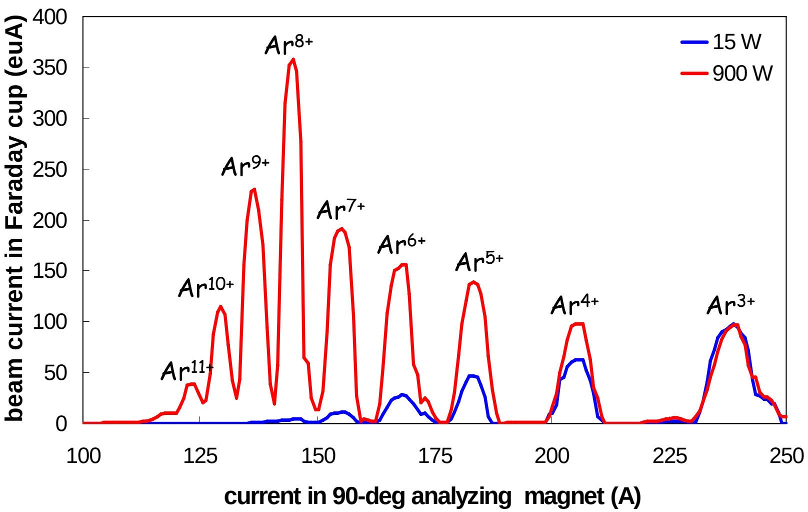
- **ECR – solenoid – magnet - beam viewer**
  - Viewer ~1.5 m after analyzing magnet / Line scaled with Br to image all Ar^{q+}

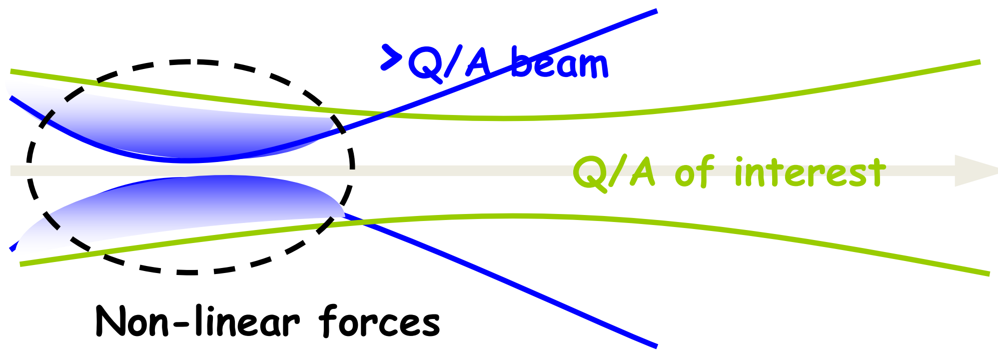


15W plasma



900W plasma



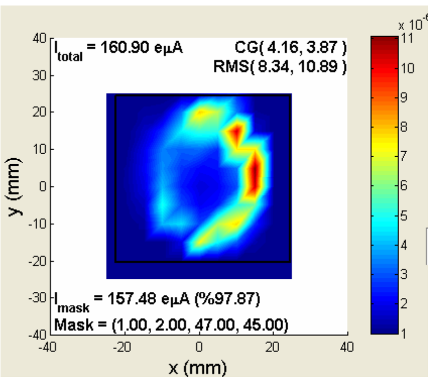


- arger Q/A over-focused
- Non-linear space charge forces on beam of interest
- Beam emittance degradation

Kr 13+ from Susi

Setup: SuSI –Bending Magnet-Einzel Lens FC-Emitt.Scan

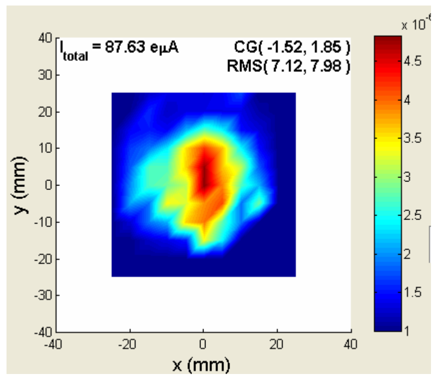
RF Power	1200 W
Extraction Voltage	24kV
Extracted Current	3mA
Puller Gap	50 mm
Kr 13+ Current	150 euA
$\varepsilon_{RMS-XX'}$	55 π.mm.mrad
$\varepsilon_{RMS-YY'}$	41 π.mm.mrad



Real space image

Emittance ε (π.mm.mrad)	Current (eua) within ε
25	36.4
50	65.4
75	90.0
100	107.6

RF Power	900 W
Extraction Voltage	24kV
Extracted Current	2.4mA
Puller Gap	55 mm
Kr 13+ Current	95 euA
$\varepsilon_{RMS-XX'}$	14 π.mm.mrad
$\varepsilon_{RMS-YY'}$	16 π.mm.mrad



Real space image

Emittance ε (π.mm.mrad)	Current (eua) within ε
25	61.1
50	80.2
75	87.4
100	90.7

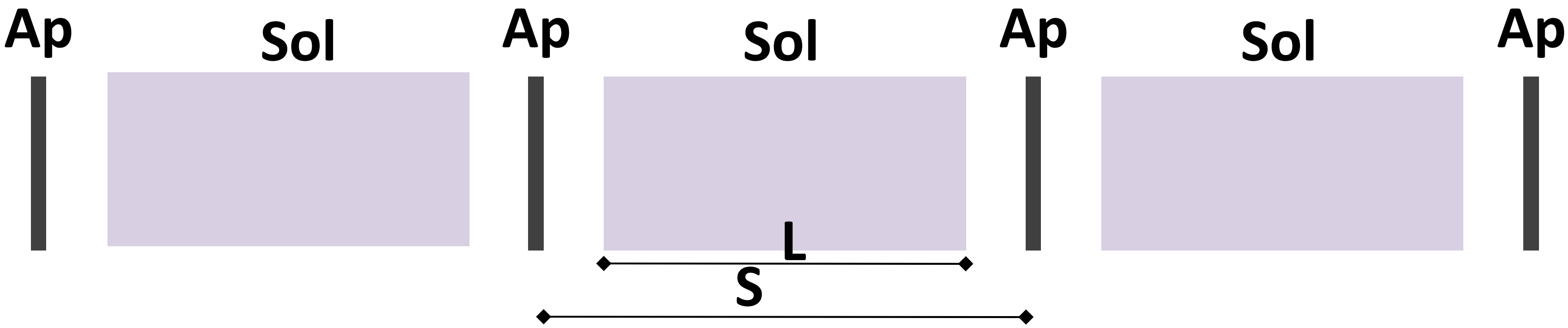
Scheme to transport SuSI beam to K500

- Avoid tuning the ion source "blindly" for maximum current
  - Avoid beam brightness degradation
- Achieve reasonable beam parameters at end of beamline
- Easy to tune beamline (clear guidelines for operators)
- Effective collimation in phase space to optimize ratio emittance/acceptance for any beam in CCF

- Multiple-stage collimation with phase-space rotation in between
  - Looking at available hardware and space available after SuSI selection magnet
  - Possible to use solenoid lenses to do the phase space rotation

- Design Settled on using 3 solenoids with 4 apertures (3 cells)
- Proof of principle using beam simulations

Collimation Channel (I)



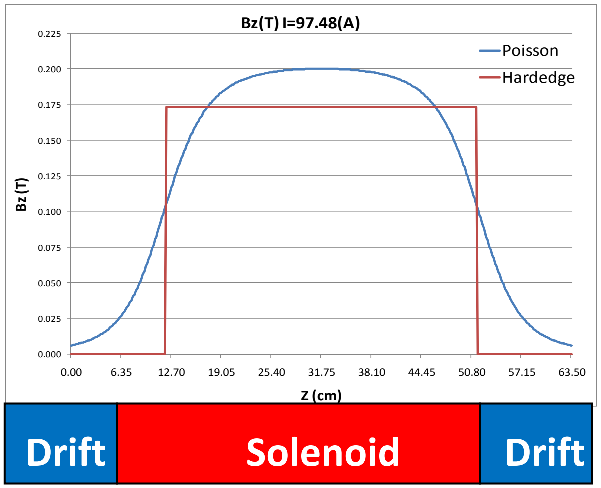
- 3 cells each made of drift +Solenoid+drift (Length S)
- Transfer Matrix: $R_{cell} = R_{drift}.R_{solenoid}.R_{drift}$
- Phase advance in each cell $\sigma \approx \frac{B}{2B\rho}\sqrt{SL}$
- Real space rotation $\theta \approx \frac{BL}{2B\rho}$
- X,Y Coupling in solenoid
  - Solution: Generate 30 degree rotation/cell to reach 90 degree rotation(XY Exchange)

Collimation Channel (II)

- Design Parameters of Collimation channel

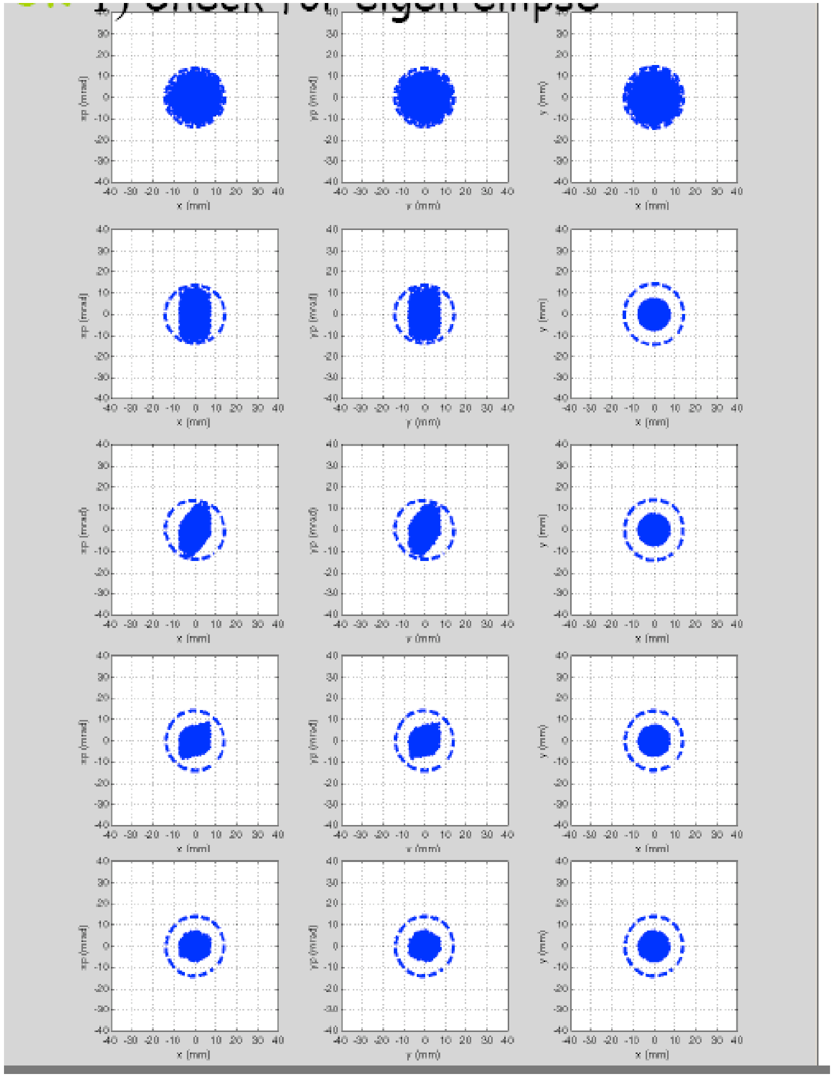
Solenoid Length	0.428 m
Drift Length	0.141 m
Overall channel Length	2.130 m
B needed in Solenoid	0.132 T
Phase advance per cell (σ)	38 degree
Rotation in real space (ϕ)	30 degree
Eigen beta (β)	1.05

- Careful Mapping of Field of Solenoid for modeling

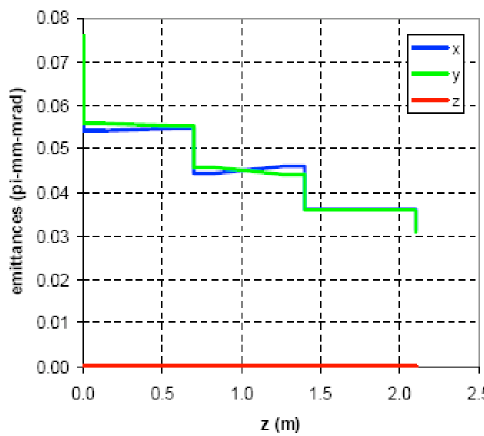


- Simulation of magnetic field in Poisson
- Import field profile on-axis into MATLAB beam dynamics code and optimize the equivalent hard-edge model

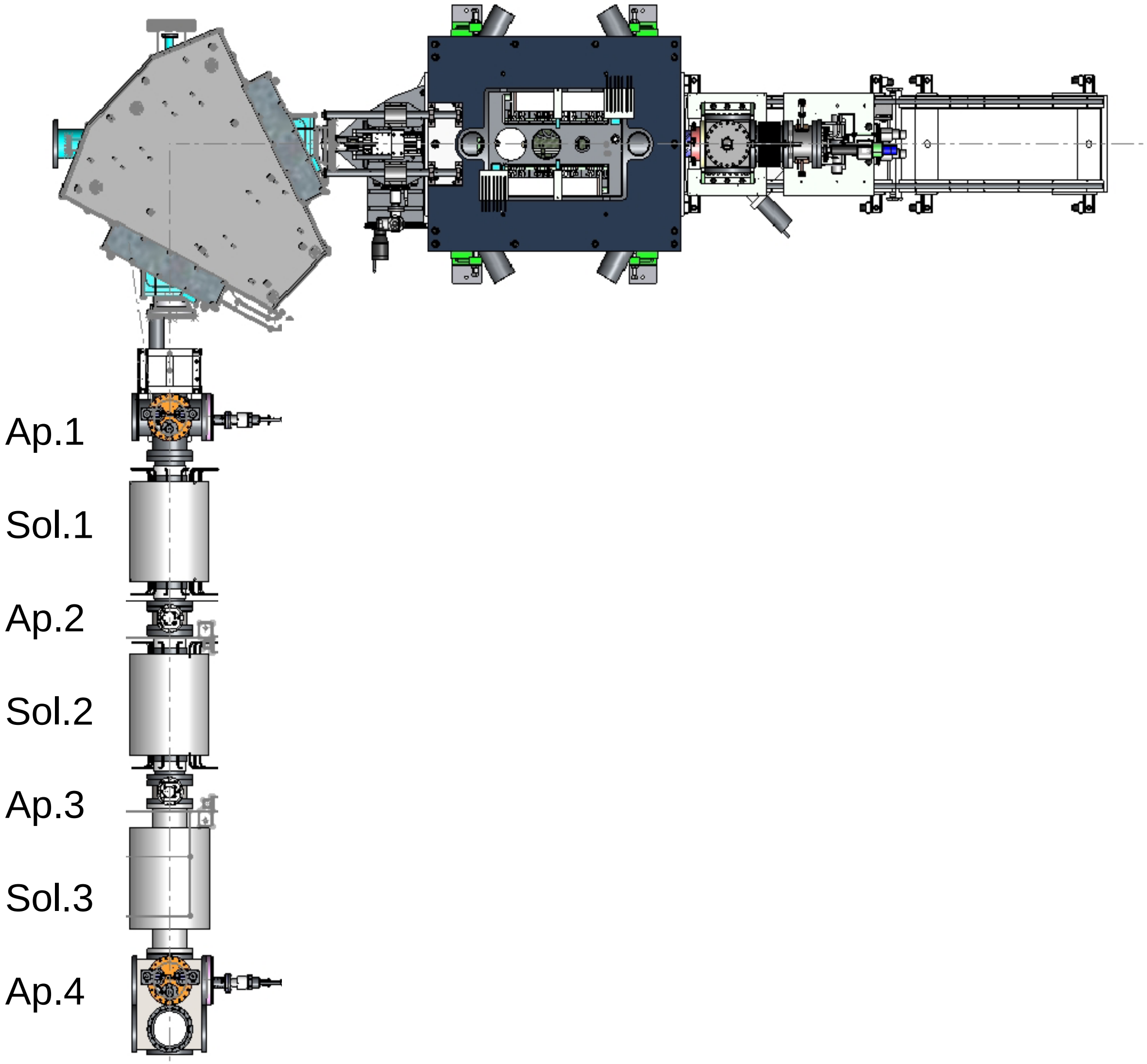
Simulations for an eigen ellipse



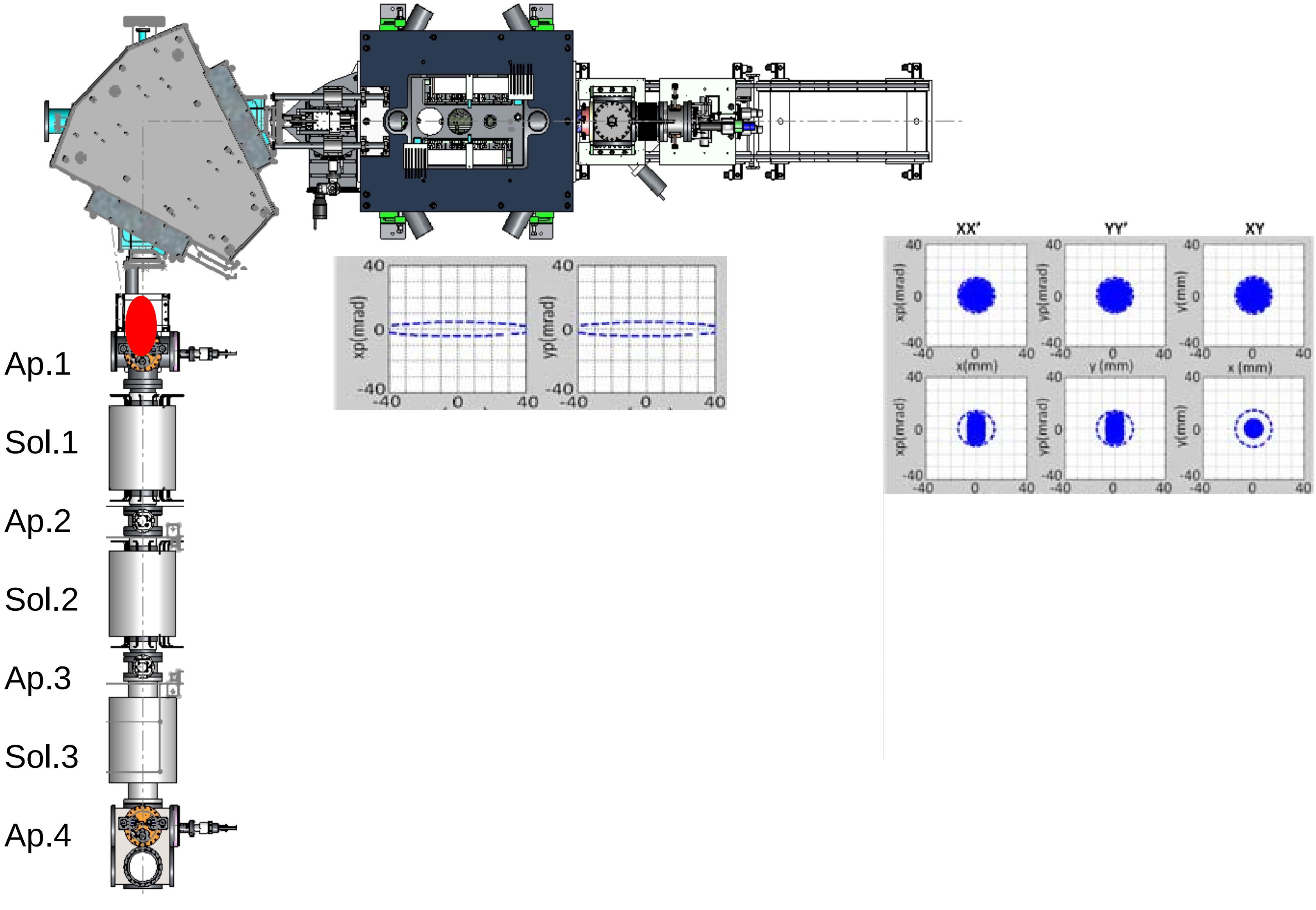
- 200 pi-mm-mrad beam full emittance Ar 7+
- Used-Beam with eigen twiss parameters (α =0 β =1.05 m)-
- 5k particles (blue dots) run through-
- Beam envelope (dashed ellipses) ran also showing the beam without collimation for comparison
- Four circular apertures of 15 mm diameters were used for proof of collimation (final emittancesare ~ 50 pi-mm-mrad in this case).
- Beam xx'-yy'-xy spaces shown at the entrance and after the four successive collimators



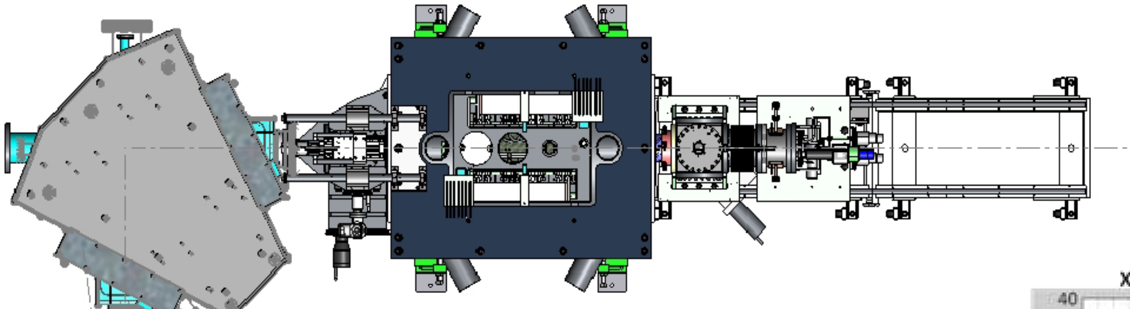
Collimation channel animation

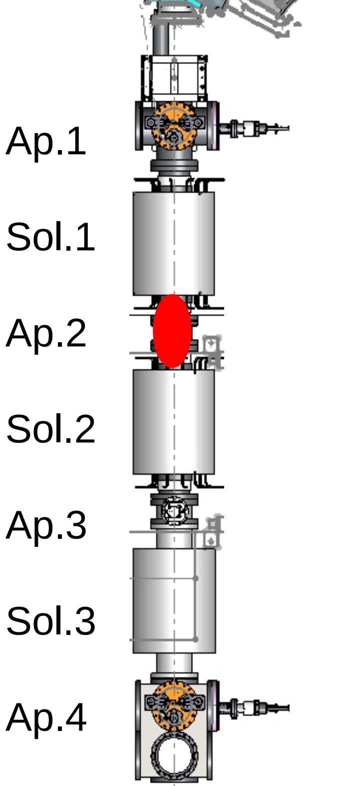


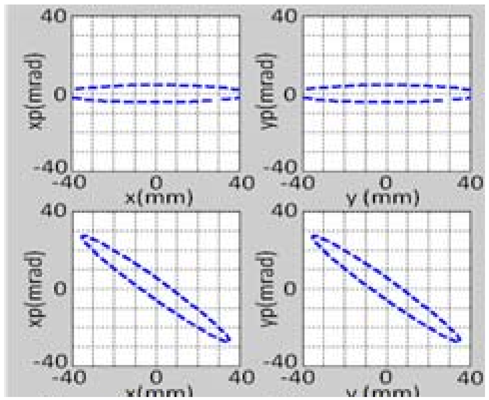
Collimation channel animation

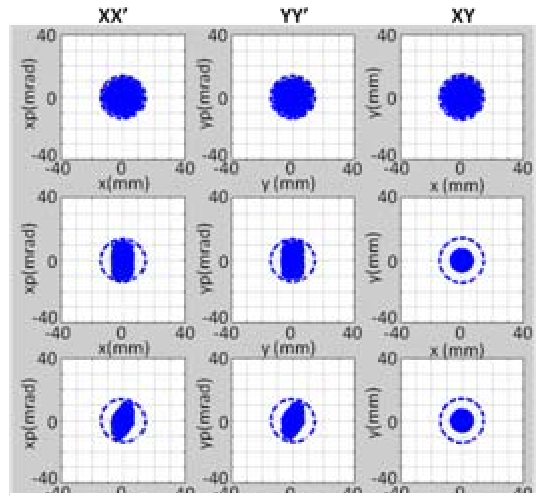


Collimation channel animation

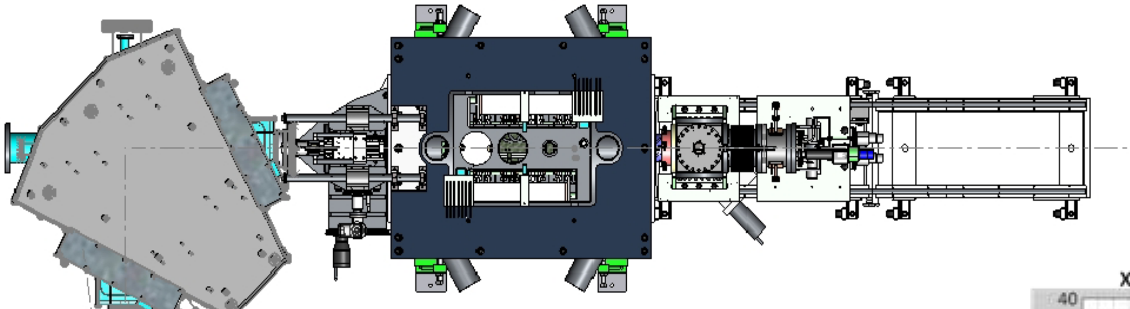


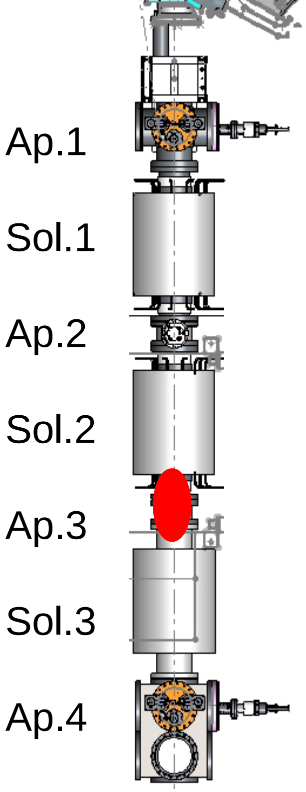


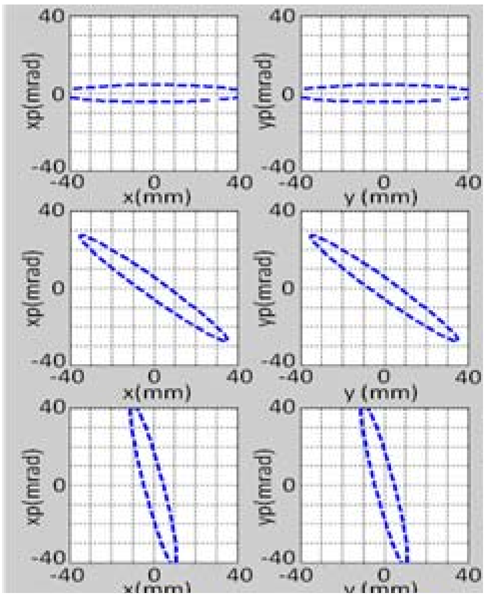


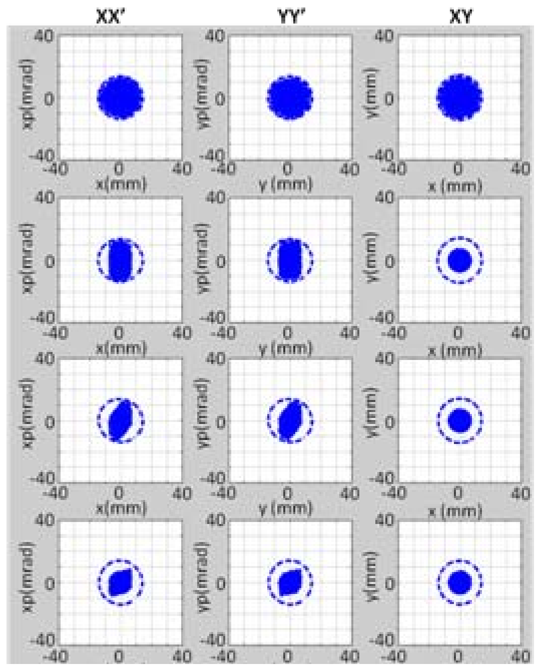


Collimation channel animation

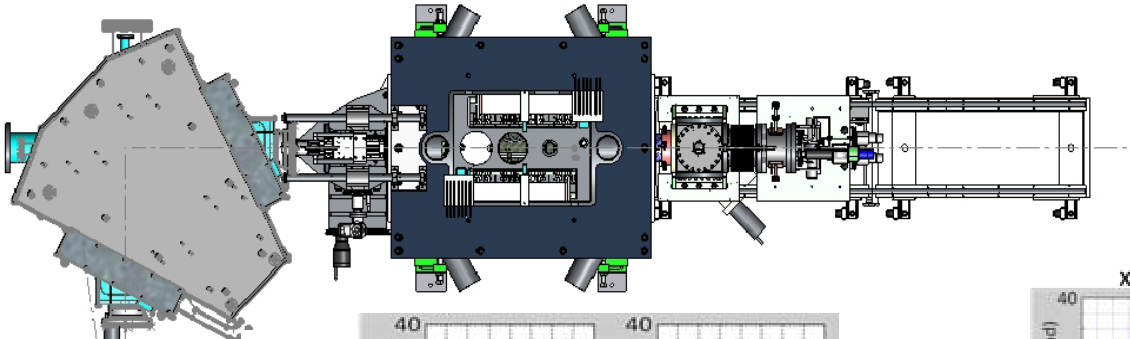








Collimation channel animation



Ap.1

Sol.1

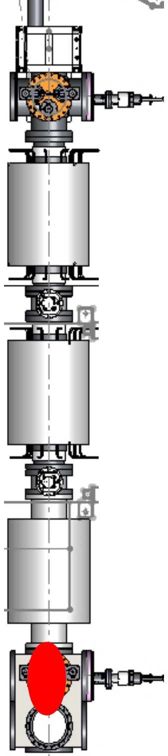
Ap.2

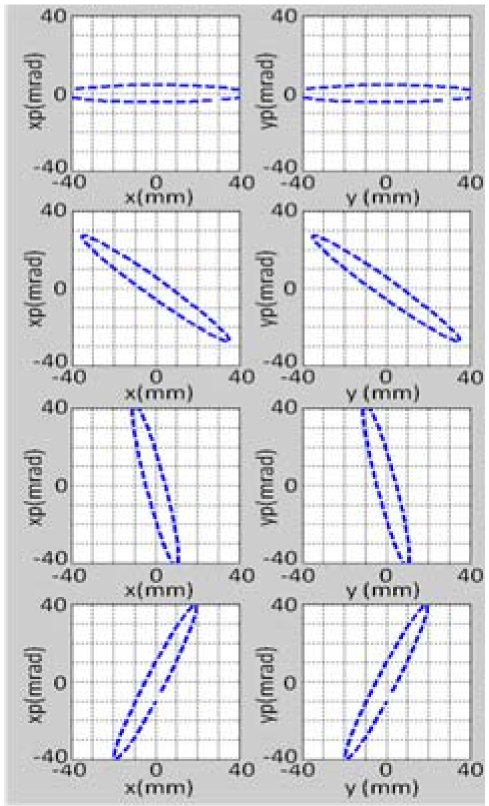
Sol.2

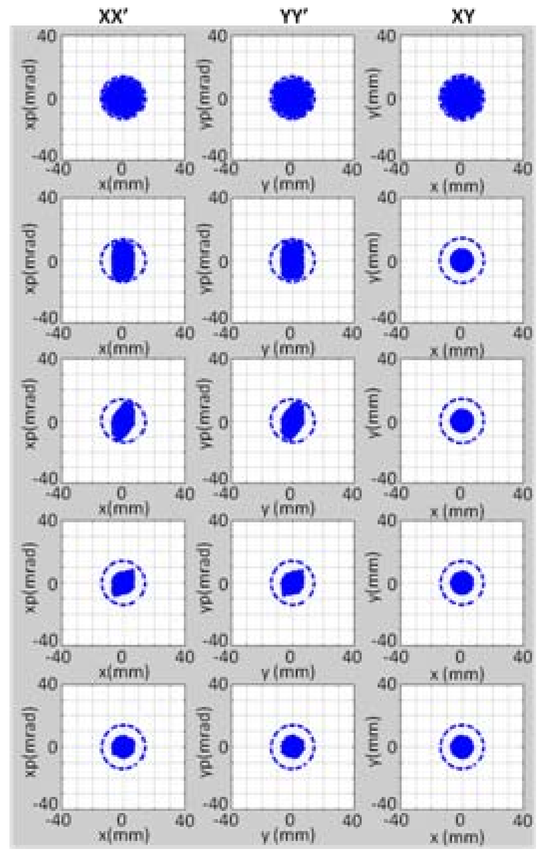
Ap.3

Sol.3

Ap.4







Channel Acceptance

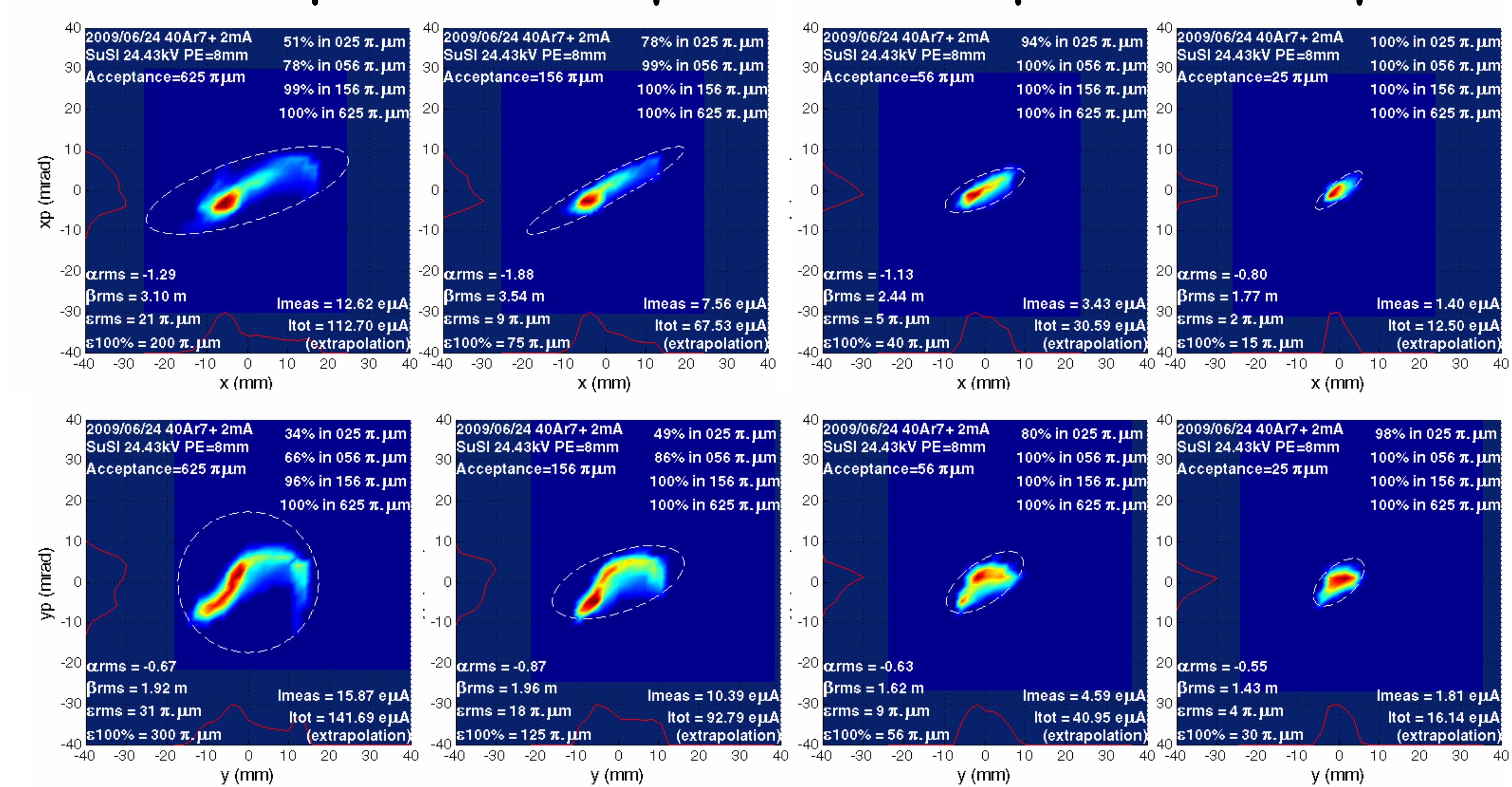
- All solenoids set at same field (scaled with magnetic rigidity of beam)
- All apertures set at same width

$$\text{Channel acceptance} = \frac{(\text{aperture width})^2}{4\beta_{\text{channel}}}$$

Apertures (mm)	Acceptance (pi.mm.mrad)
7.5	14
10	25
15	56
25	156
50	625

SuSI - Argon Beam Collimation

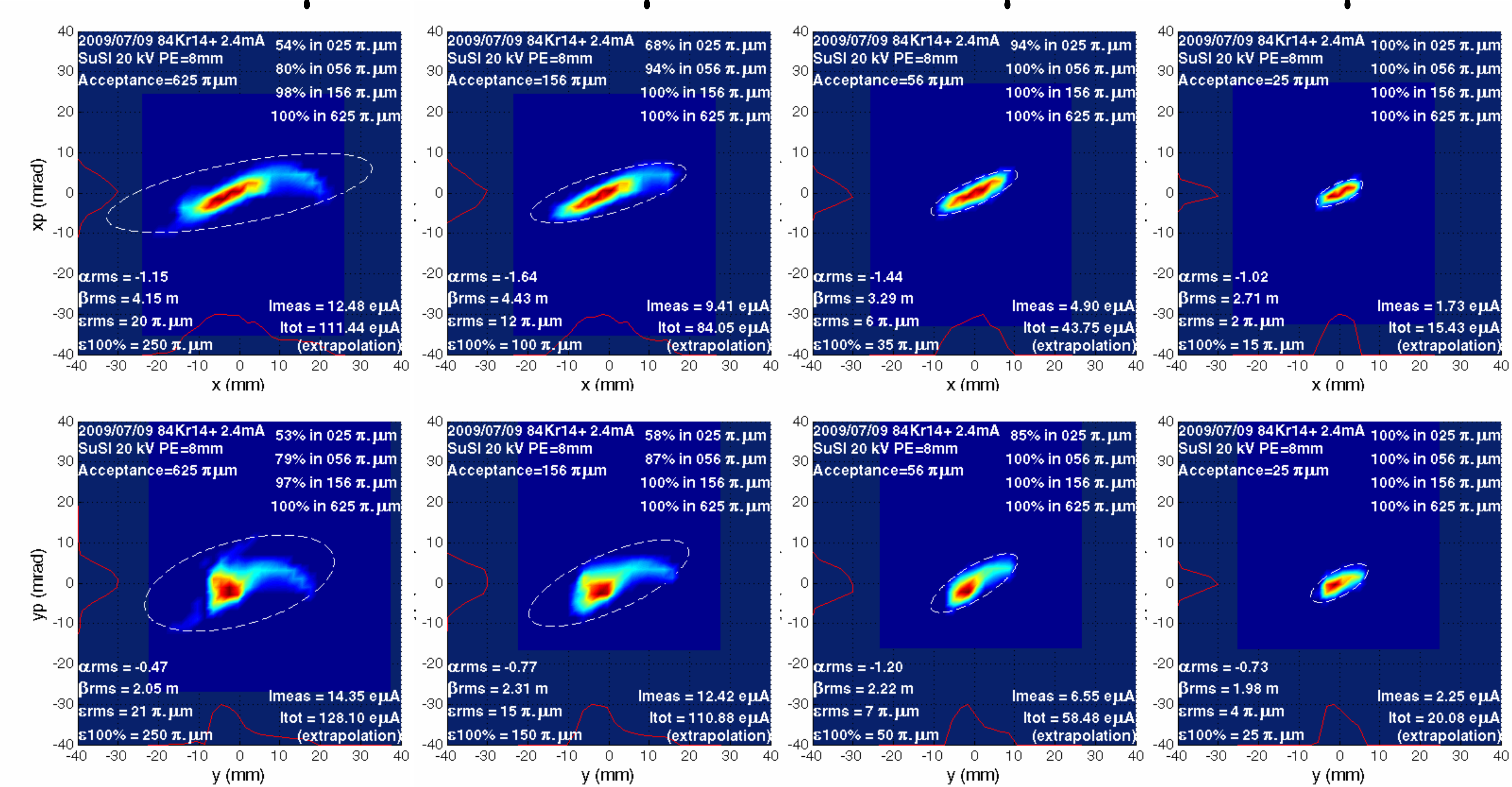
Acc: 625 π.μm 156 π.μm 56 π.μm 25 π.μm



FC: 150 eμA 96 eμA 43 eμA 17 eμA

Krypton Beam Collimation

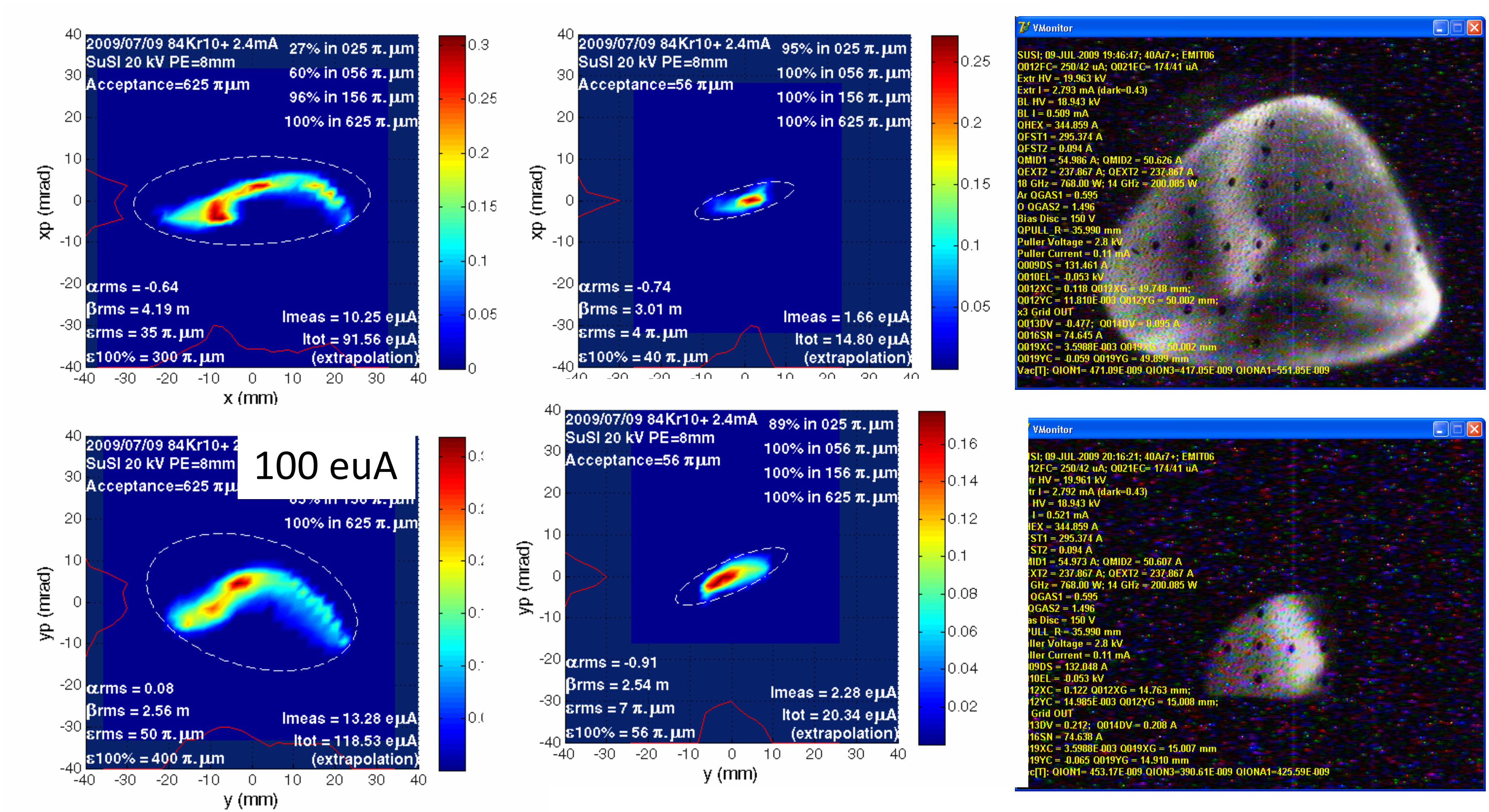
Acc: 625 π.μm 156 π.μm 56 π.μm 25 π.μm



FC: 138 eμA 100 eμA 55 eμA 19 eμA

Example :Krypton 10+

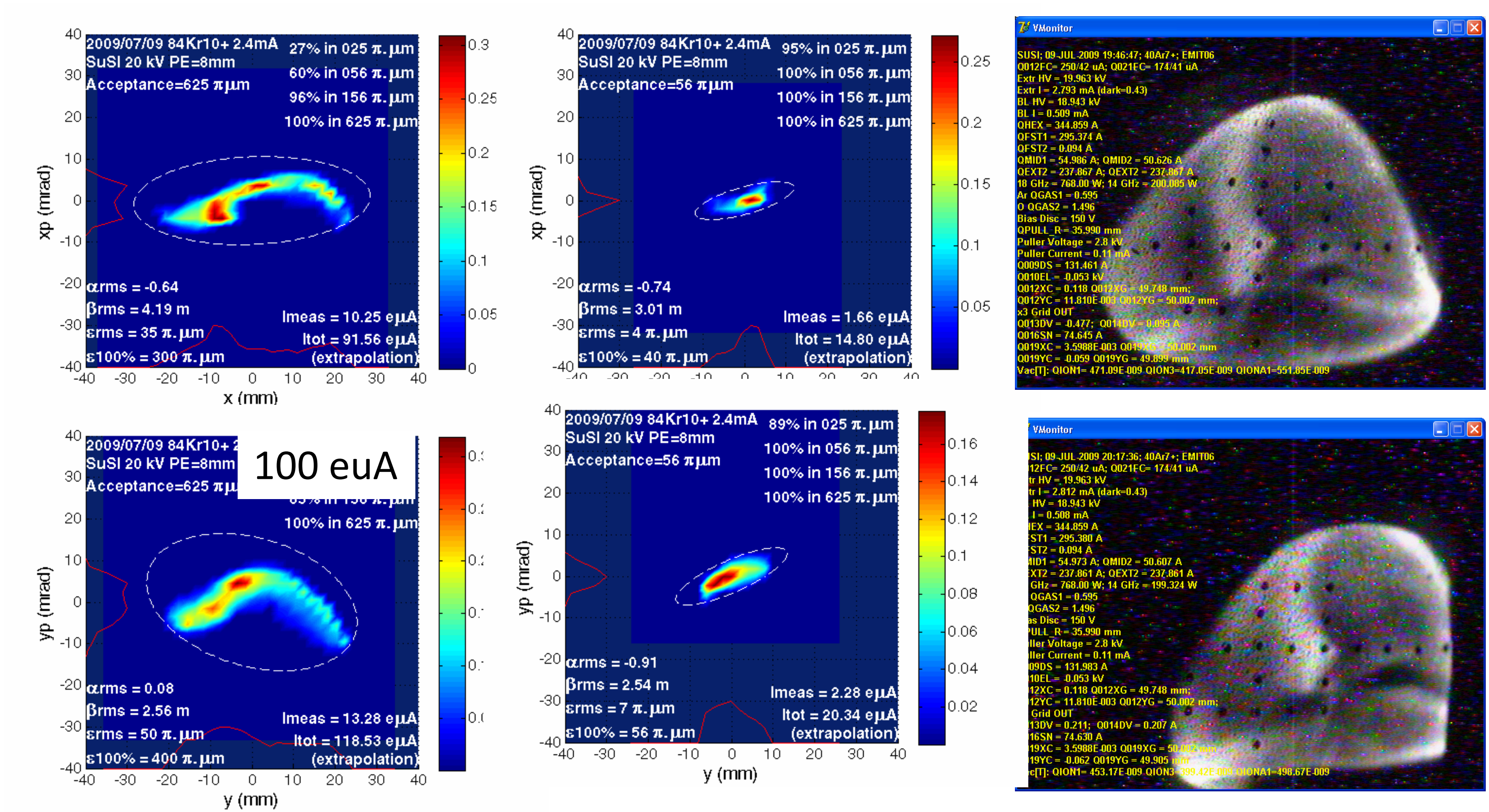
- The medium charge Kr10+ phase space is more distorted by space charge forces
  – But, the filtering action of the channel is similar to Kr14+



18 eµA

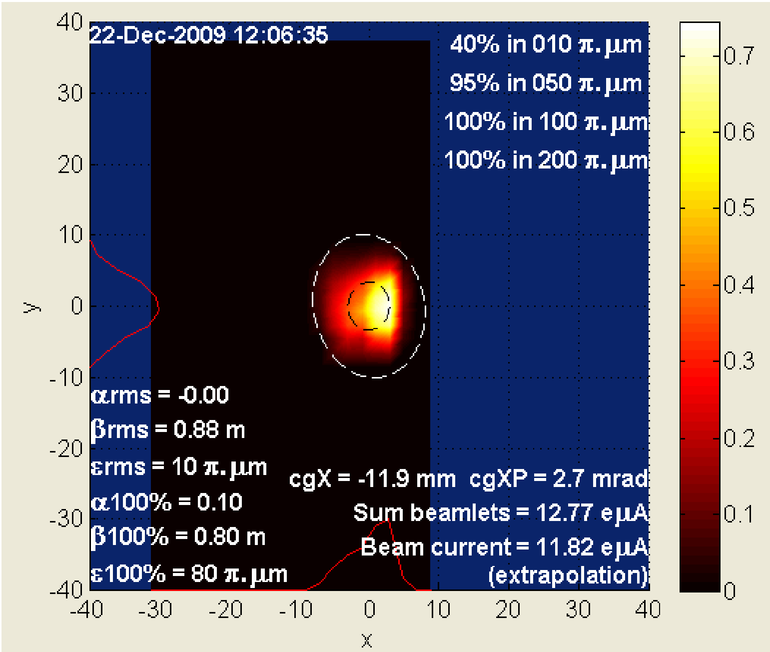
Example :Krypton 10+

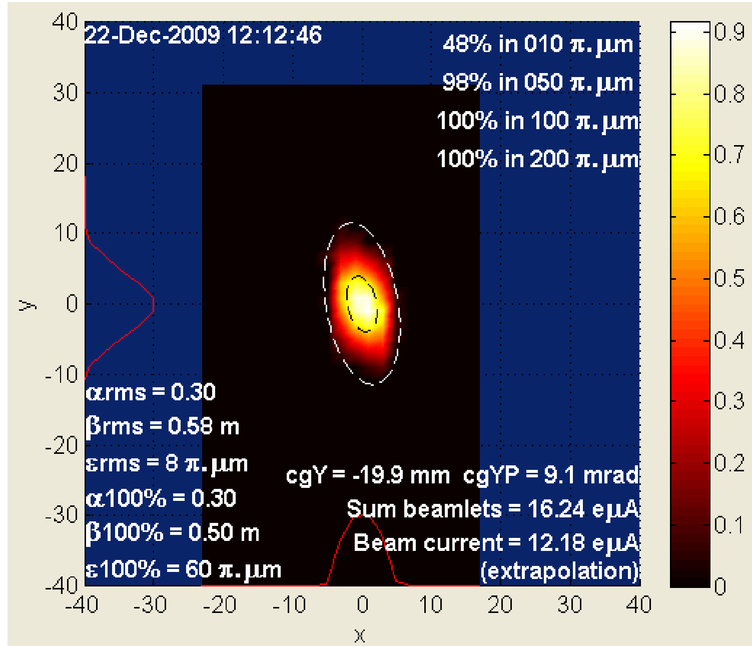
- The medium charge Kr10+ phase space is more distorted by space charge forces
  – But, the filtering action of the channel is similar to Kr14+



18 eµA

Injection of SuSI through K500





Source	Beam	Intensity at the source (eµA)	Channel Acceptance (π.mm.mrad)	Current Extracted from K500 (enA)	K500 Extraction eff. (%)	Current Extracted from K1200 (ena)	Current Extracted from K1200 (pna)	K1200 Extraction eff. (%)	Beam List (pnA)
SuSI	$^{78}Kr^{14+}$	17.0	25	8300	80.2%	Ran Only from K500	Ran Only from K500	0.0%	25
ARTEMIS	$^{78}Kr^{14+}$	28.5	n/a	5600	80.0%	4200	123.5	82.0%	25

Extrapolation: K500 → 8300 enA ➡ K1200 → 6000 enA (>2kW)

Conclusion

- Successful development of SuSI (Started in 2003)
- Intensity Performances similar to SECRAL
- Upgrade to higher power 18 Ghz and 24 Ghz planned
- Successfully connected to CCF. More than 1200 hours used for operation. Stable and reliable operation
- Collimation scheme developed and tested. Measured emittance demonstrated the validity of principle
- Demonstrated capability with CCF. More development in the future.

Thank you!

ECR group

Dallas Cole
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Accelerator Dept

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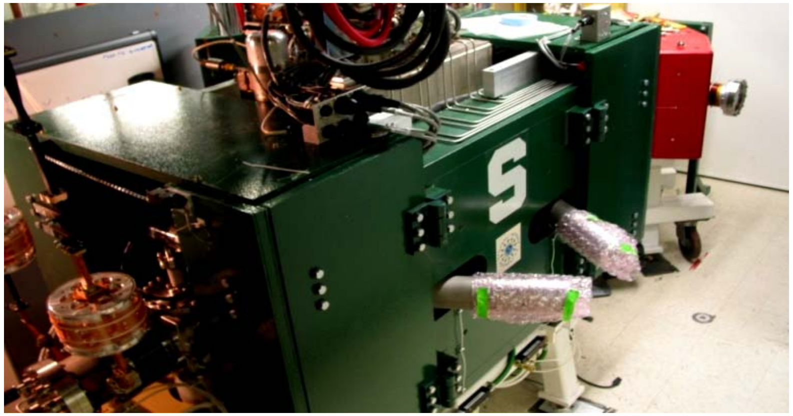
Oliver Kester
Xiaoyu Wu



Operation Dept

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RF Group

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John Vincent

Use channel to optimize SuSI-ECR tune (example)

- Started to use the channel as a tuning guide for SuSI-ECR parameters
- Set the channel at a given acceptance, modify source parameter and record current after the channel
- Readjusting the steering can be necessary for some source parameters (e.g. puller position)

Use channel to optimize SuSI-ECR tune (example)

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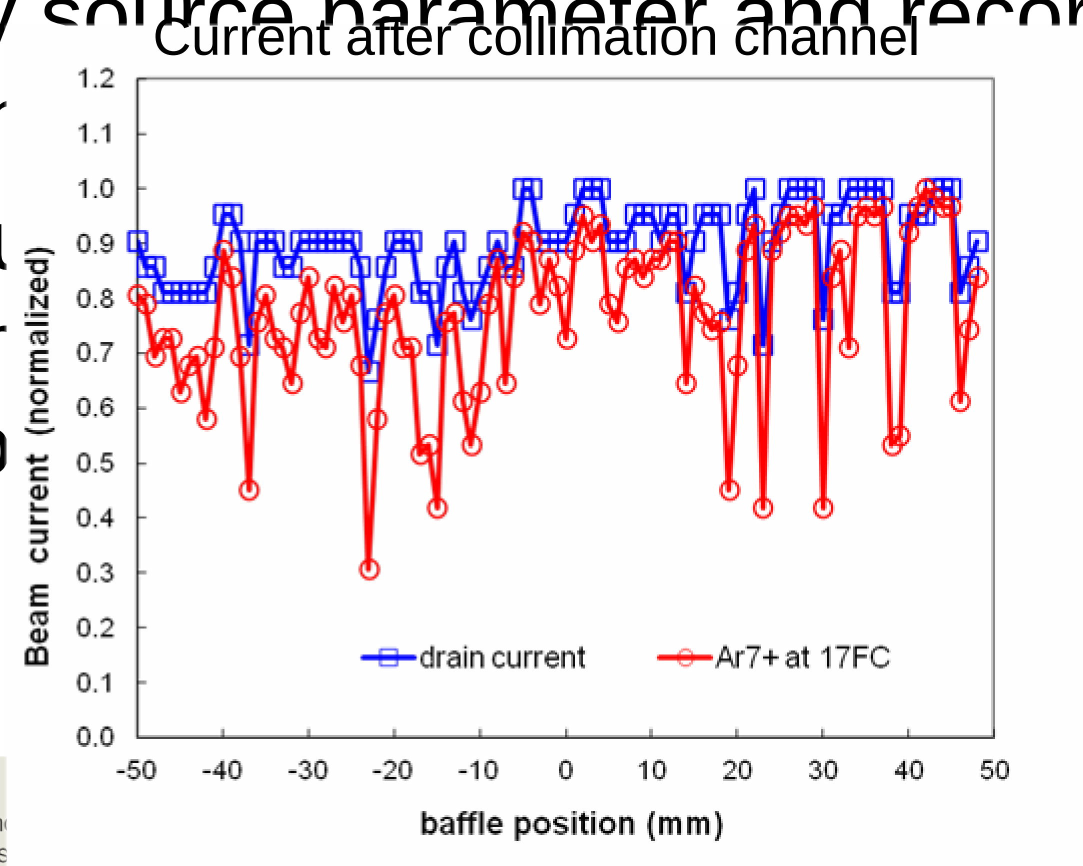
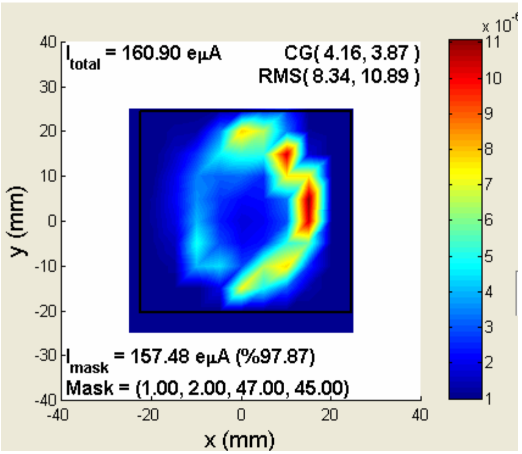
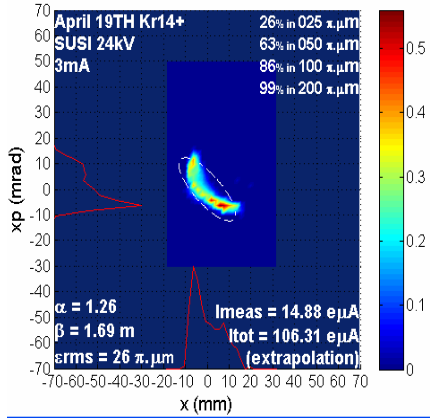


Observations with SuSI with Krypton Beam

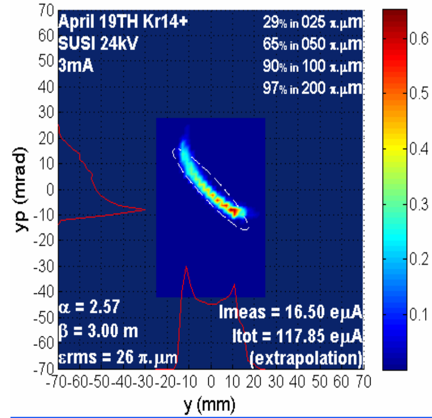
Kr^{13+}



XY

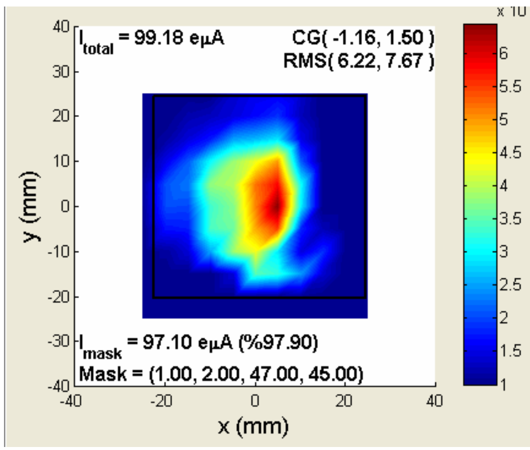


XX'

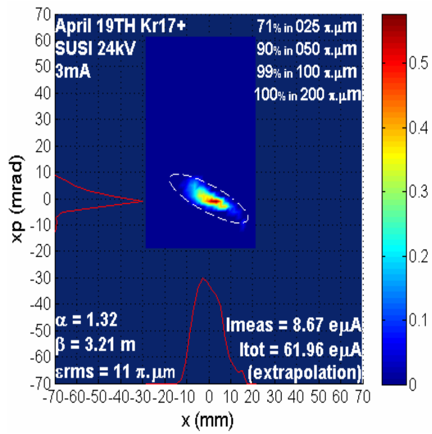


YY'

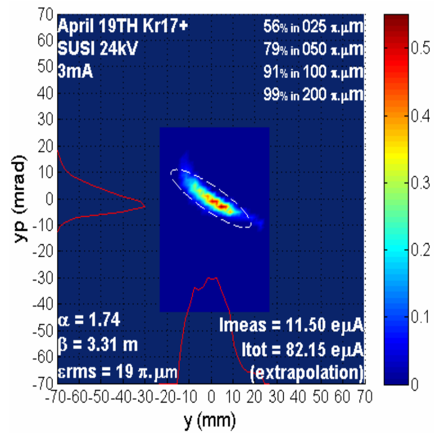
Kr^{17+}



XY

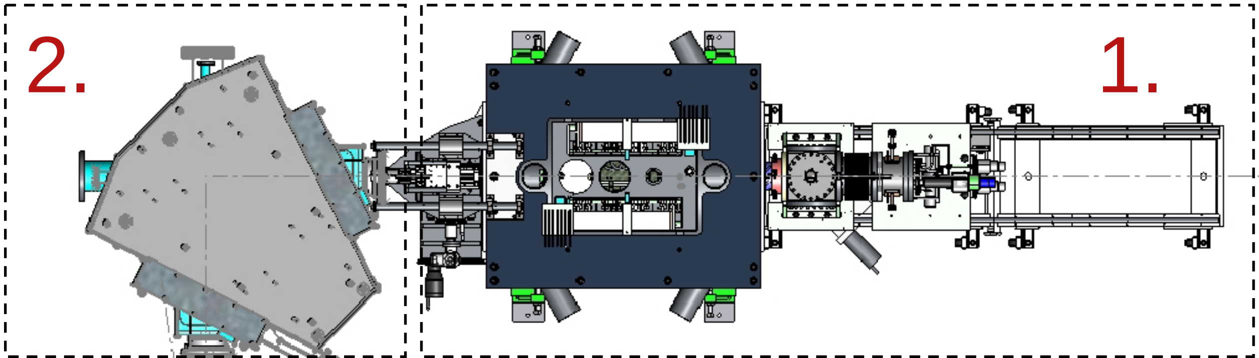


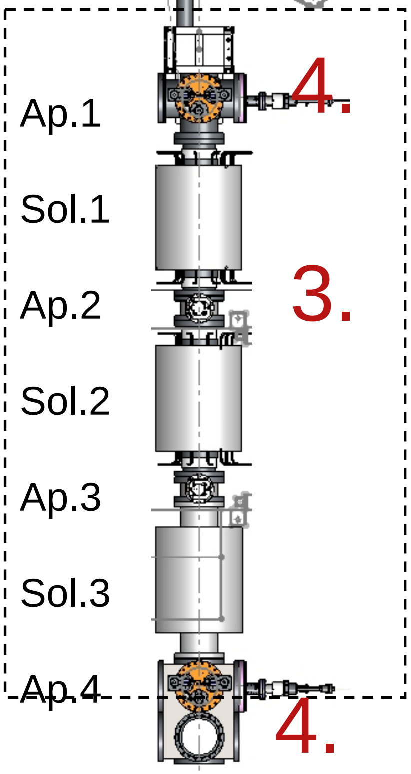
XX'



YY'

SuSI Beam Line Setup





1. SuSI Ion Source
   - Accel-Decel extraction
   - Einzel Lens (1st focusing element)

2. Selecting Magnet
   - Large gap
   - Sextupole correction

3. Collimation Channel
   - 4 collimators (4-Jaws Slits- Aperture-Aperture- 4-Jaws Slits)
   - 3 solenoids

4. Diagnostic: Allison Scanner + FC+ Viewer