A Method of Tuning ECRIS Beam Transport Lines for Low Emittance, ECRIS08

On-Line version with added Notes

J. Stetson, NSCL/MSU

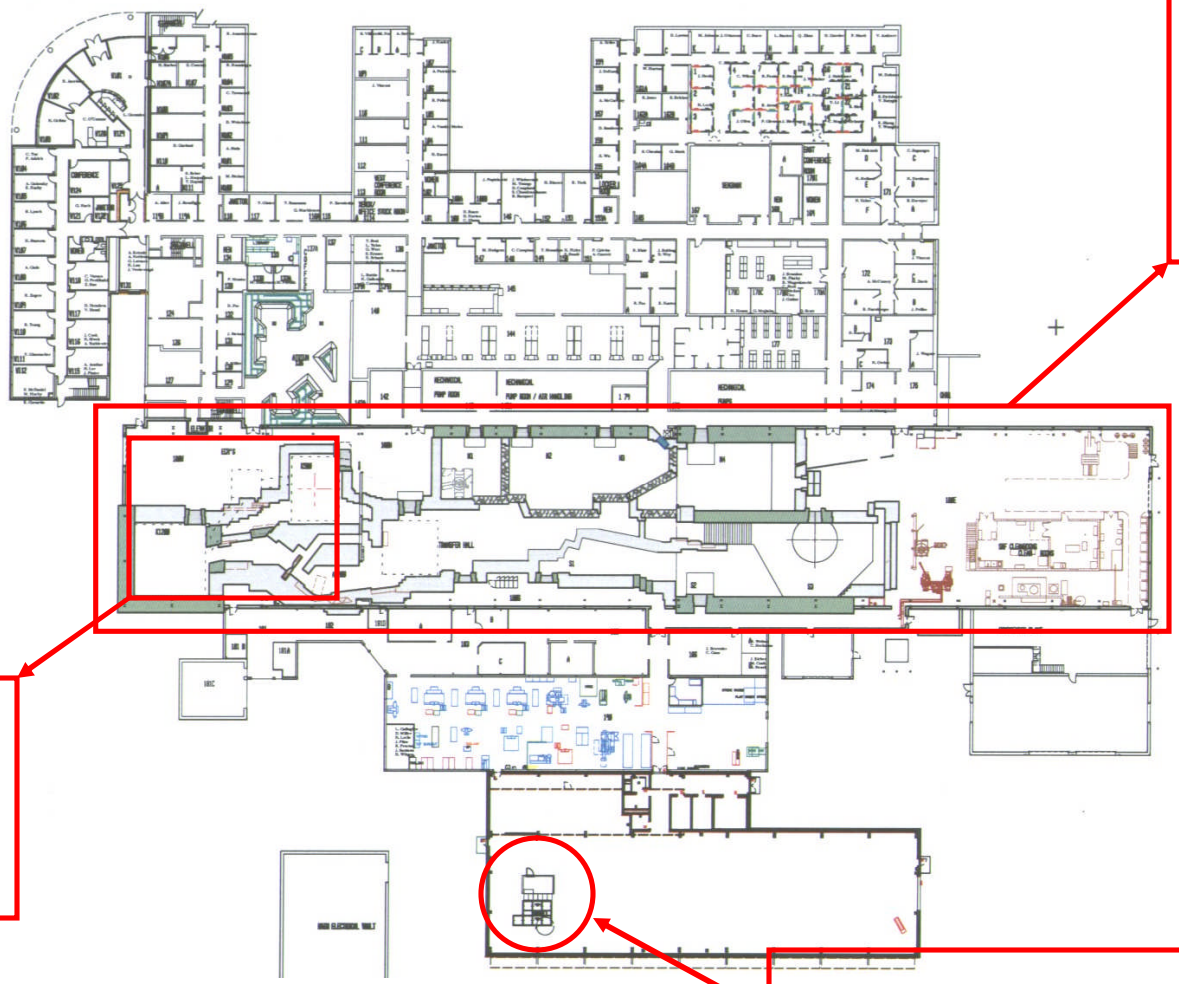
THE OPTICS OF TERRIBLE OBJECTS

Not So

A highly-caffeinated overview

J. Stetson, NSCL/MSU

NSCL Layout

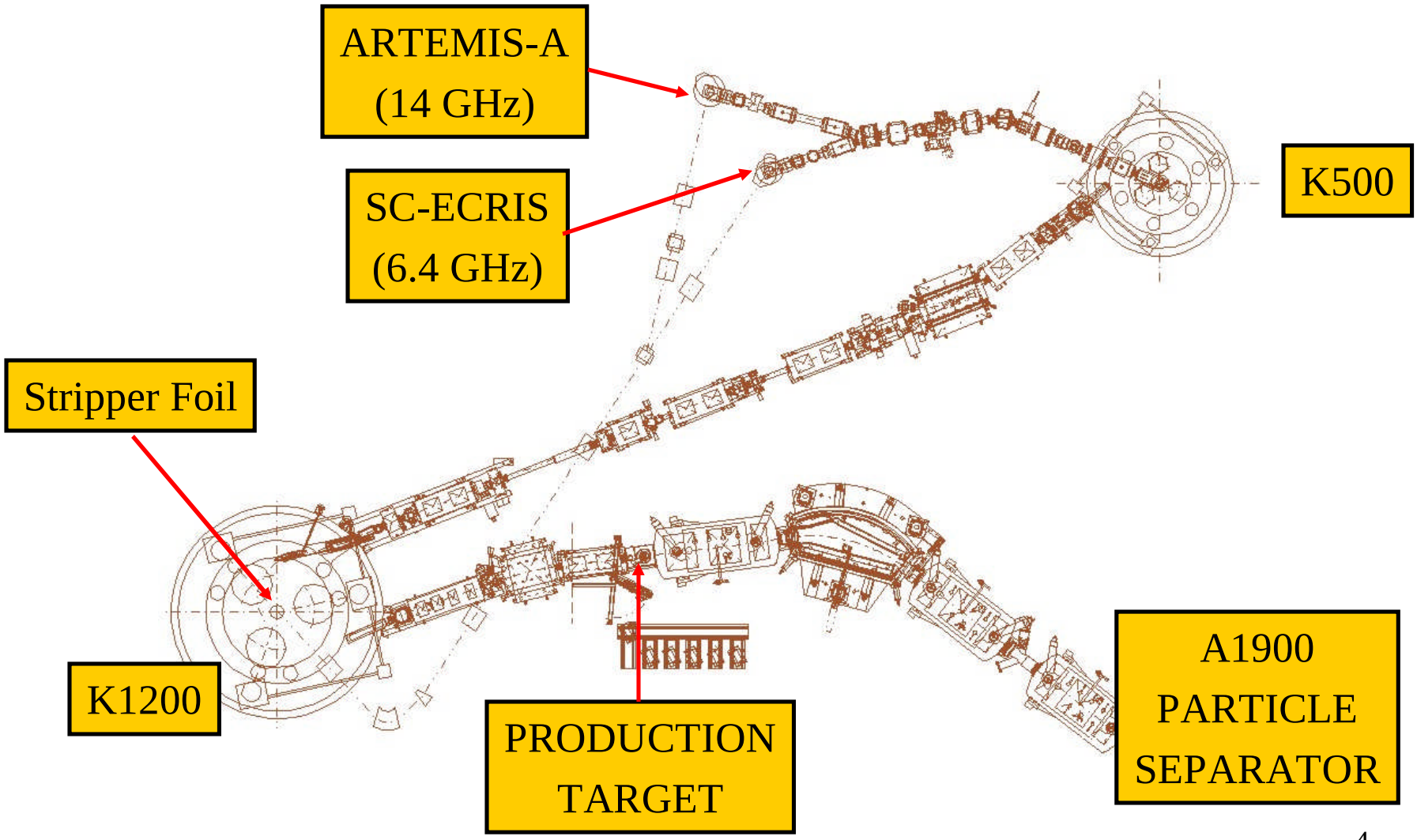


Cyclotrons And Experimental Vaults

Ion Sources And Cyclotrons

ARTEMIS-B IOS TEST STAND

Top View: Compact Machines
(K1200 Extraction Radius = 1 m)



K500 Injected Beam Requirements:

1) Small-sized cyclotron → tight emittance requirement [calculated to be 75 pi*mm*mr]

2) K1200 Stripper → ECRIS M/Q ~ 6

3) Production Target Shielding Limit ~ 4kW → K500 Output < 10 euA → K500 Injection Beam < 30-40 euA

4) First Orbit Radius → 20-27 kV extraction potential

5) 22 different "beam list" isotopes → rapid and repeatable tunes required

From PAC07 (talk MXOXKI03)

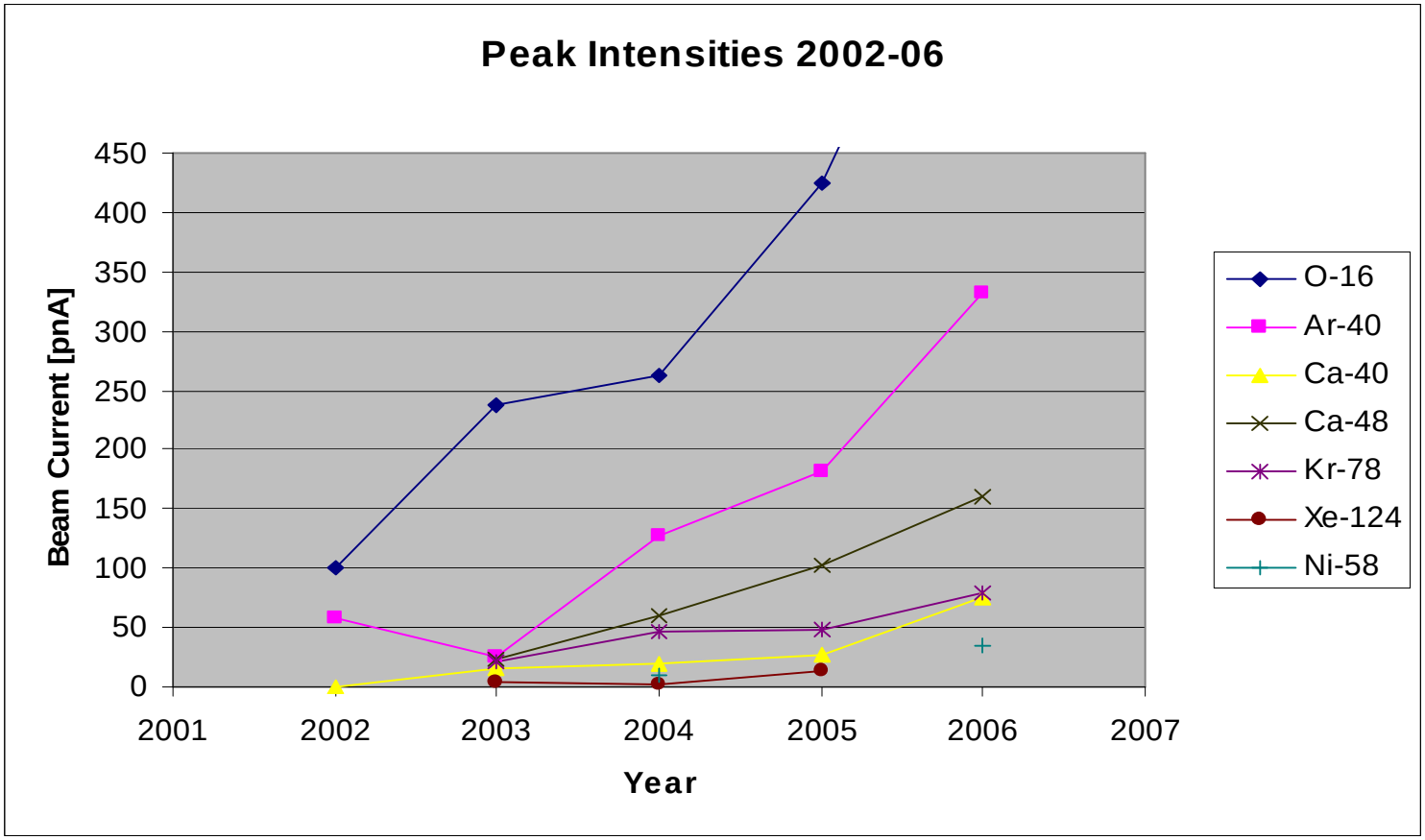
"The key to high intensity and low beam losses is very careful control of ***injection*** *and extraction."*

Stuart Henderson, ORNL

Hardware Changes Affecting Beam Dynamics 2003-2007 (Injection line In Orange)

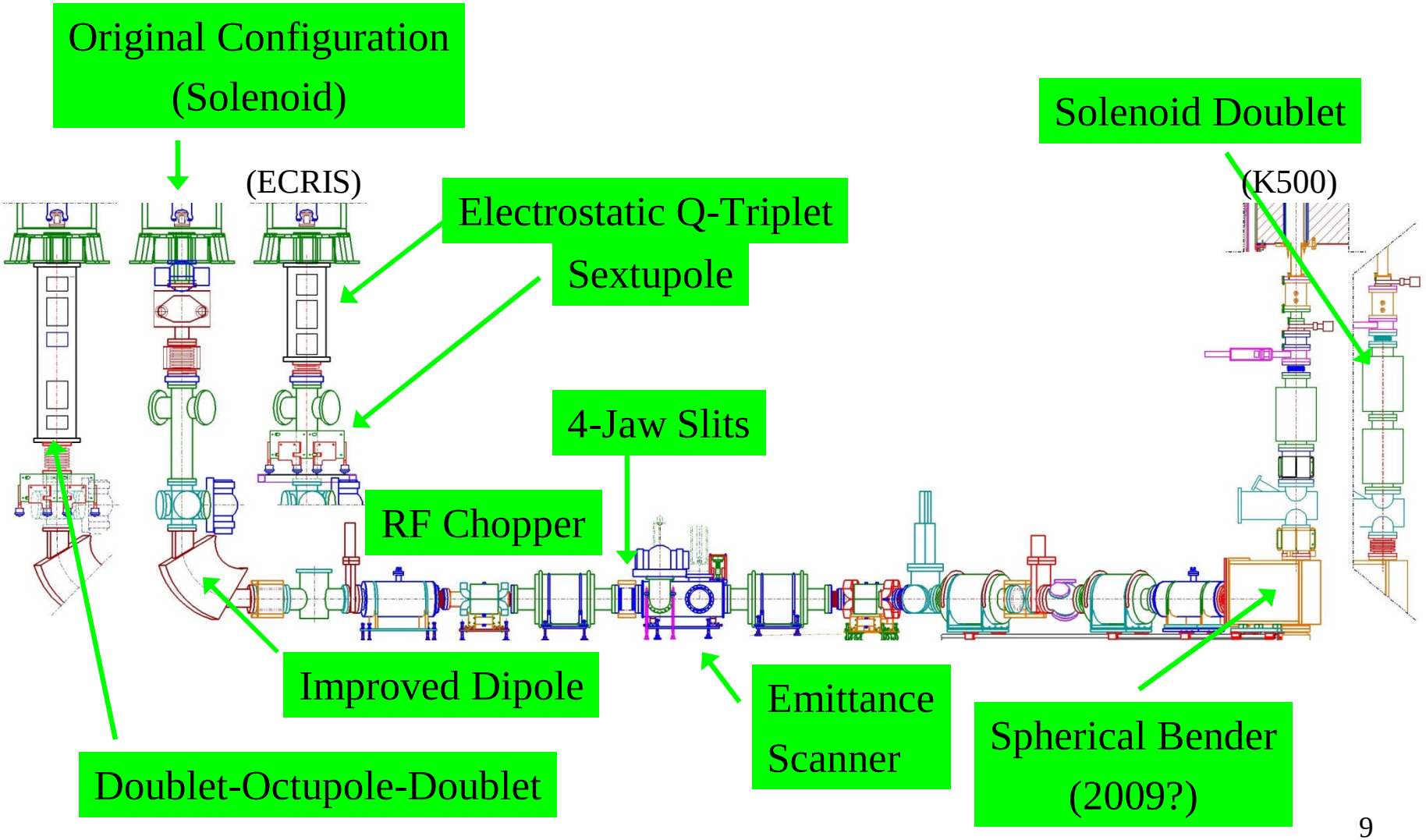
May 2003: Revised ARTEMIS-A Extraction Region
July 2004: Problem with ARTEMIS-A Hex field
05-Sept-04: Install Small Bore Triplet (SBT) on SC-ECR
17-Nov-04: Install S006SX, Remove Aperture 1
7-Dec-04: Repair K12 injection & K12C3,4
Jan-05: ARTEMIS-A Permanent Magnet Sextupole Bars Replaced
Jan-05: SBT on SCECR moved up 5"
Jan-05: Buncher moved up 12"
Jan-05: K8C4 Beam Scraper (0.42") Installed
16-Feb-05: remove S007AP
10-Dec-05: Double Solenoid under K500; Buncher moved down 4"
10-Jan-06 Large Bore Triplet (LBT) installed on ARTEMIS-A
10-Jan-06: Moved Plasma Electrode and Puller on ARTEMIS-A
10-Jan-06: remove R007Aperture
10-Jan-06: Installed 0.3" Vt Collimation at Full Radius on K500 K5MPSC
7-Apr-06: Add K500 Phase Slits
7-Apr-06: Add J033 4-Jaw Slits
7-Apr-06: K5MPSC Gap reduced to 0.25"
11-May-06: Reverse J046SN Polarity
12-Jun-06: Install Double Doublet System (DDS) on ARTEMIS-A
12-June-06: Replace Buncher grids with 1 cm dia washers
12-Jun-06: Swap R013QA/14QB with J042SN
15-Jan-07 Inflector Collimator 4.2 → 2 mm (failed, returned to 4.2 mm)
15-Jan-07: K5MPSC Gap reduced to 0.19"
15-Jan-07: Einzel Lens + LBT installed on SCECR; remove S006SX
15-Jan-07: Water-cool K12E1D drive rod
19-Jan-07: reversed polarity of J056SN

Max Recorded Beam Intensities 2002-2006

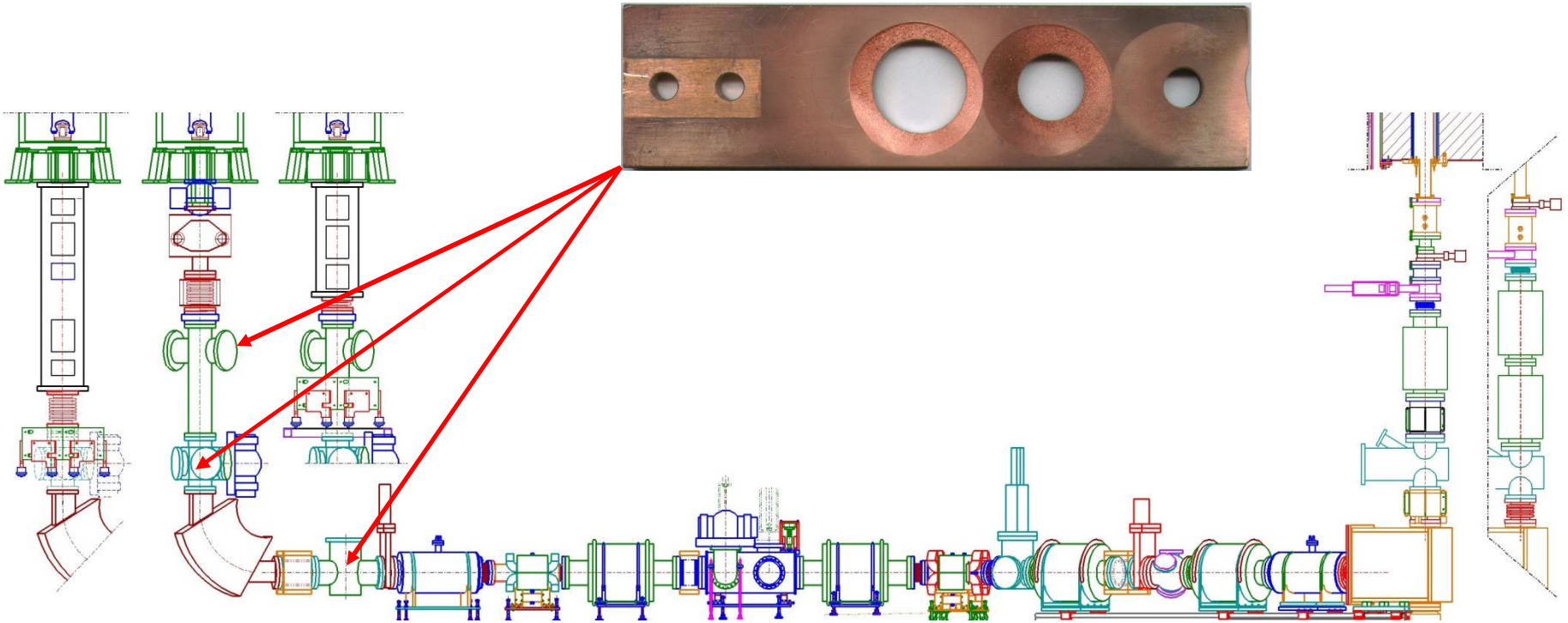


→ Gains Largely from Injection Line improvements

Injection Line (~16.5 m) to K500



~2000: Add Aperture Plates

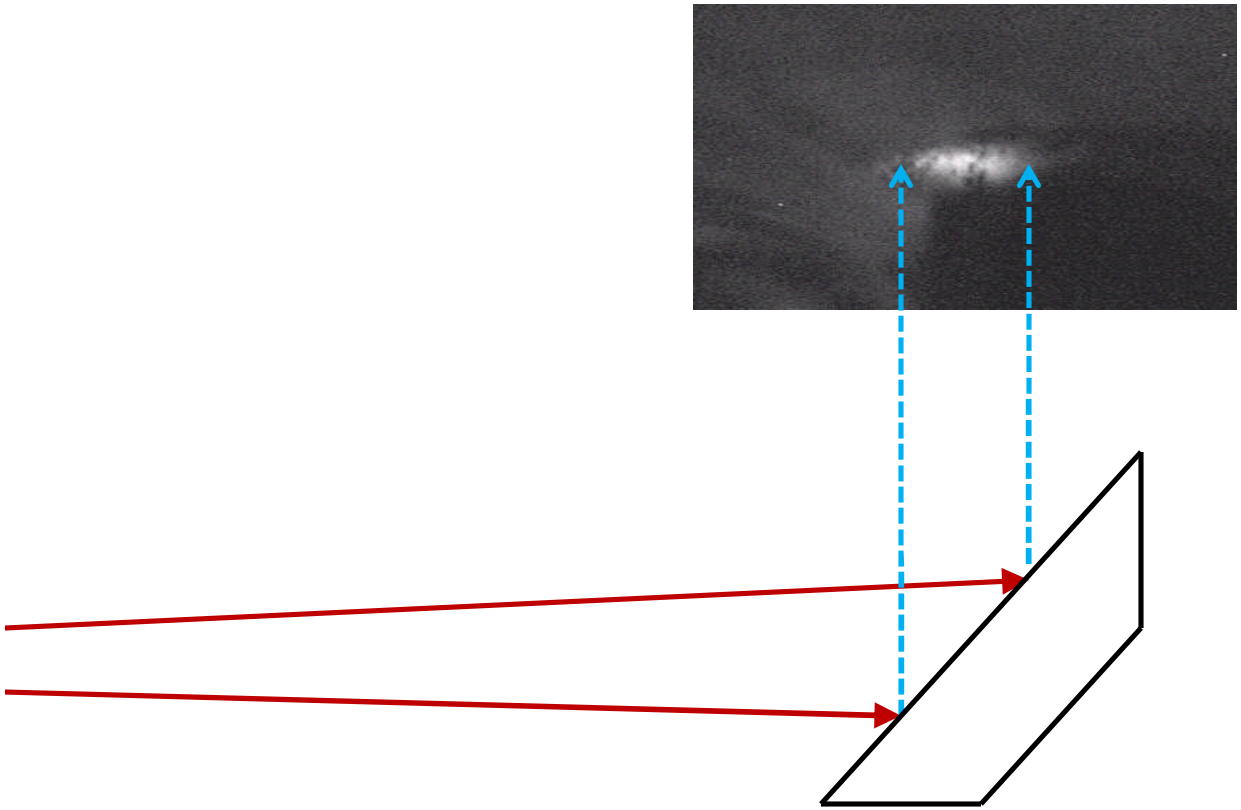


Less = Better

Apertures [mm]	Beam	Analyzed Beam [eμA]	K500 Inflector [eμA]	K500 Extracted [eμA]
none	$^{16}O^{+3}$	400	159	1.1
7, 12, 25	$^{16}O^{+3}$	36	5	1.1

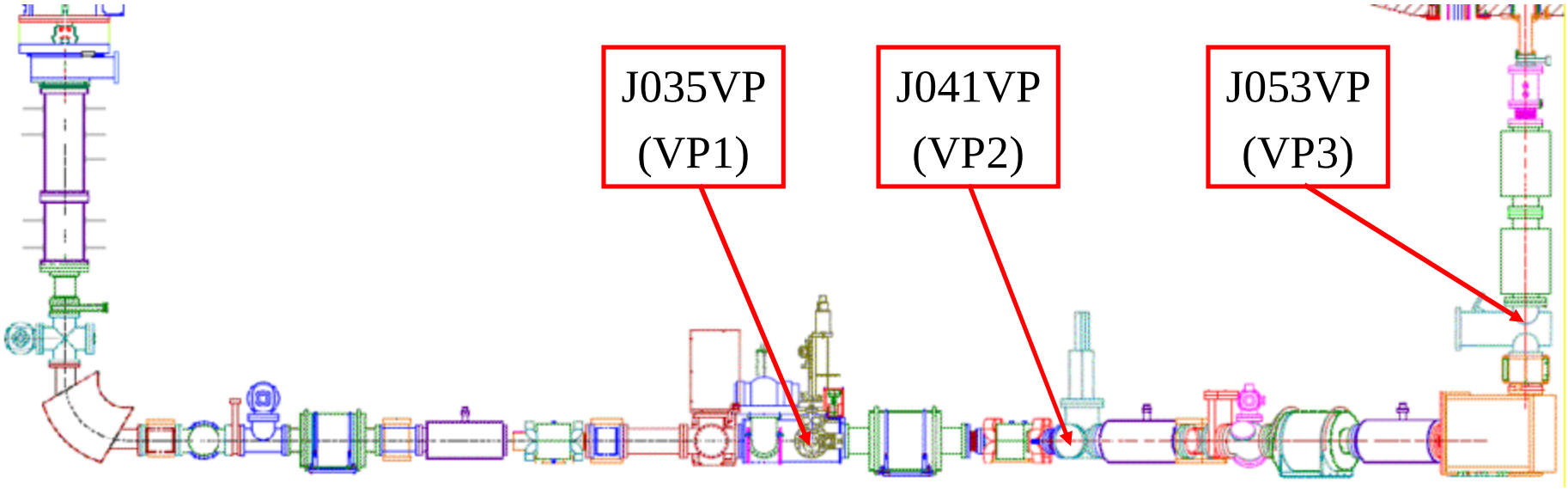
(from 2003)

Viewer Plates:
Aluminum Coated with Phosphor (KBr or BaF_2)



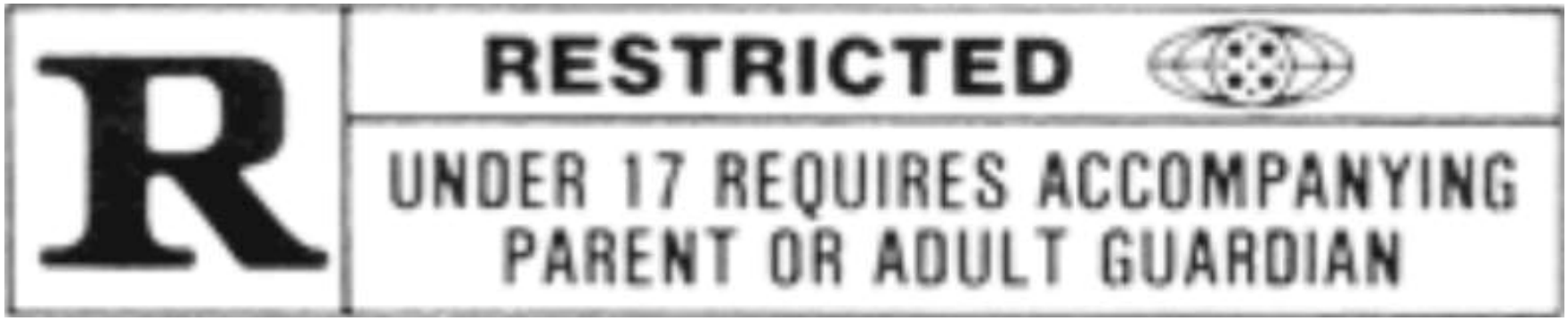
Viewer Plate Locations

The number part of the device name refers to its relative location.

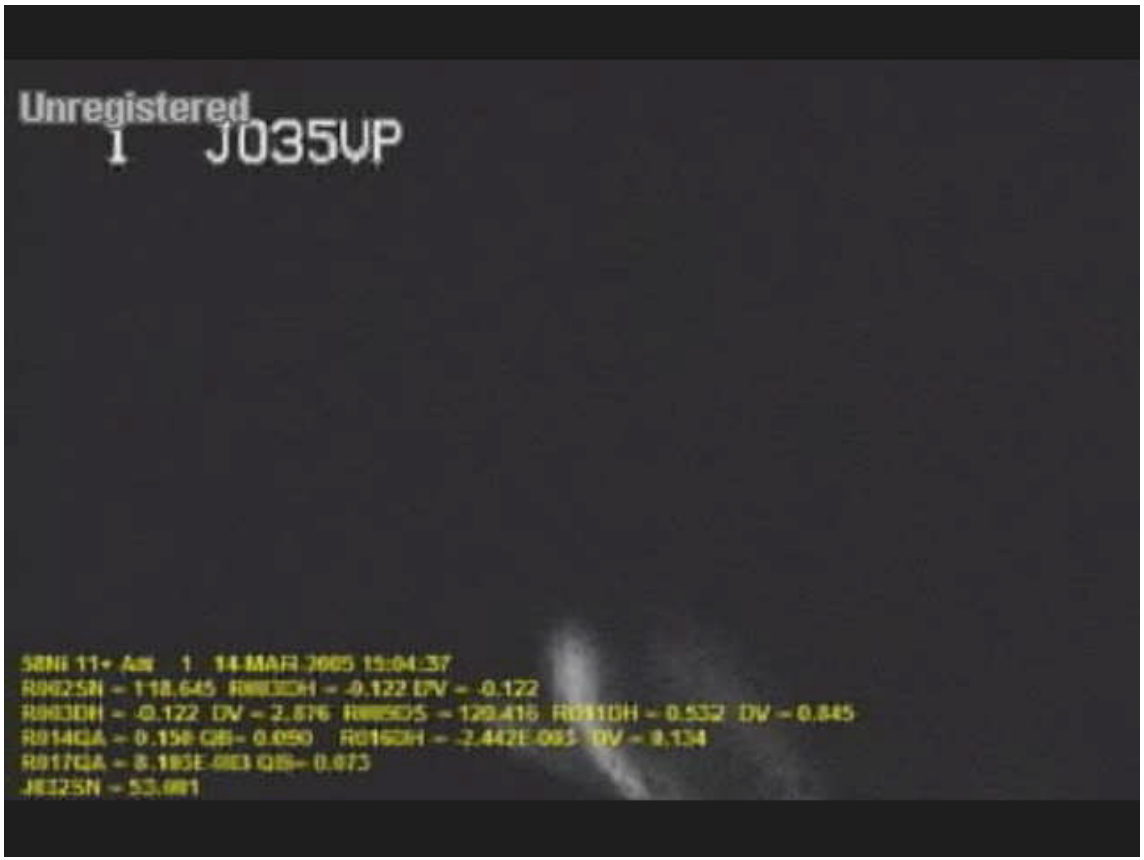


(Side View)

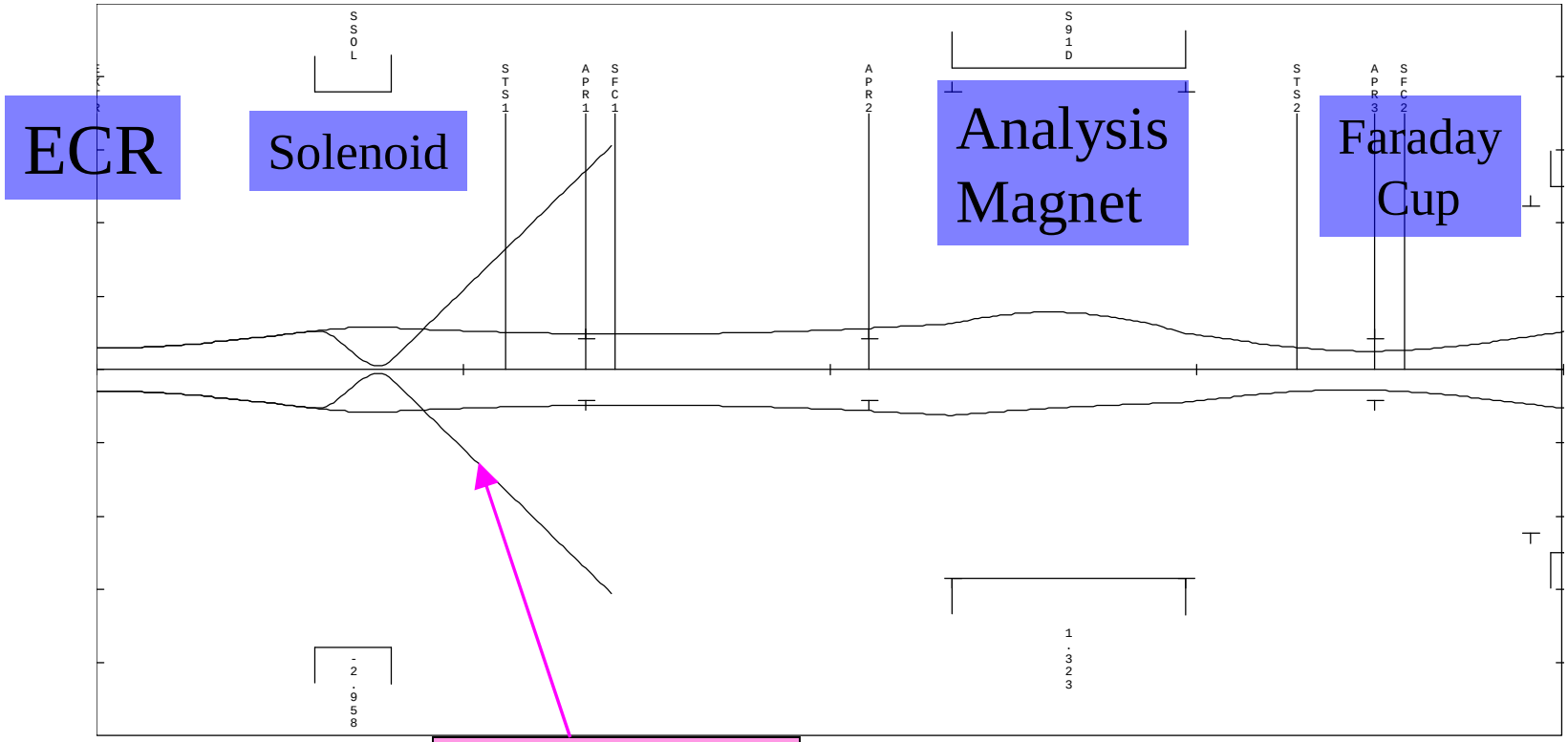
The Following Movies Are Rated:



Rings of ^{58}Ni Charge States (Vary R009 Dipole)
(ECRIS →Solenoid →Dipole →Solenoid →Viewer)



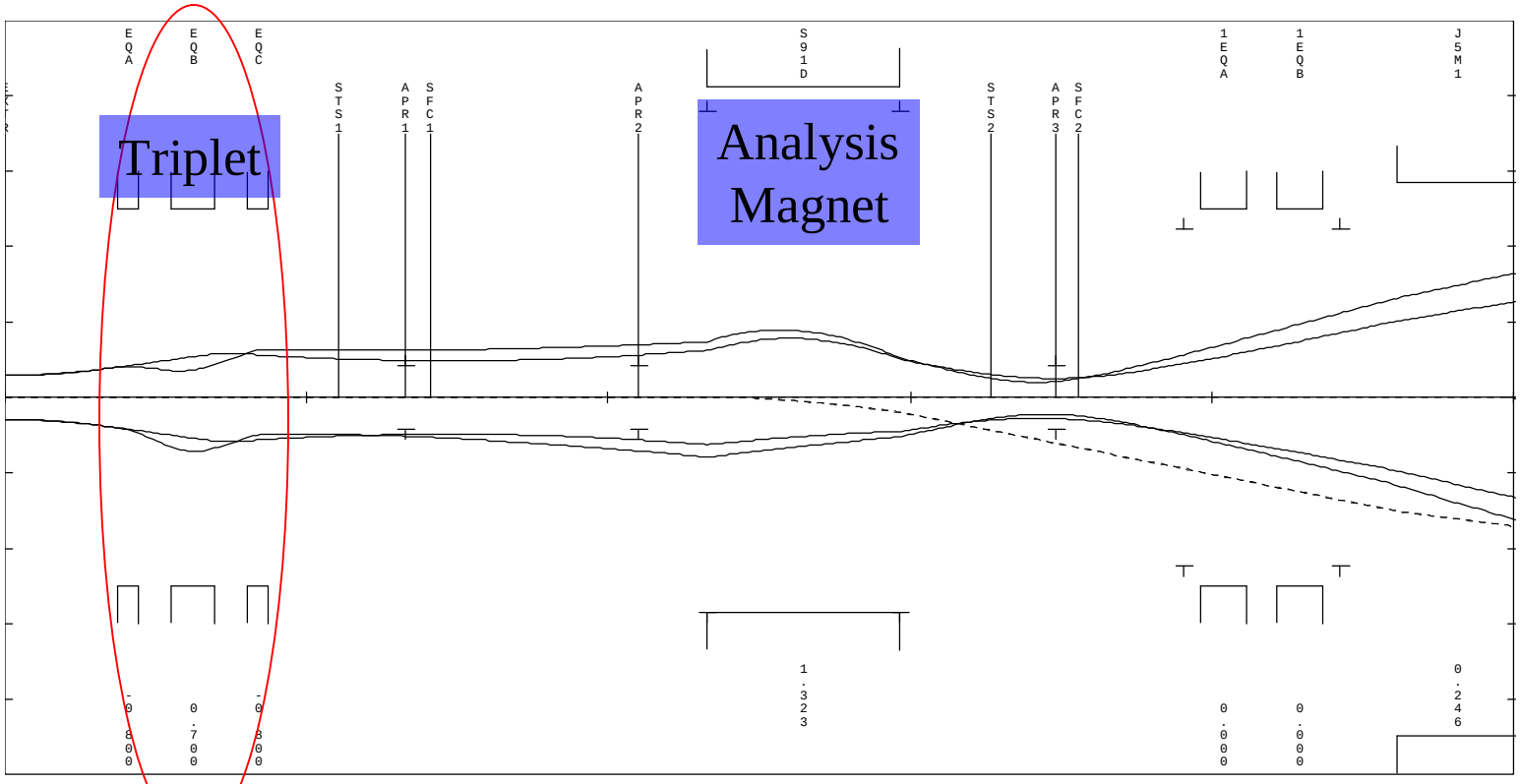
Beam Transport for $^{48}Ca^{8+}$



(from 2004)

With Electrostatic Triplet

All Ions Remain Together until Magnetic Bend



(from 2004)

Short Focusing

Beam Line is tuned to transmit a Q/A ≅ 1/6 Beam

ECR Beams often have Q/A > 1/6 Ions of significant intensity (support gas)

Q/A > 1/6 ions are tightly focused before reaching the analysis magnet

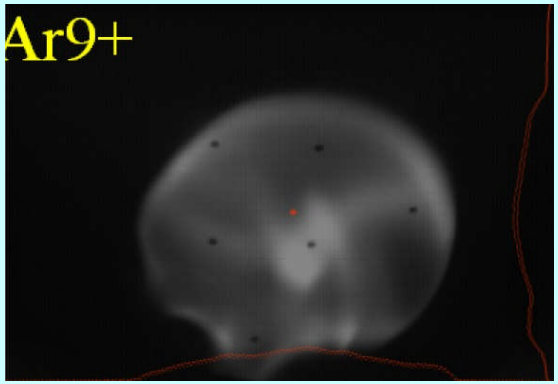
Beam at “short foci” creates high space-charge forces driving desired beam ions radially outwards

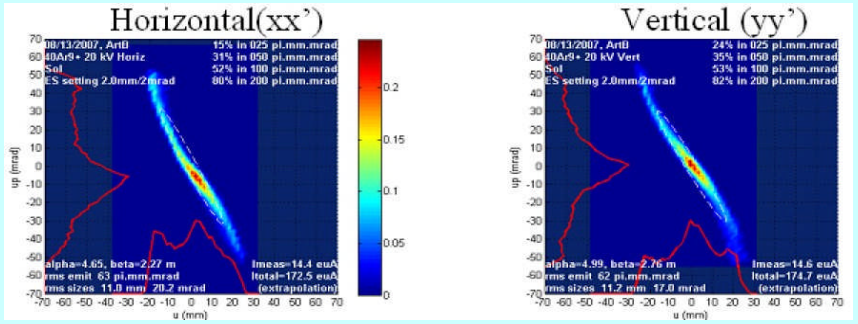
(from 2004)

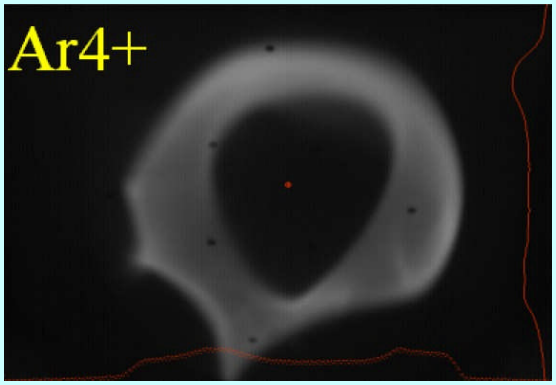
Definitive Solenoid Test Artemis B - 2007

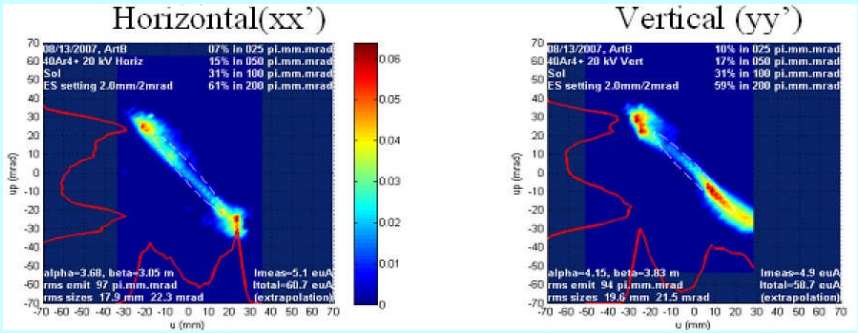
G. Machicoane (ICIS07)

Space-Charge Blow-Up from Solenoid Focusing

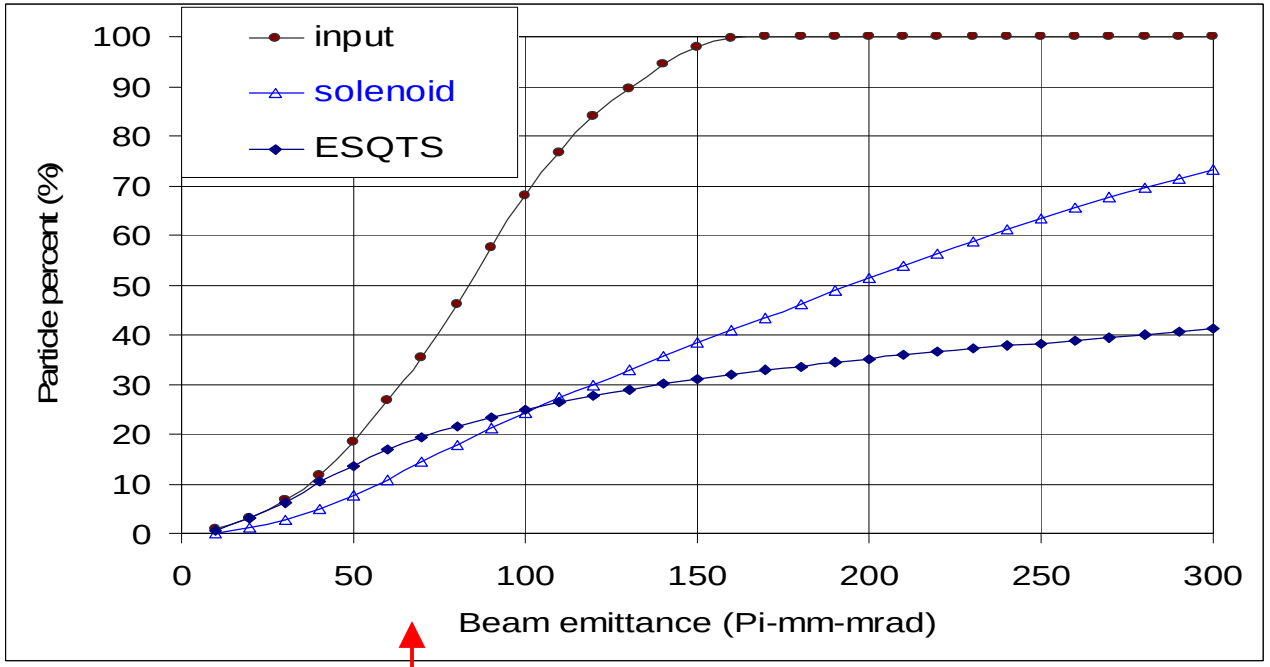








Maximize the Good at the Expense of the Bad
50mm Triplet vs. Solenoid Case



Region of Interest

Not Useable Beam

So Get Rid of It Early

(which is not easy to do)

Gains From better Tranmission

	~2003 SOURCE OUT → K1200 OUT	~2006 SOURCE OUT → K1200 OUT	GAIN
^{40}Ar	2280 → 58	1920 → 222	4.5
^{48}Ca	1275 → 32	1400 → 160	4.6
^{76}Ge	690 → 17	725 → 63	3.5
^{78}Kr	2640 → 22	2760 → 79	3.4

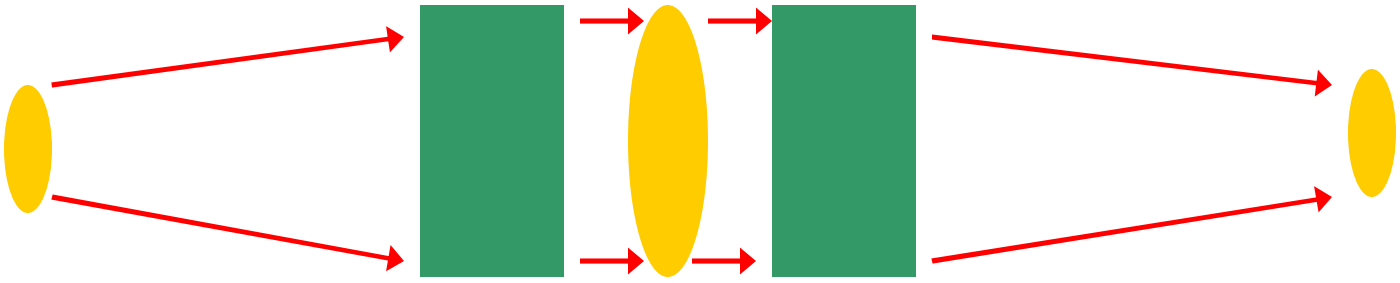
Analyzed source beam output (in pnA) and the resulting beam intensity extracted from the K1200. The net efficiency normalized to source output has increased by about a factor of four from 2003 to 2006.

Problems Remain

Now: Overall beam intensities often limited to about 800W by losses in the cyclotrons at beam extraction. (Deflectors!)

Future: How to beneficially use high intensity from SUSI?

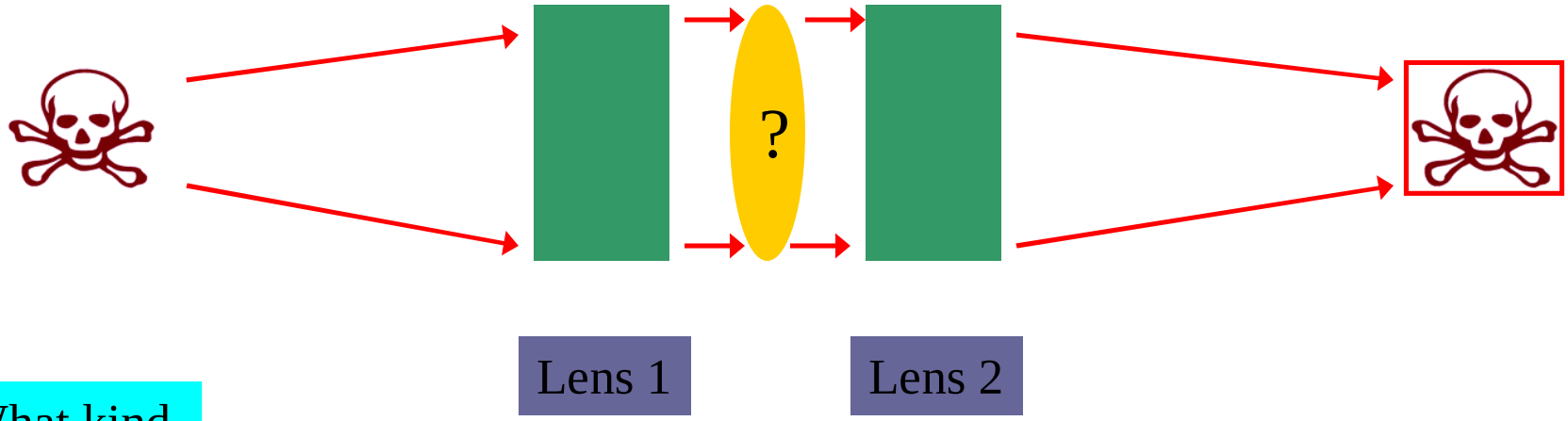
Ideal Case for Perfect Injection



Lens 1 Lens 2

Uncorrelated Round Beam (Object) → "Round" Beam → Uncorrelated Round Beam (Image)

Our Less-than-Ideal Situation

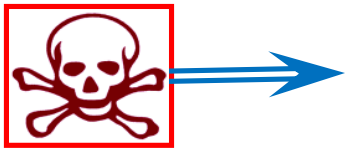


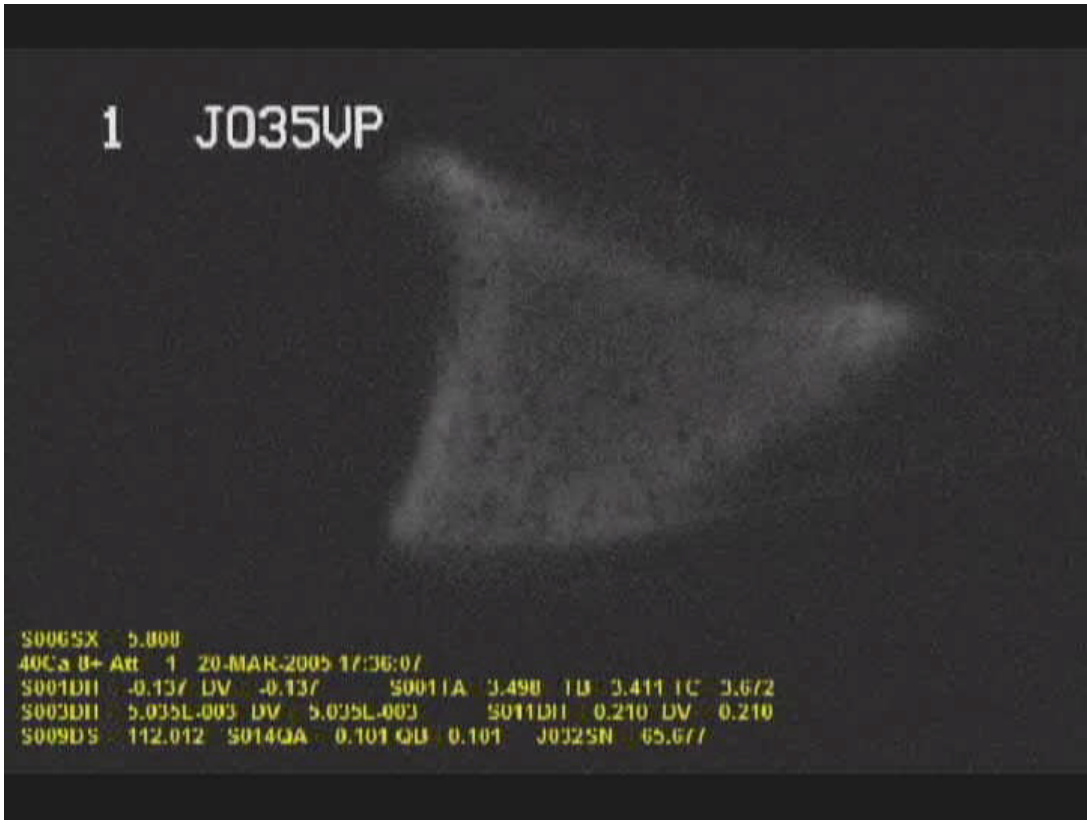
What kind of Object gives ***Strange Stuff*** as an Image?

Strange Stuff

Close Round Aperture: 25, 17, 12, 7 mm

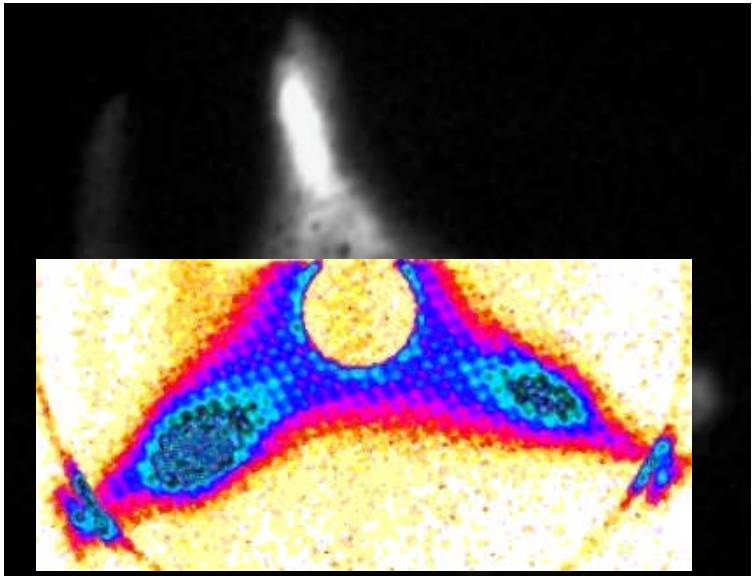
(ECRIS →Triplet →Dipole →Quad Doublet →Viewer)





Round Cut give Triangular Beam!

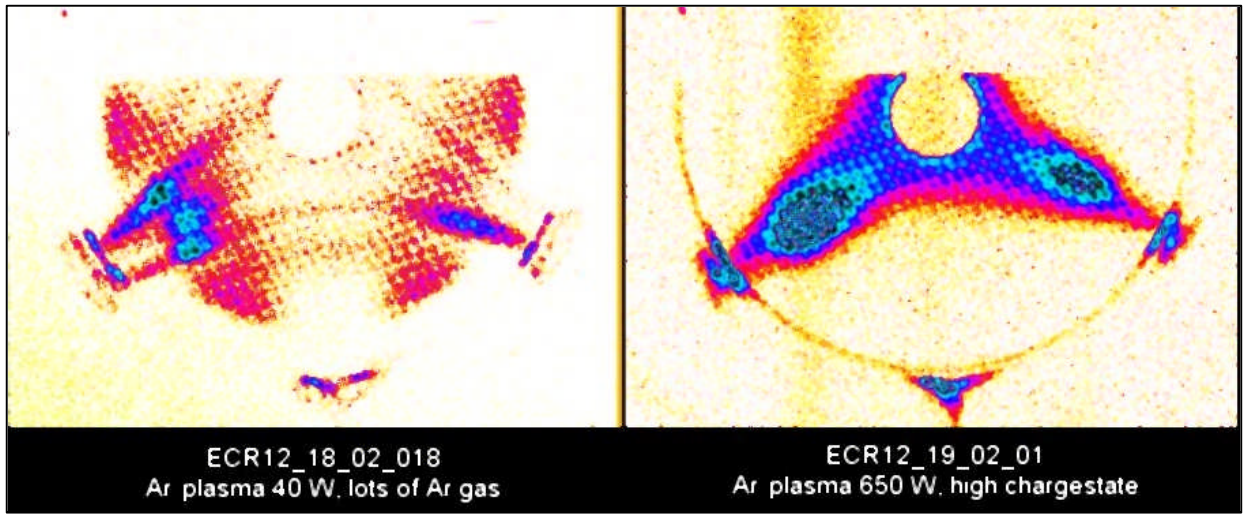
“Star” Features more Evident w/o Solenoid Space Charge Issues



$^{16}O^{+3}$ (using Electrostatic Triplet)

(from 2004)

Highly Structured Object

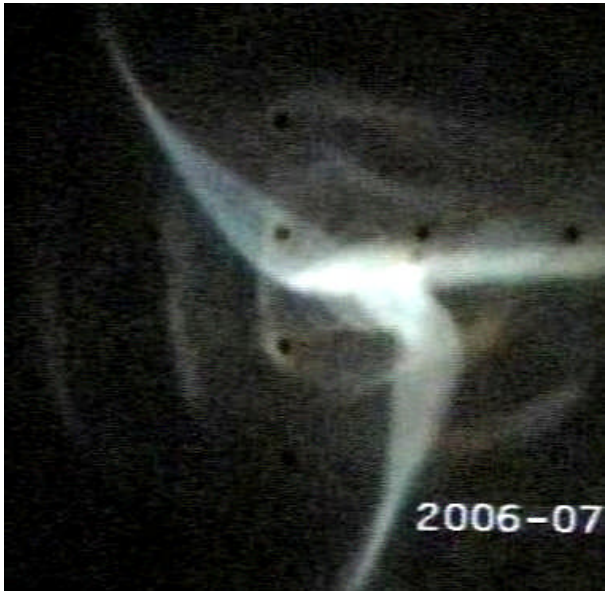


X-Ray Image of Ionization Within the ECRIS

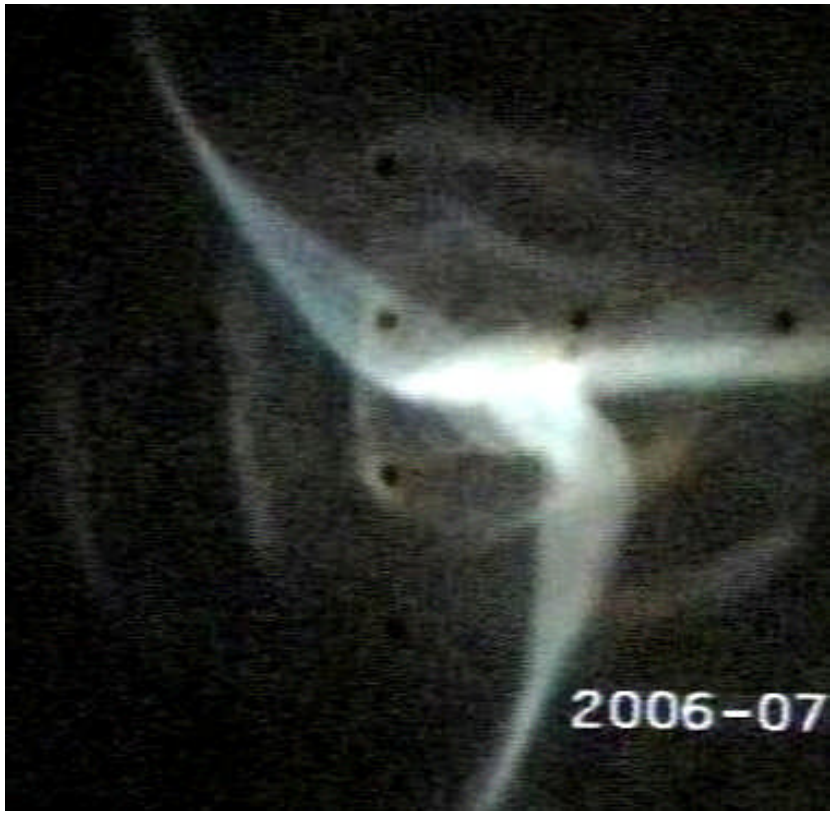
(from 2004)

S. Biri, et. al.

VT2 view after first Beam Line Solenoid (GSI, 2006)



ECRIS Beam has a Special “Tag”



“Rings” morph into “Stars” by varying the focusing strength of lenses.

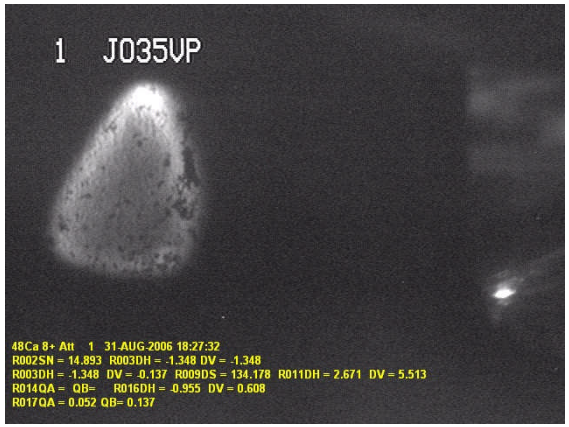
(Simulations:

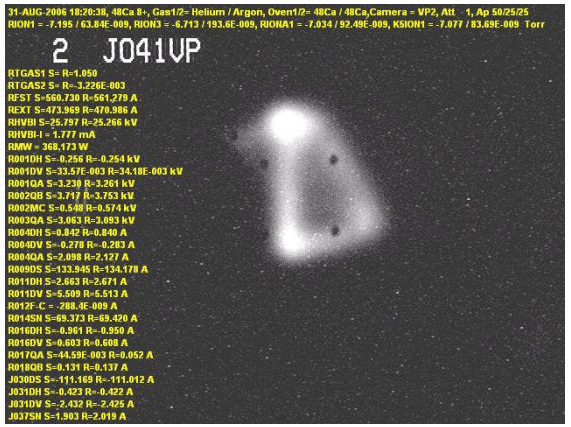
This is not explained by 2nd Order Alone)

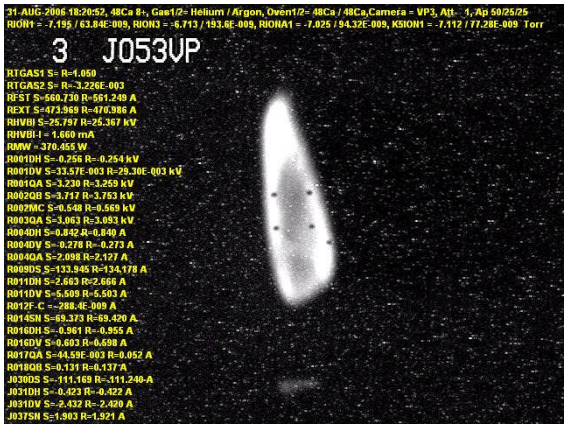
Ring to Star @ NSCL using Beam Line Solenoid

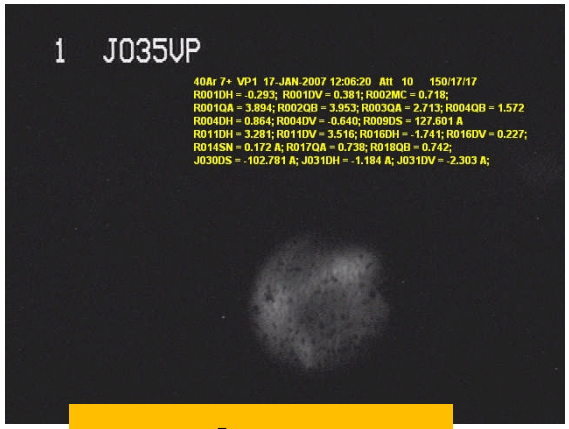
(ECRIS →Double Doublet →Dipole →Solenoid →Viewer)

Image Propagation thru Injection Line

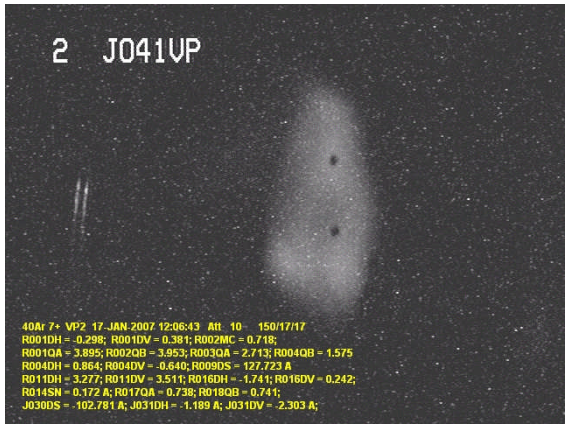


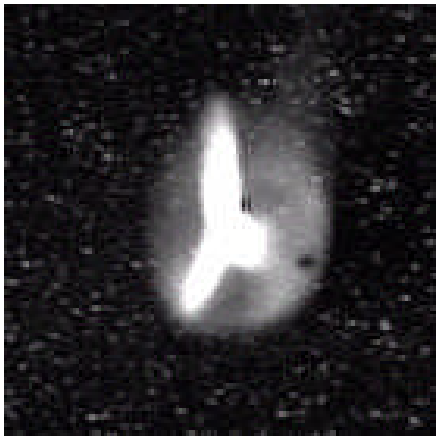




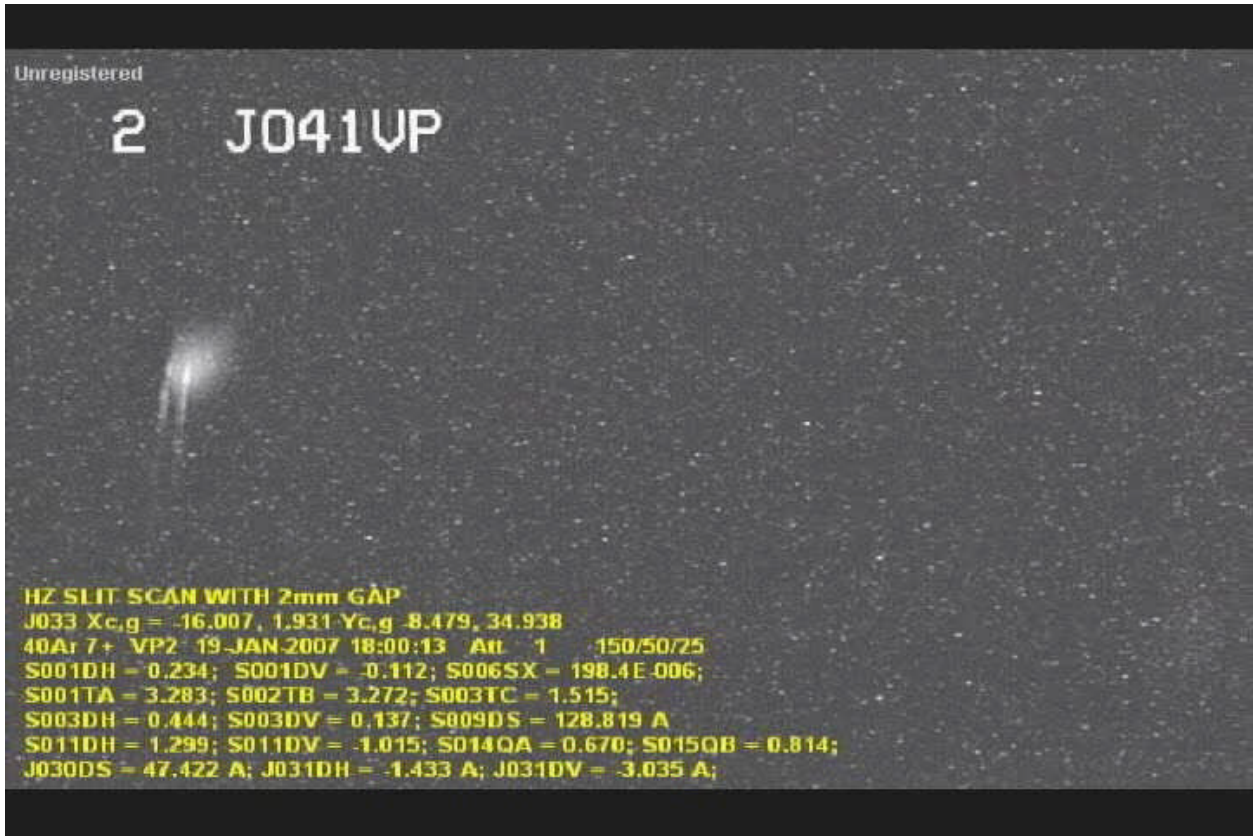


Round Aperture





Hz Slit Scan J033XGap = 2 mm

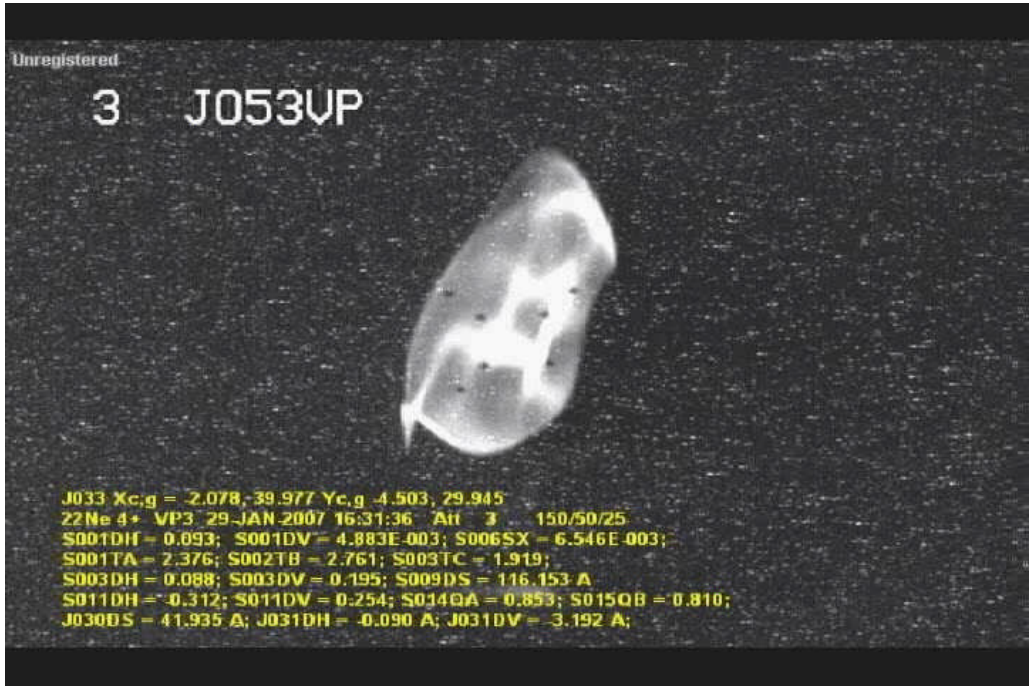


"Should" show a narrow vertical line

Vz Slit Scan J033YGap = 4 mm

"Should" show a narrow horizontal line

Cut 90% of Intensity with J033 Slits centered on Beam



Slits are cutting only Intensity, NOT overall Emittance

(Slit half-way thru Injection Line, Viewer Just Before K500)

ECRIS Beam Characteristics

1) **Transverse Structure**
2) **Large 2nd Order Aberrations (Triangle)**
3) **Strong Phase space cross-coupling (beam is correlated)**
4) **Focusing morphs Triangle into Star**
5) **Under some conditions, a fractal nature (round cut can redevelop into a triangle-star)**

The Question:

Can the extracted beam be dealt with in a way that gives good 2D emittance without large correlations but with reasonable intensities?

The Surprising Answer: Yes!

A Test a of 2nd Order Correction Scheme

At NSCL (August 2007)

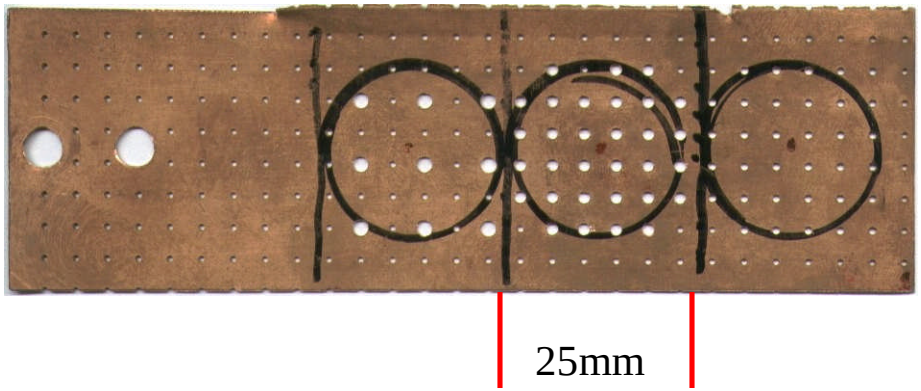
New Analysis Dipole

New, Stronger Sextupole

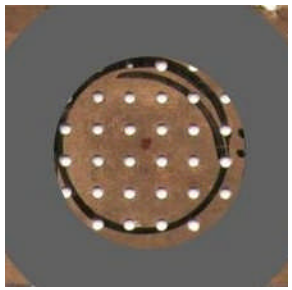
Double-Doublet moved for 2 wks to ARTEMIS-B

In Principle, a Pi Phase advance between the source sextupole and an external sextupole should allow a full correction of the 2nd order aberrations.

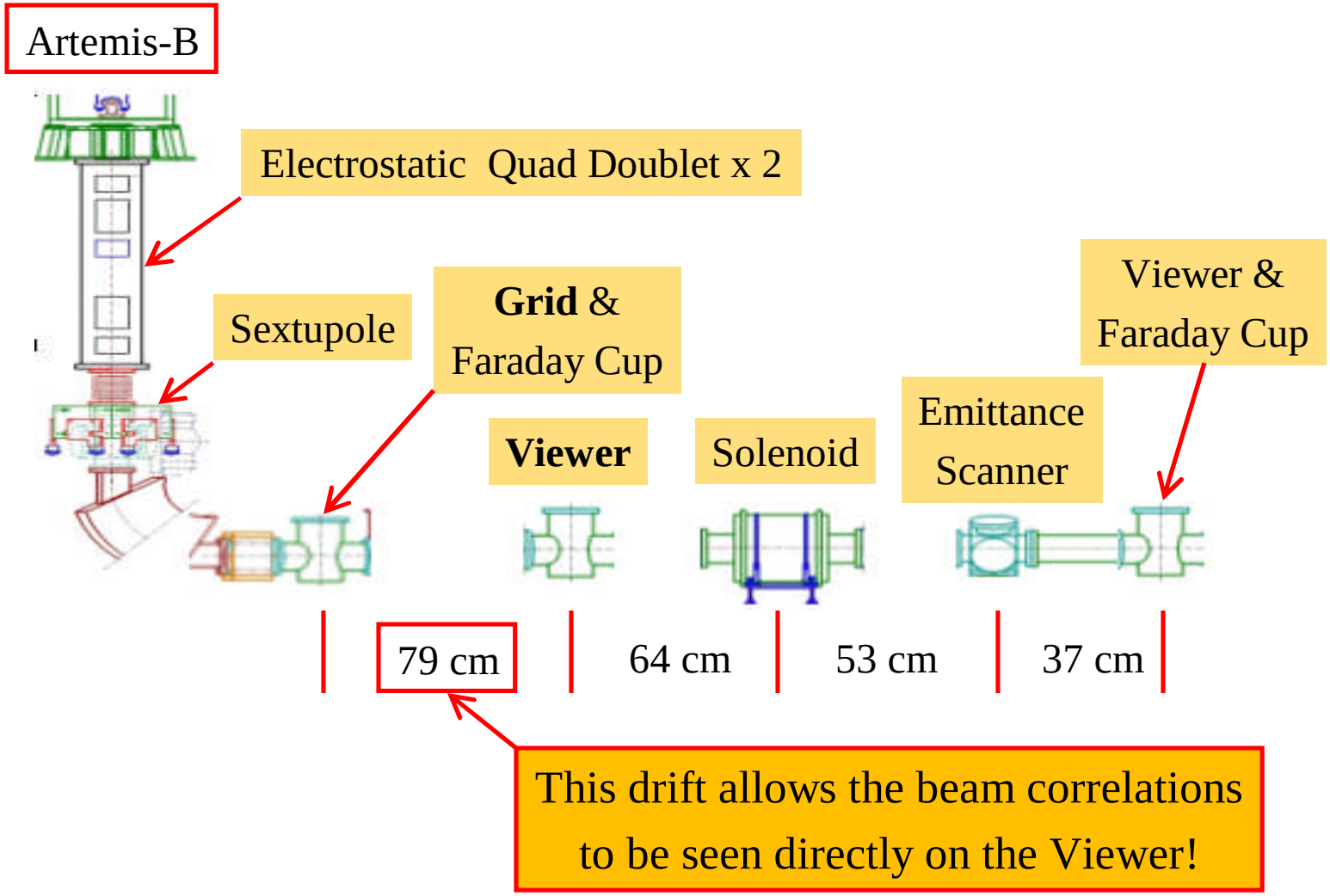
A Most Useful Device
(Poor Man's 4D Emittance Scanner)



1.5 mm dia. Holes
Spaced 4 mm apart

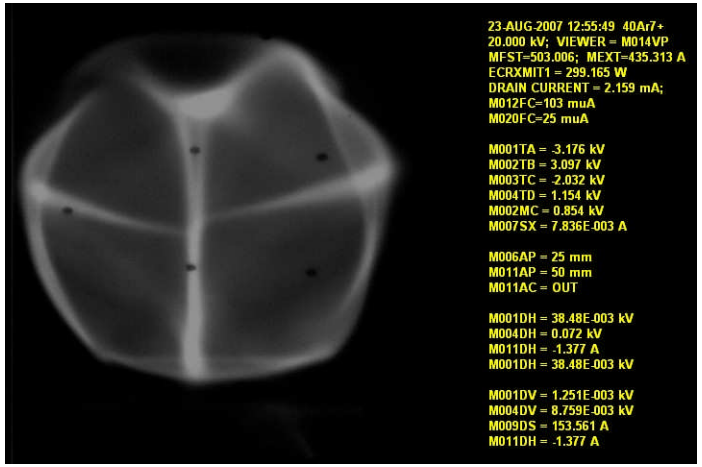


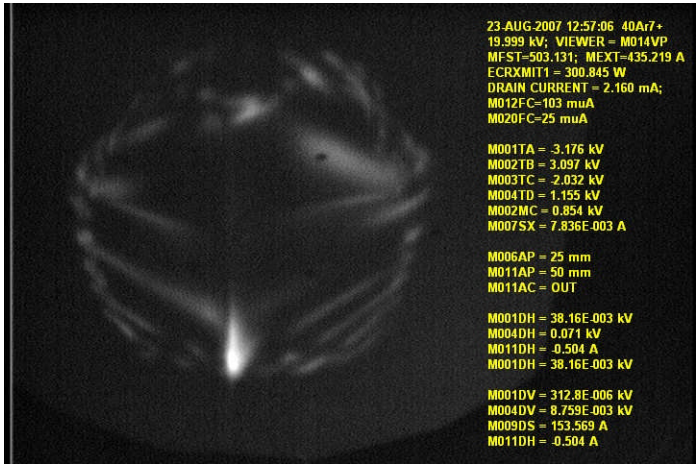
Layout for August 07 ARTEMIS-B Test



Initial Explorations

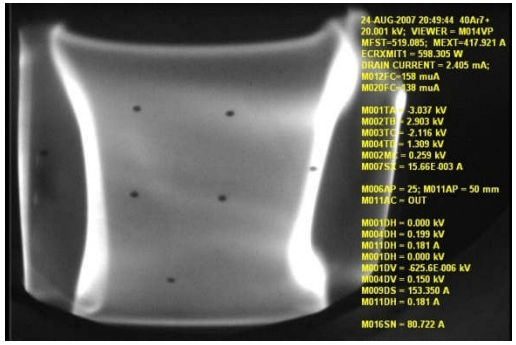
1) Tune Optics for Maximum Intensity on Faraday Cup.
2) Remove Cup, Observe beam on Viewer 79 cm Downstream
3) Take Photo
4) Insert Grid (1 mm diameter holes, 4 mm apart)
5) Take Photo

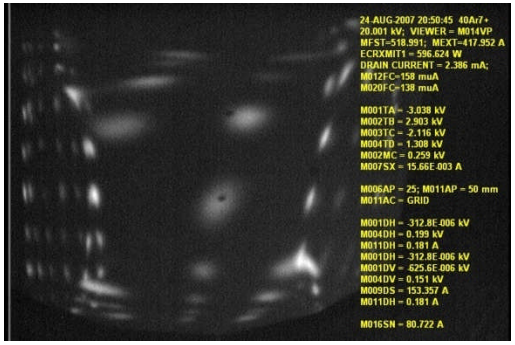




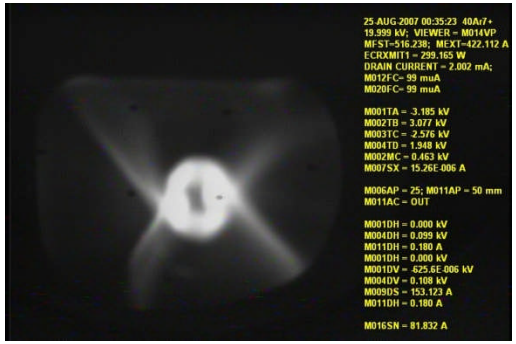
More!

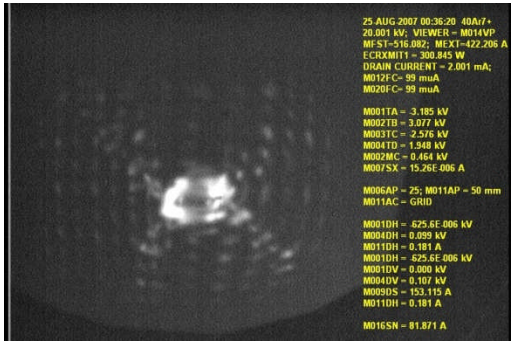
Without Grid

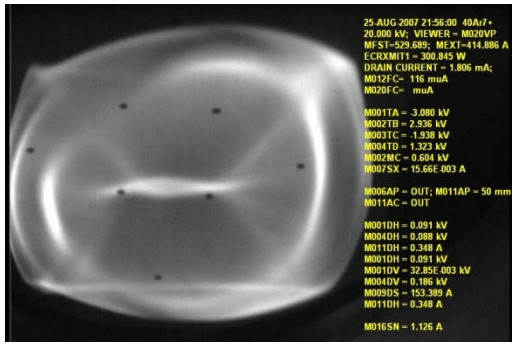


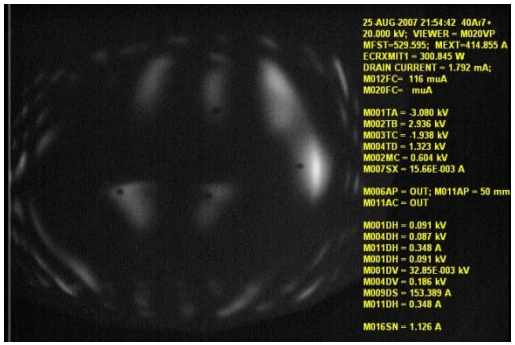


With Grid

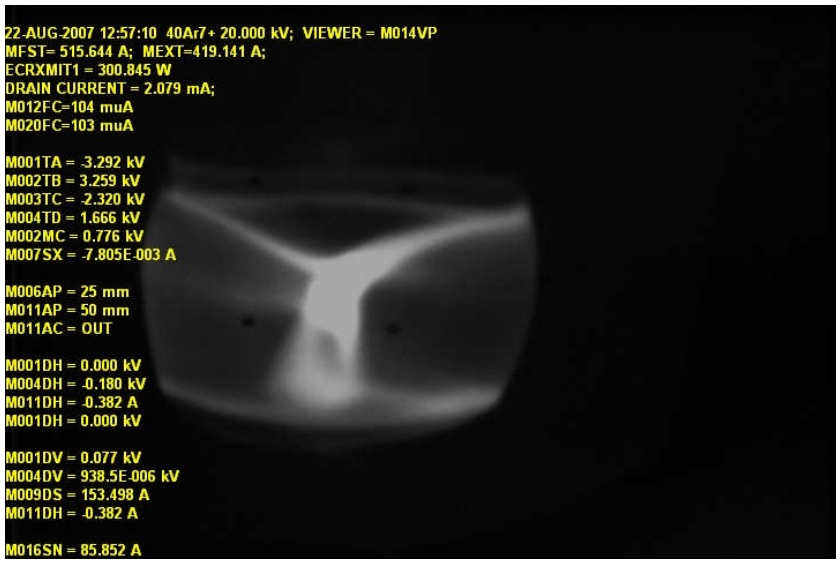


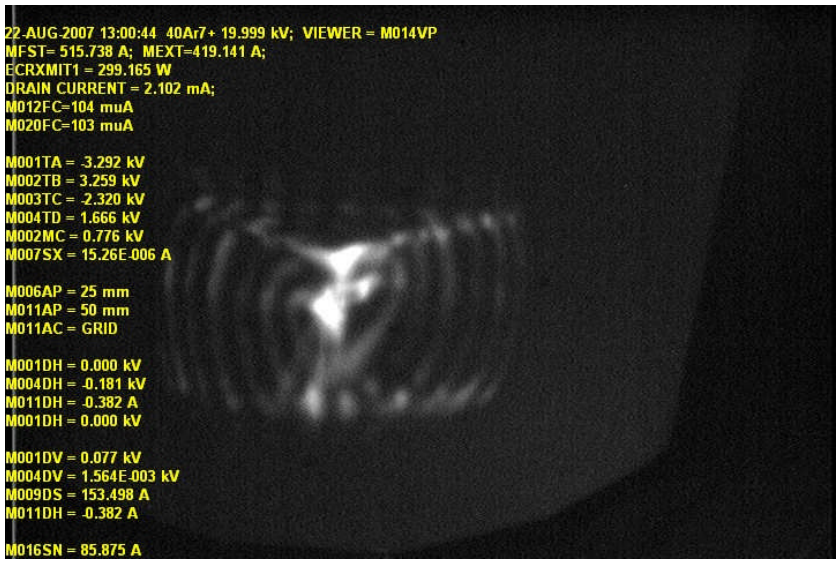


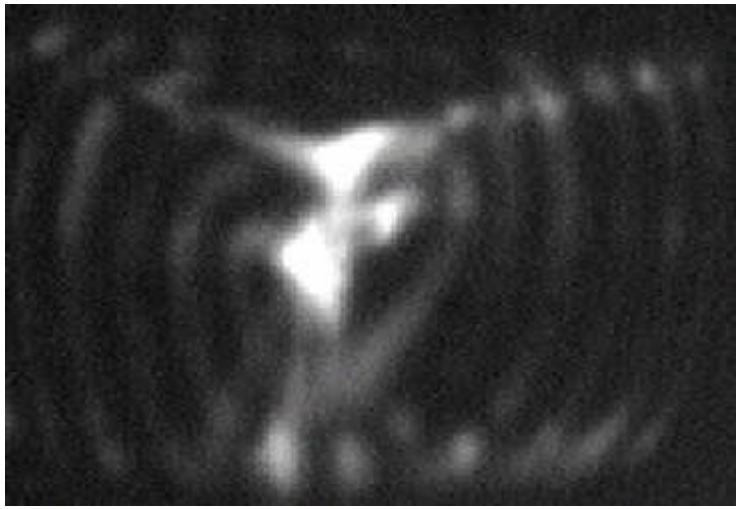




Interesting …

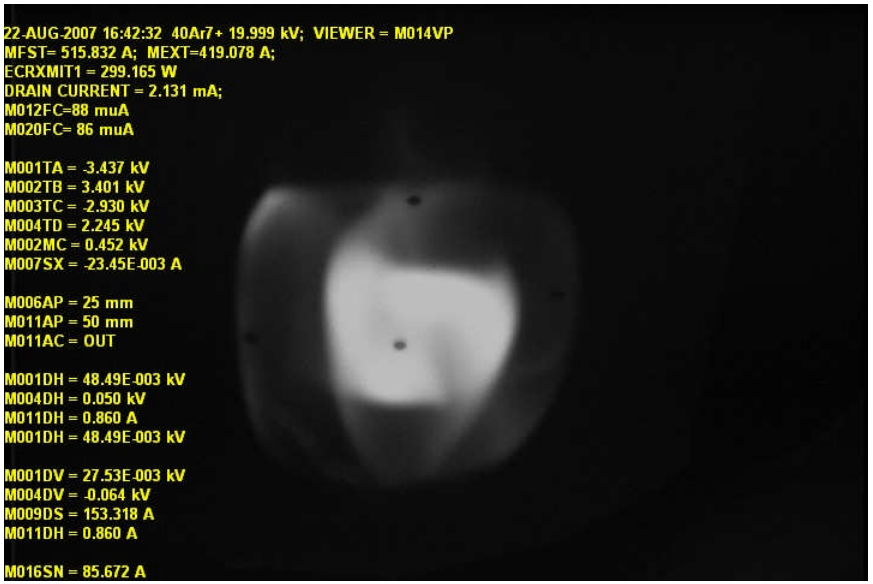






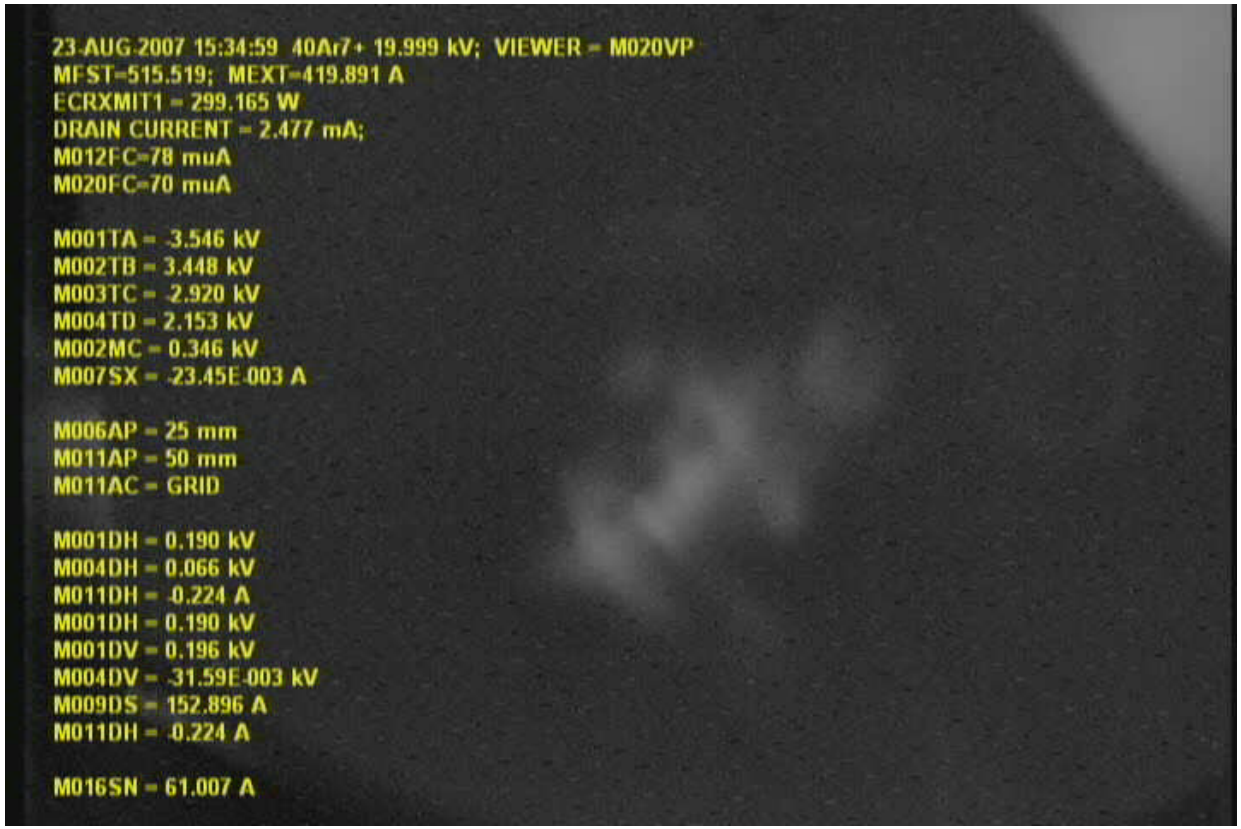
Expanded View

Then Pi-Phase Advance Optics … (Sextupole Off)

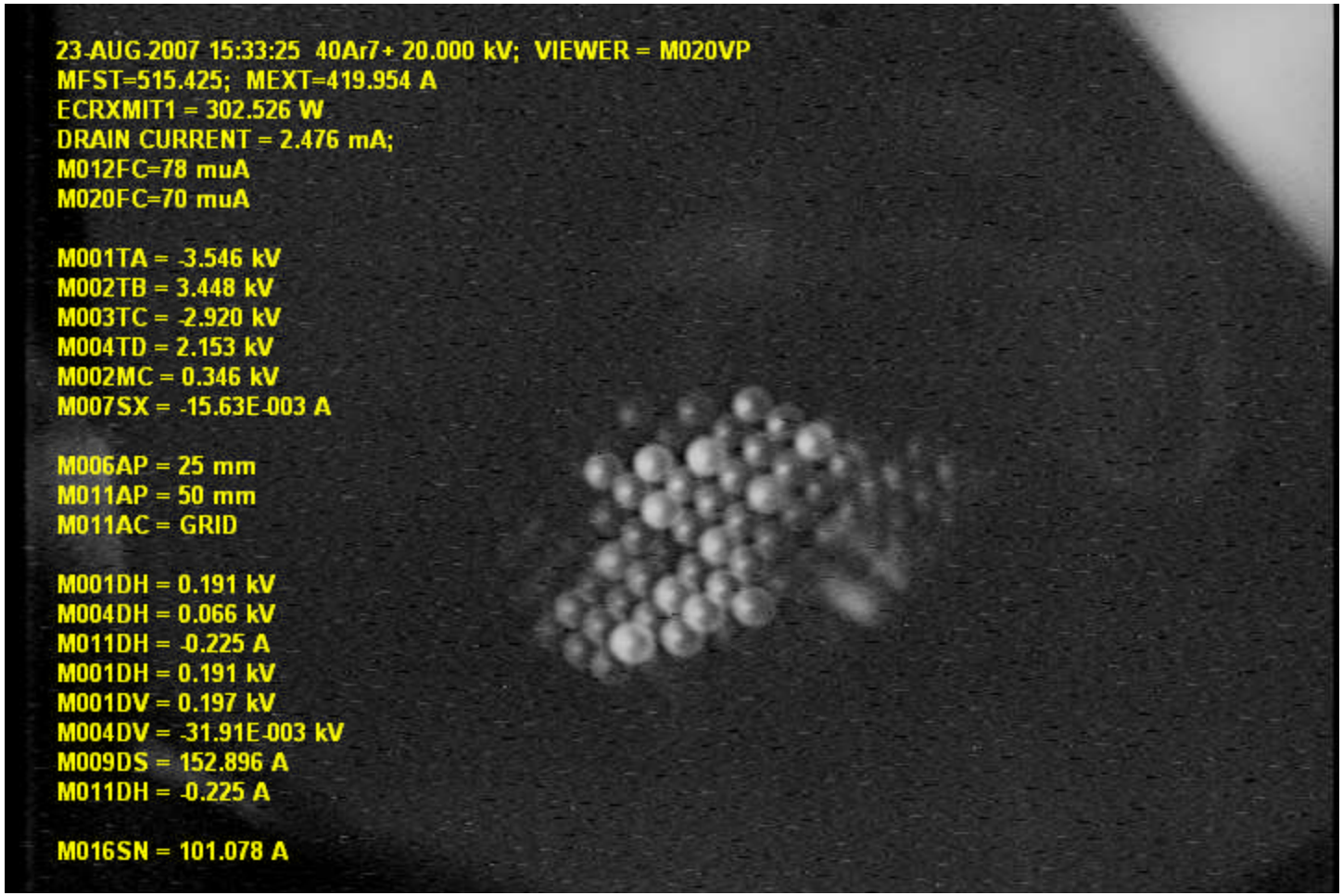


"Organized" Core!

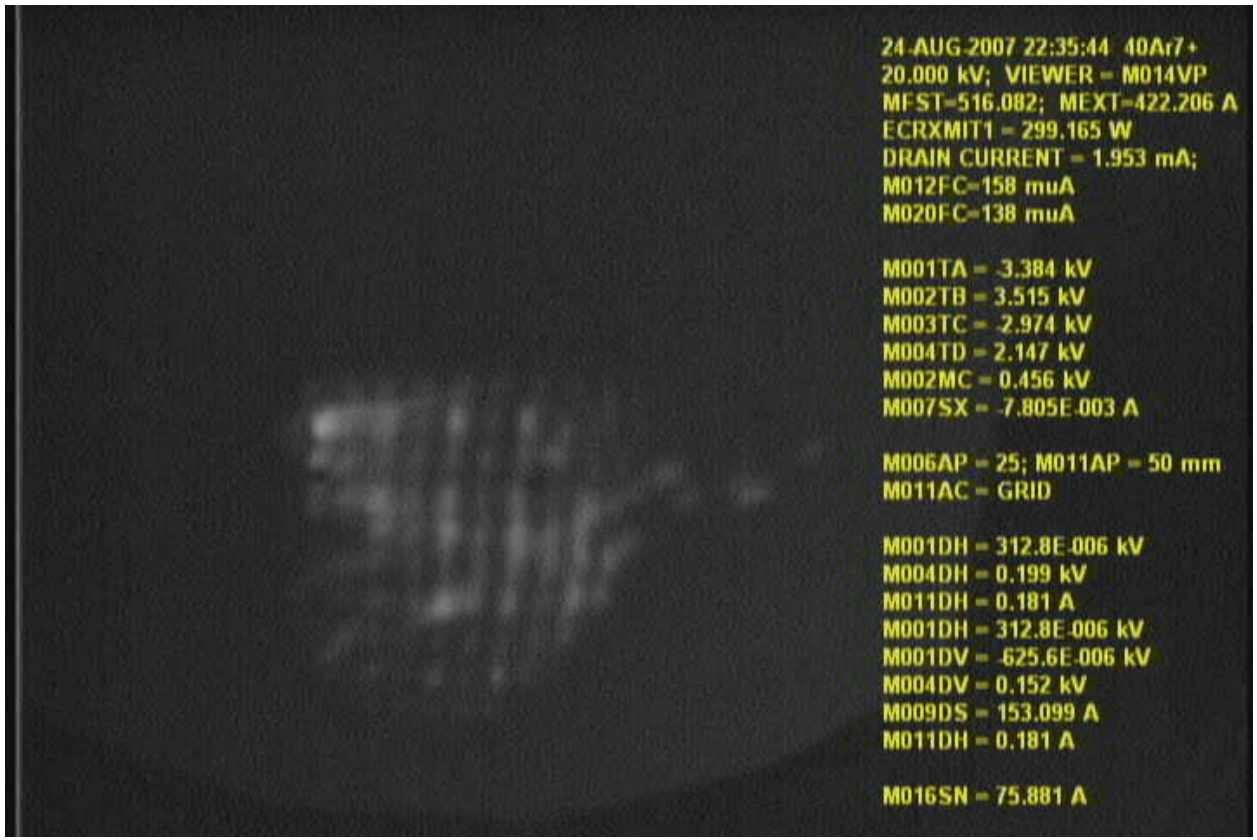
Transmit Grid-Pattern to 2nd Viewer



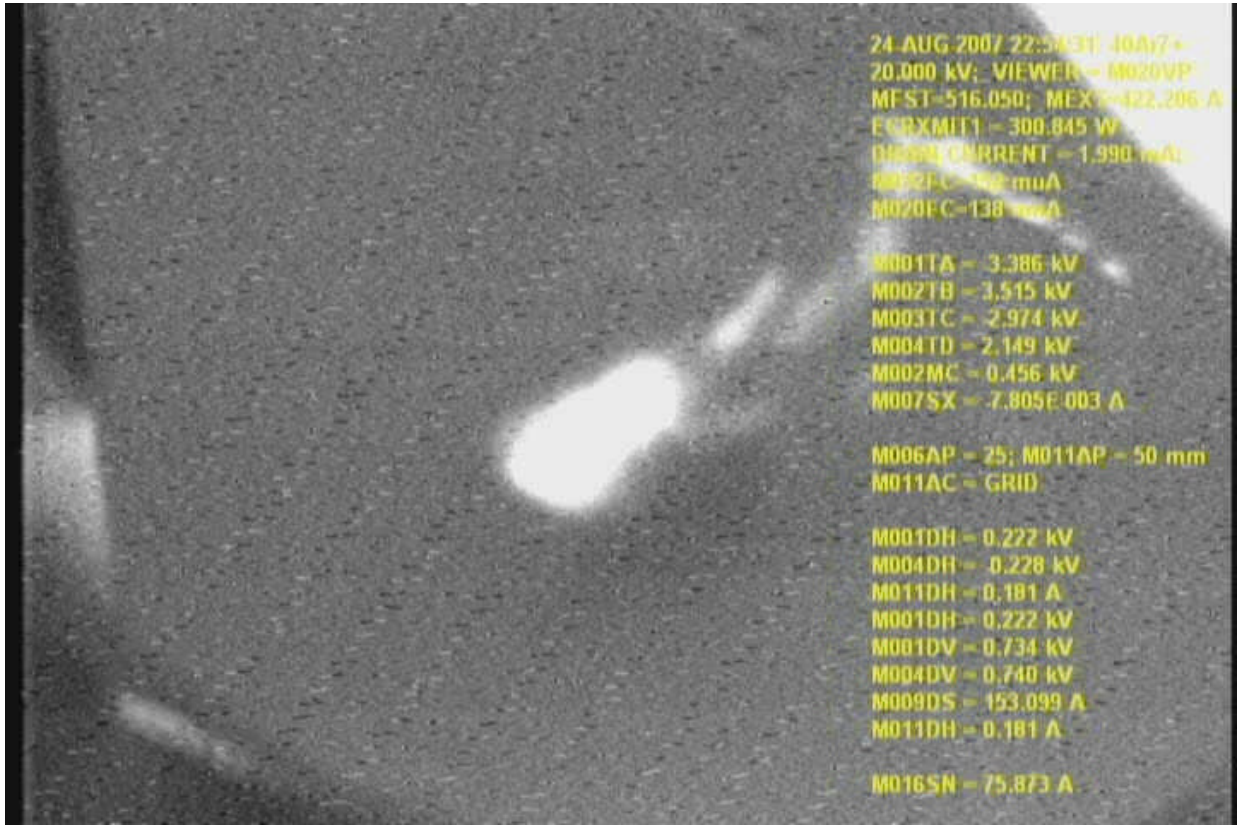
Bubble Beam


23-AUG-2007 15:33:25 40Ar7+ 20.000 kV; VIEWER = M020VP
MFST=515.425; MEXT=419.954 A
ECRXMIT1 = 302.526 W
DRAIN CURRENT = 2.476 mA;
M012FC=78 muA
M020FC=70 muA
M001TA = -3.546 kV
M002TB = 3.448 kV
M003TC = -2.920 kV
M004TD = 2.153 kV
M002MC = 0.346 kV
M007SX = -15.63E-003 A
M006AP = 25 mm
M011AP = 50 mm
M011AC = GRID
M001DH = 0.191 kV
M004DH = 0.066 kV
M011DH = -0.225 A
M001DH = 0.191 kV
M001DV = 0.197 kV
M004DV = -31.91E-003 kV
M009DS = 152.896 A
M011DH = -0.225 A
M016SN = 101.078 A

Try the Sextupole (1st Viewer)



Try the Sextupole (2nd Viewer)



The External Sextupole “brings in” highly aberrated beam, but doesn’t affect the “core”at all(!)

A Test of 2nd Order Correction Scheme

→Results not as anticipated,

(Possibly due to 3rd order effects from the quads.)

However:

→There seems to be a relatively intense part of the beam that is essentially Uncorrelated(!)

Lucky Break?

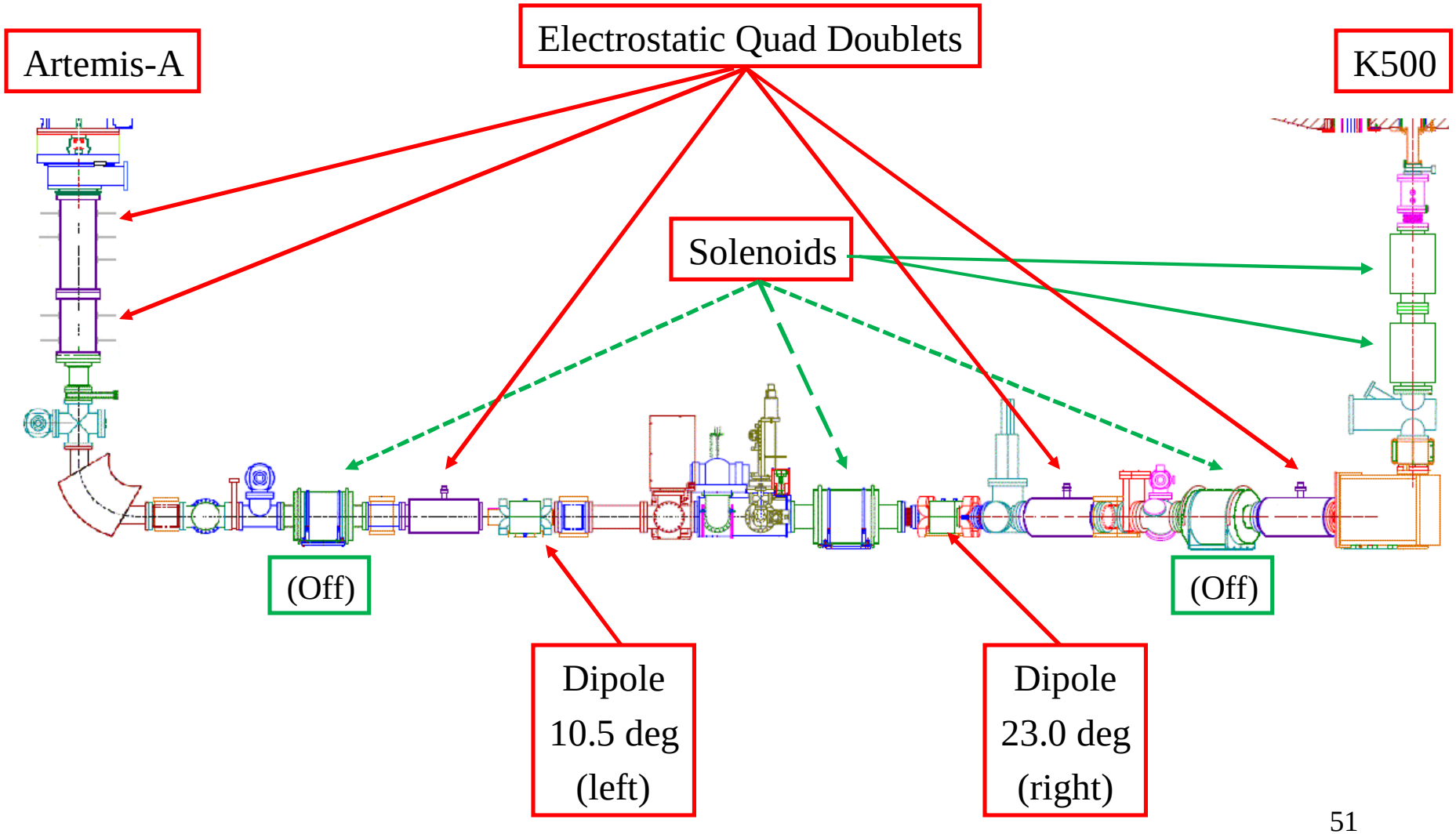
The “Why” is not known,

But

Can this “core” effect be used?

(Ultra) Low Emittance Tune for Inj. Line Artemis-A

Optical Elements



Magic Electrostatic Lens System:

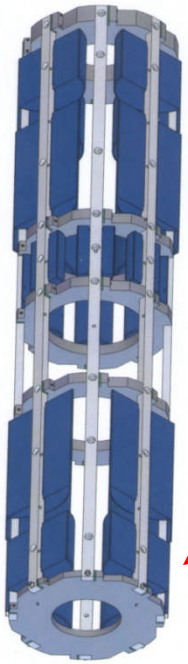
(can give a 90 Deg Phase Advance from

ECRIS Sextupole to an External Sextupole)

Quadrupole Doublet

Octupole

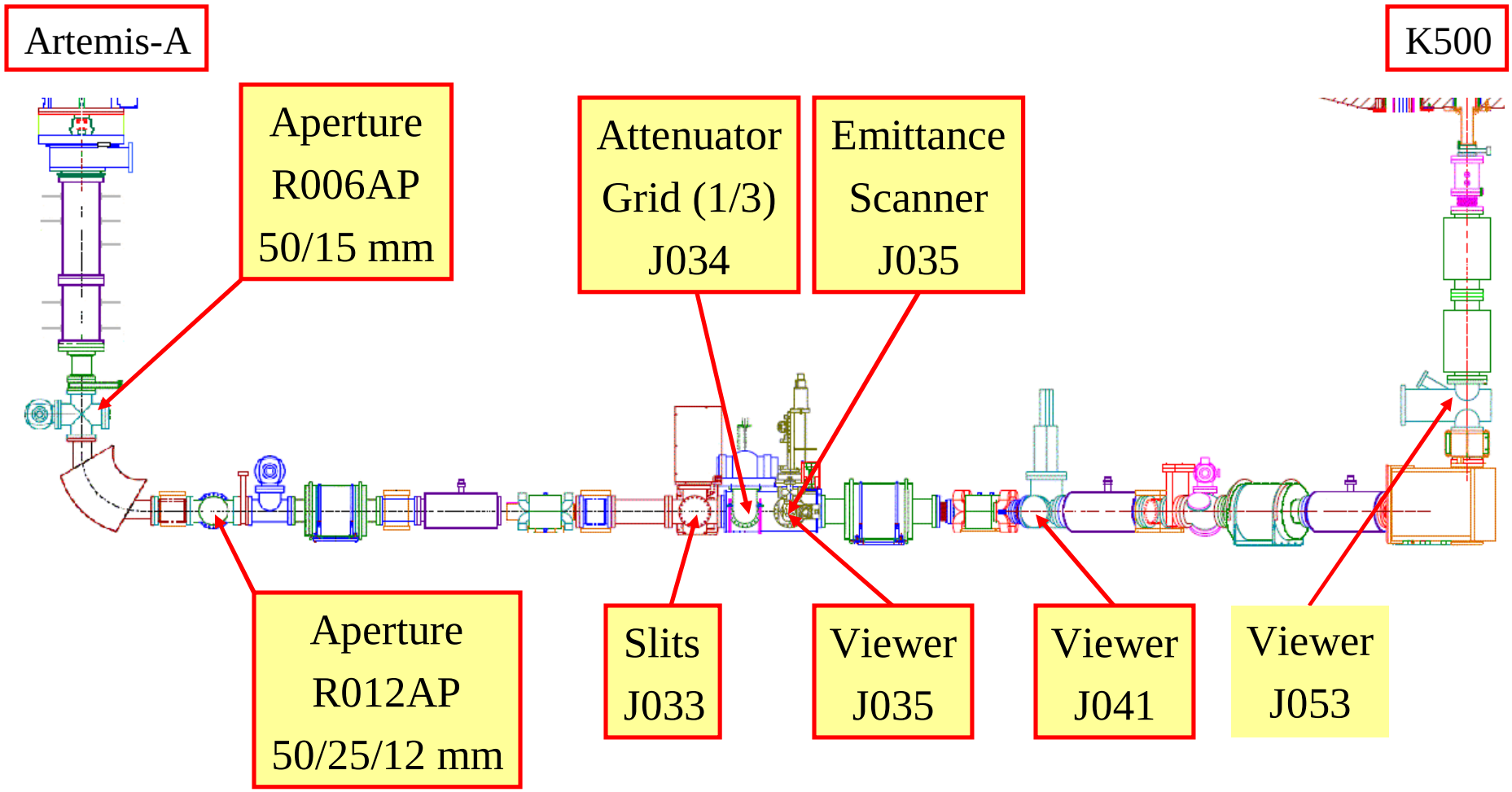
Quadrupole Doublet



Hz and Vt Steering built into first and last lens elements

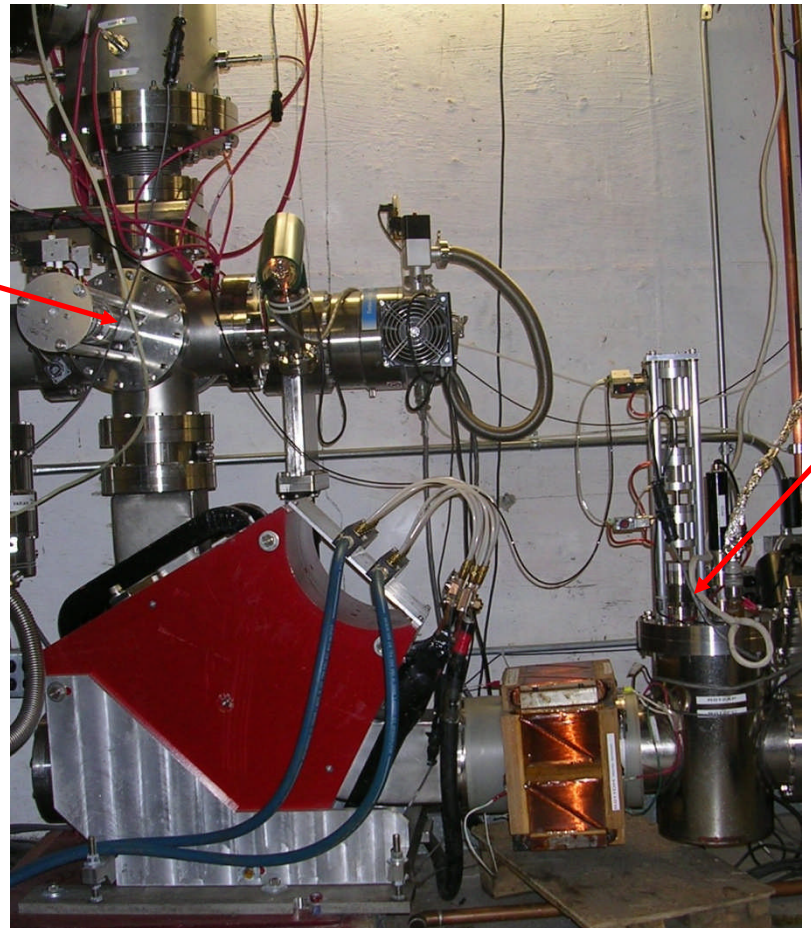
National Electrostatics Corporation calls it: The “Odd Duck”

Devices


Artemis-A
K500
Aperture
R006AP
50/15 mm
Attenuator
Grid (1/3)
J034
Emittance
Scanner
J035
Aperture
R012AP
50/25/12 mm
Slits
J033
Viewer
J035
Viewer
J041
Viewer
J053

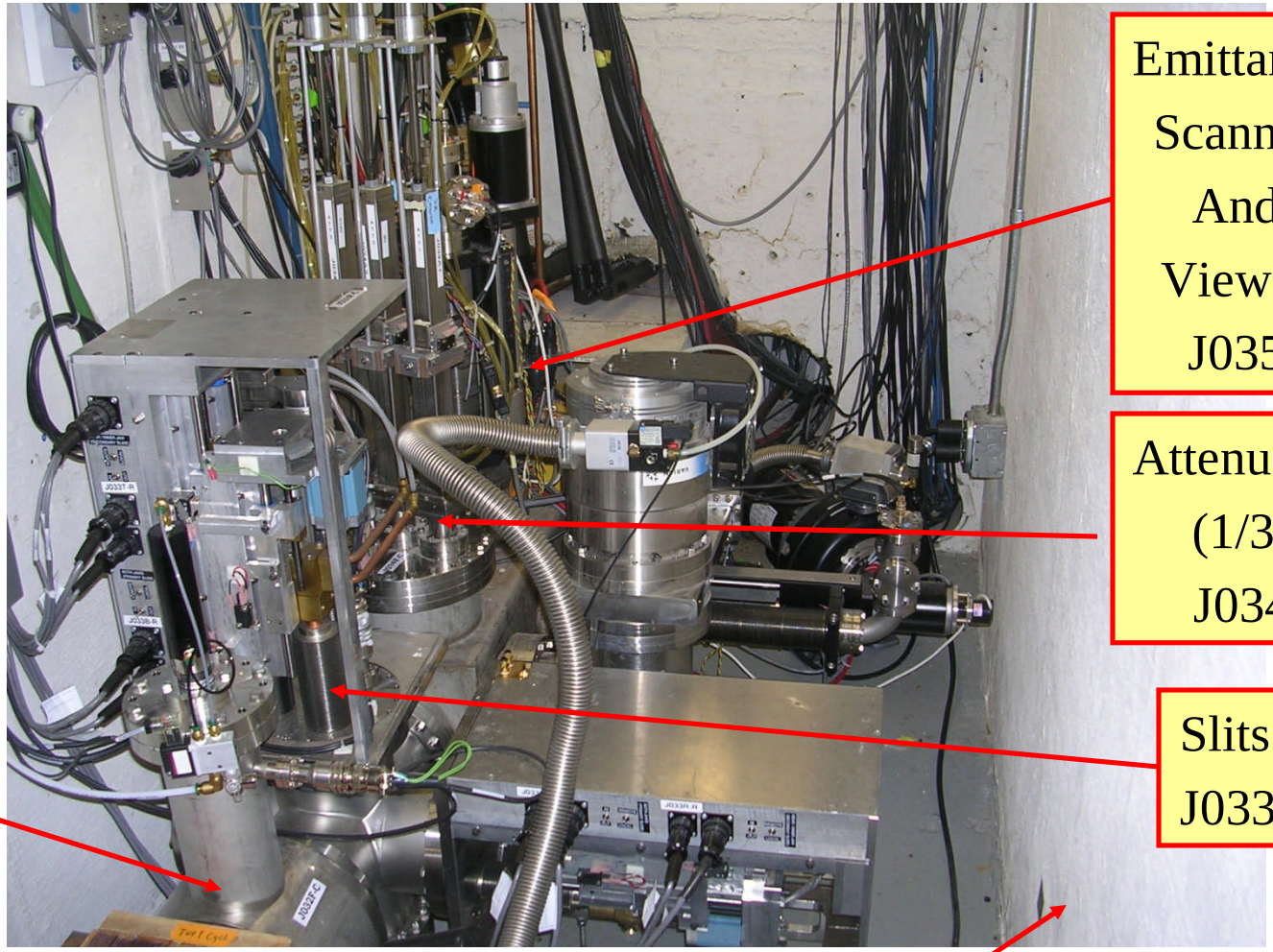
Analysis Magnet + Apertures

Aperture
R006AP
50/15 mm



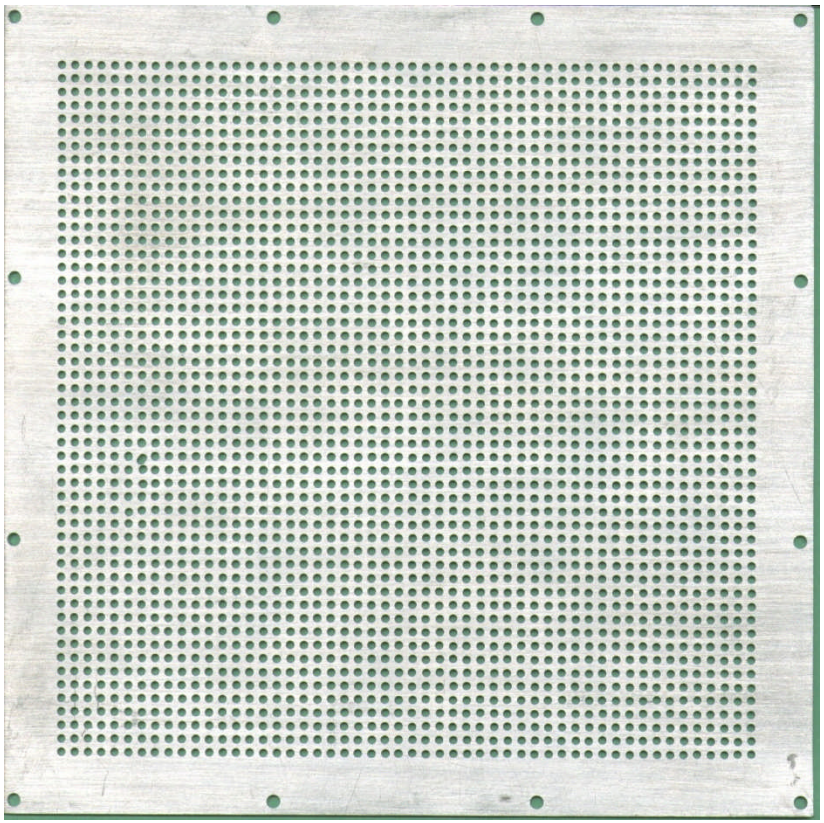
Aperture
R012AP
50/25/12 mm

Diagnostic Box ~J034



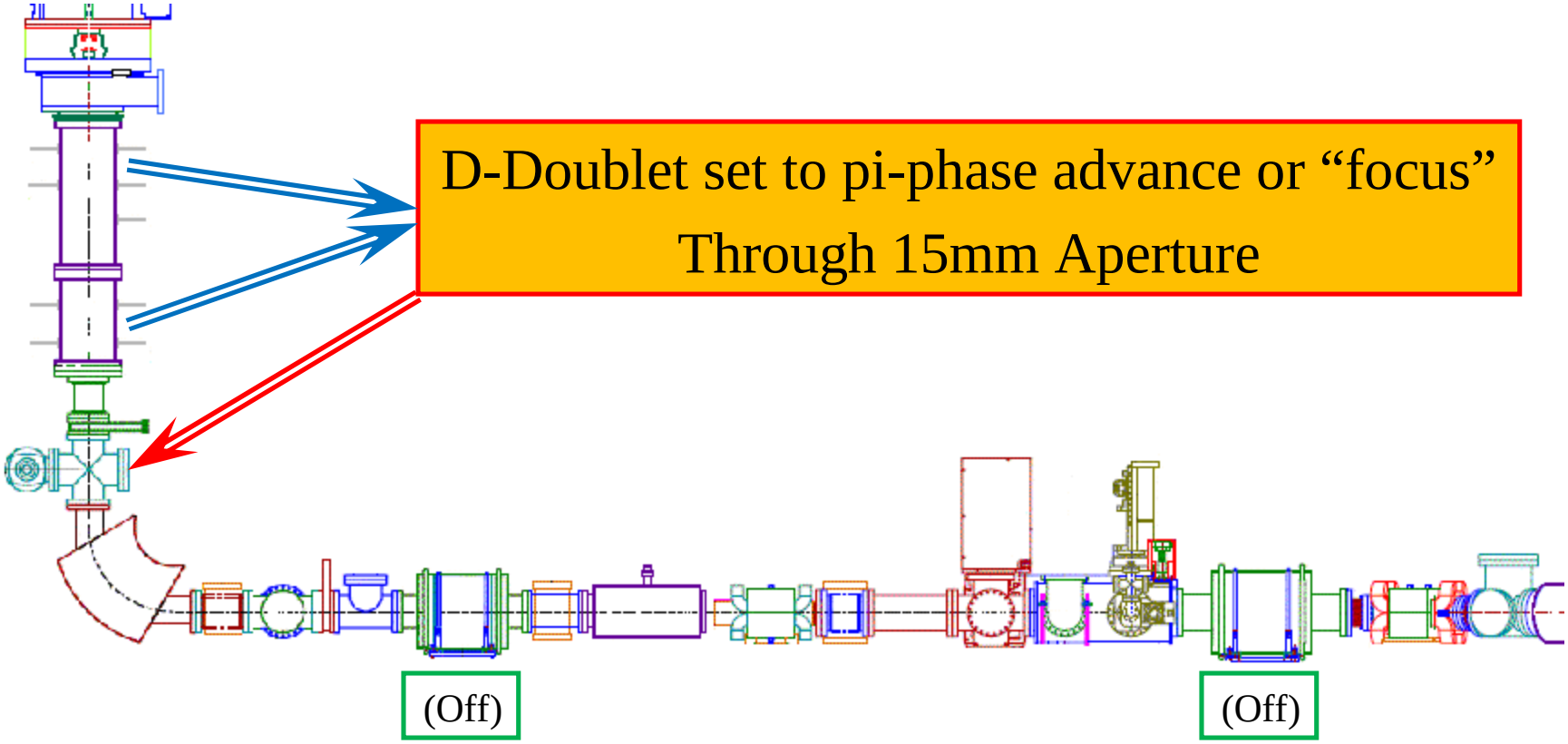
Beam Attenuator Plate (x 1/3)

15 cm

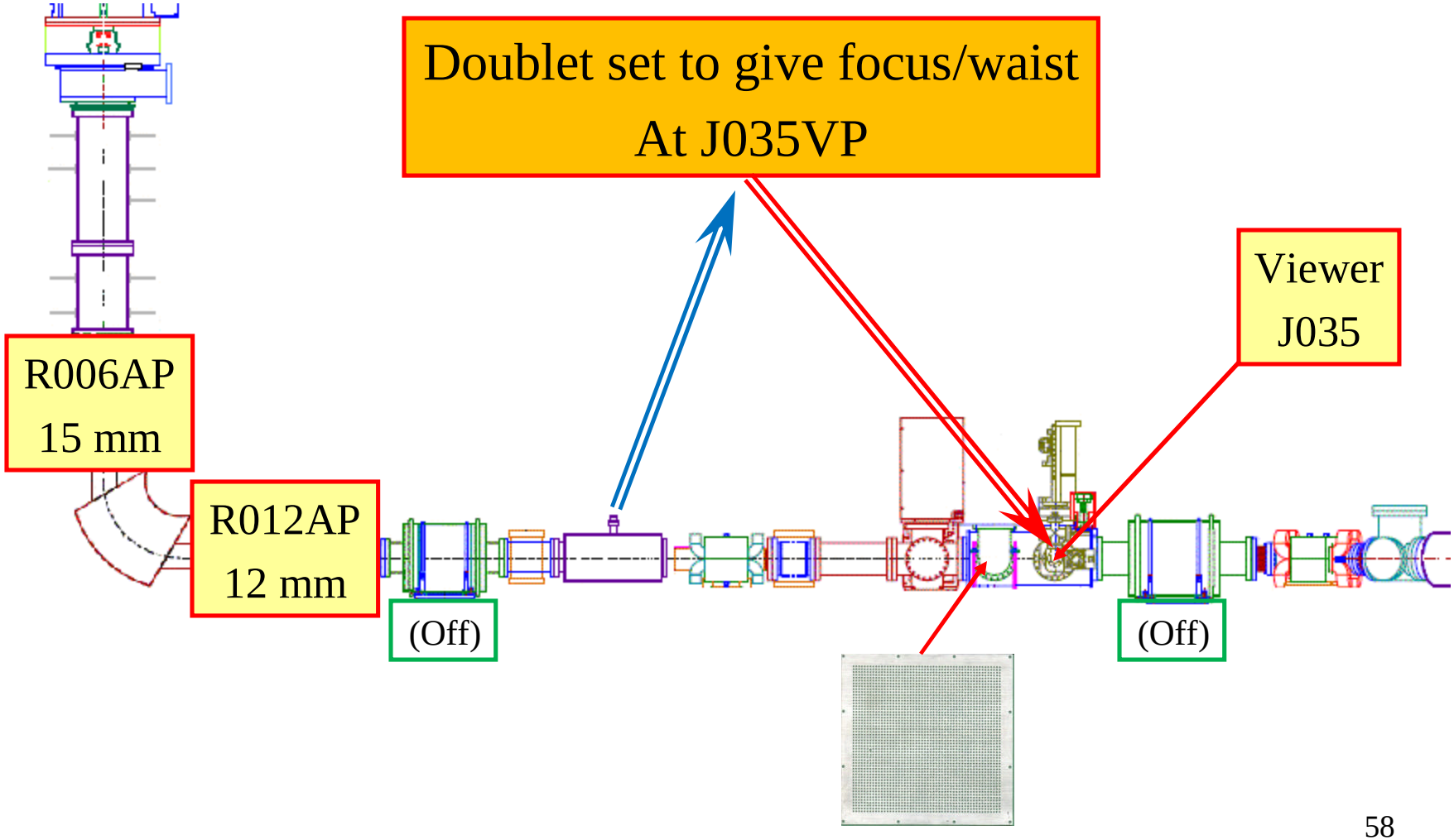


~1 mm diameter Holes
~2.5mm Center-to-center

Step 1

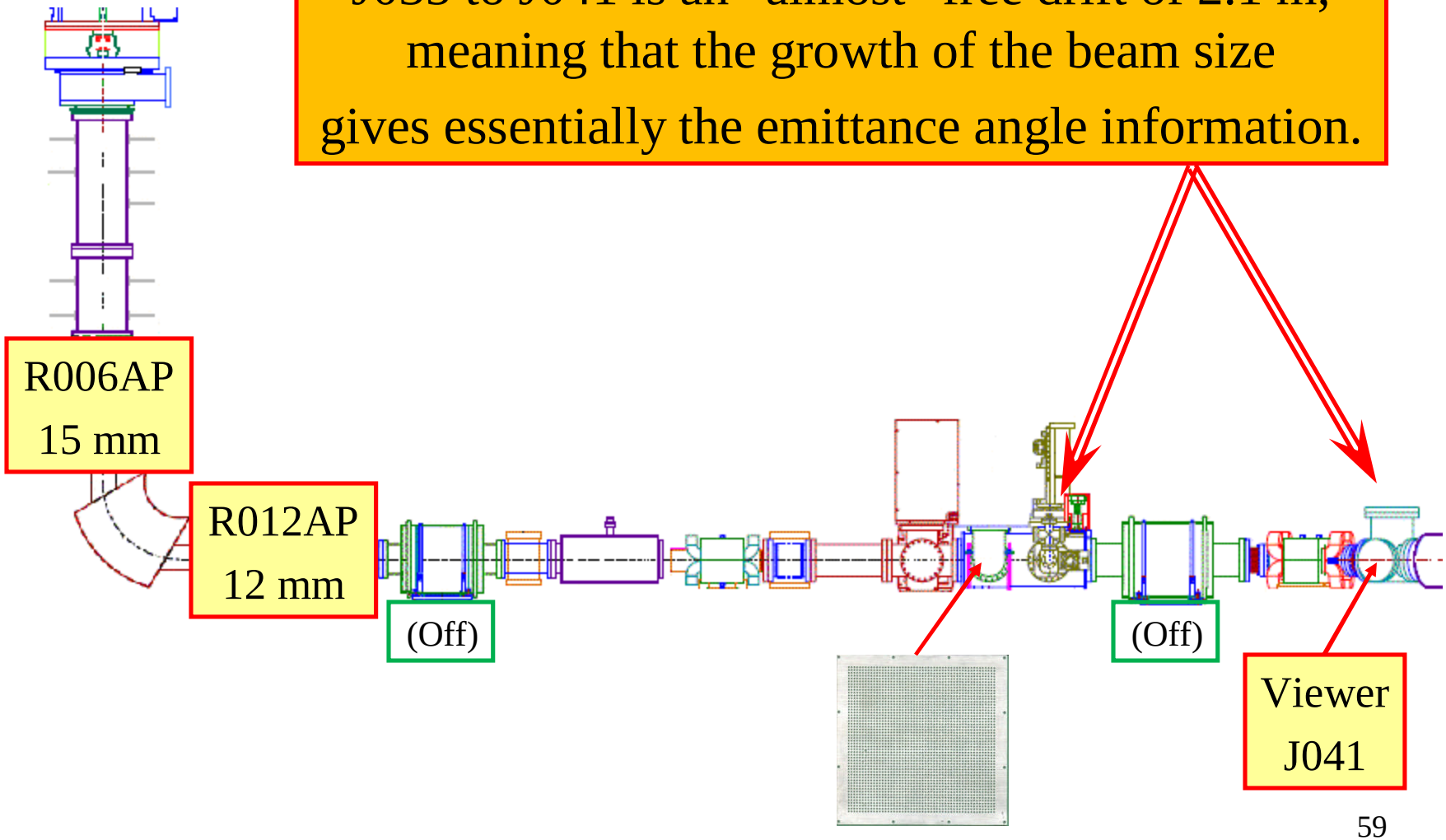

D-Doublet set to pi-phase advance or “focus”
Through 15mm Aperture
(Off)
(Off)

Step 2


Doublet set to give focus/waist
At J035VP
Viewer
J035
R006AP
15 mm
R012AP
12 mm
(Off)
(Off)

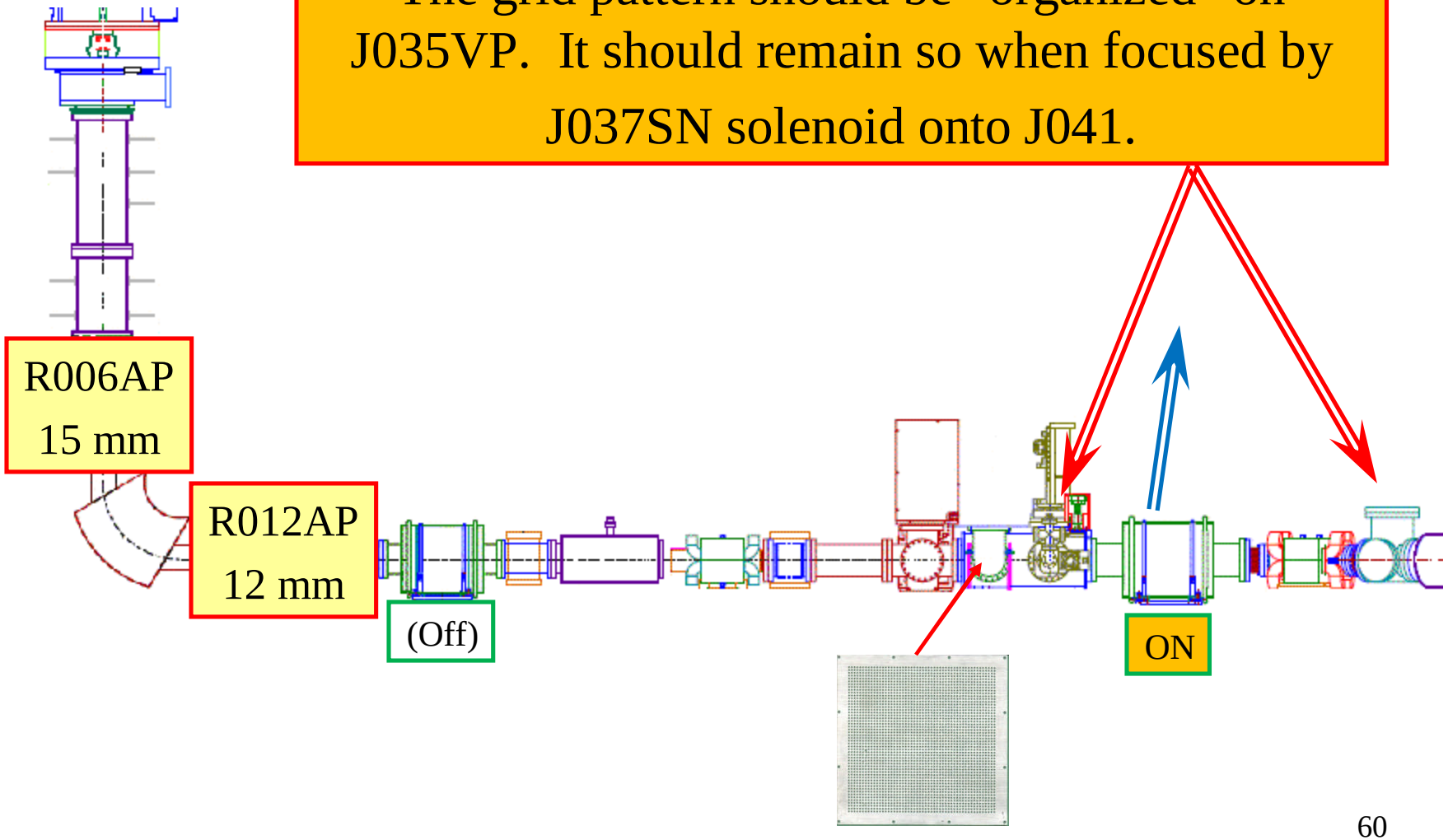
Step 3

J035 to J041 is an “almost” free drift of 2.1 m, meaning that the growth of the beam size gives essentially the emittance angle information.



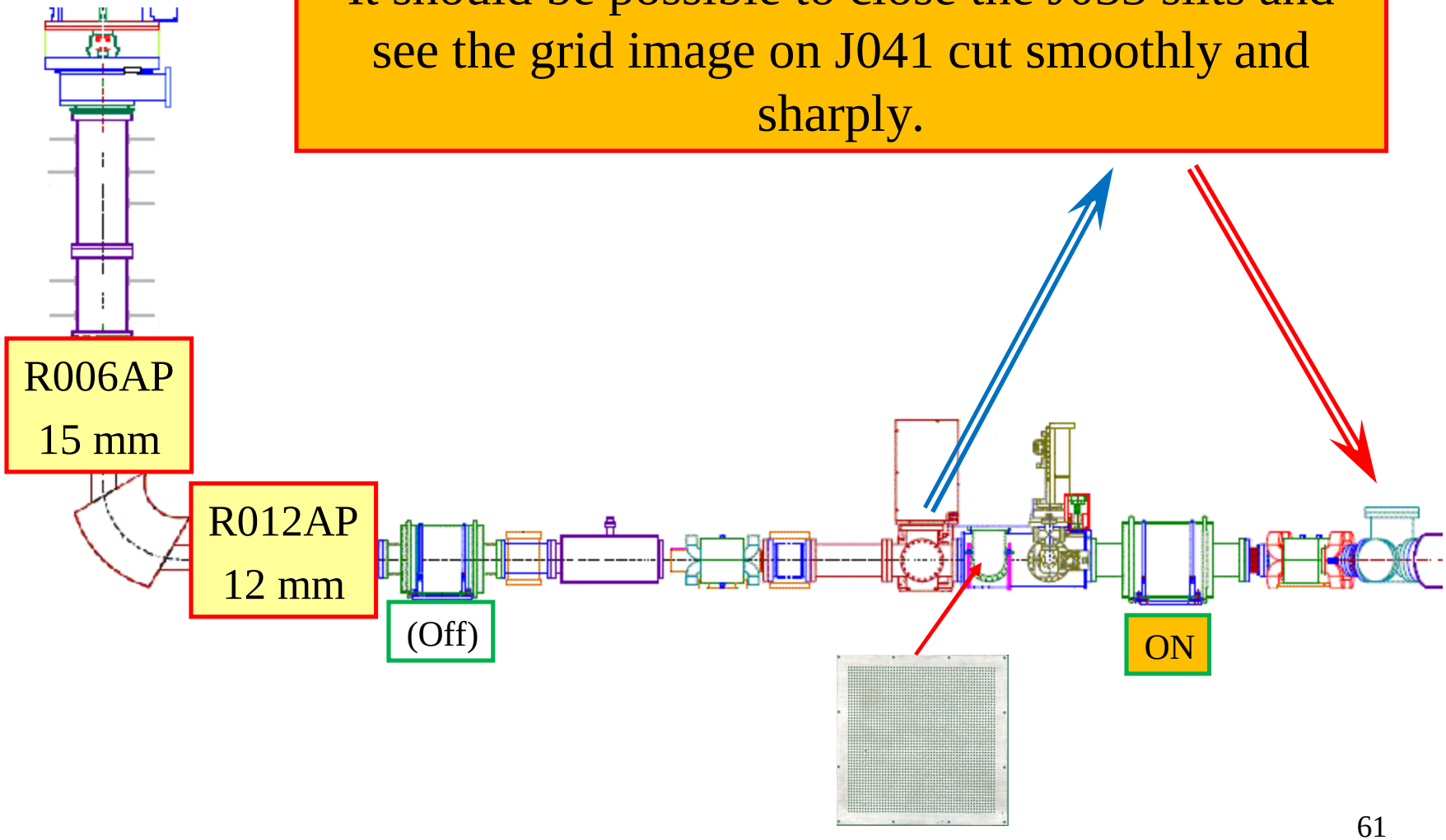
Step 4

The grid pattern should be “organized” on J035VP. It should remain so when focused by J037SN solenoid onto J041.



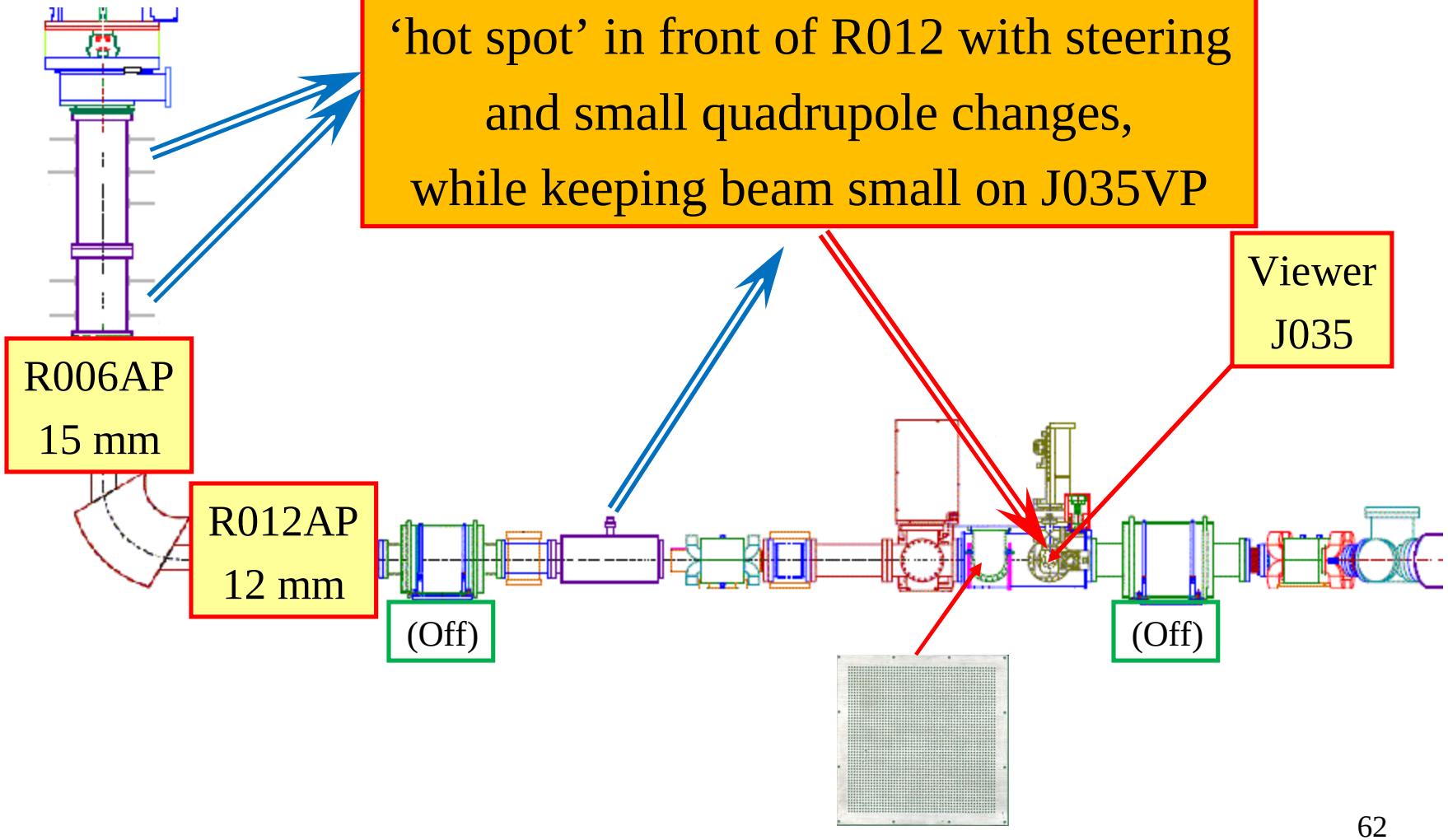
Step 5

It should be possible to close the J033 slits and see the grid image on J041 cut smoothly and sharply.

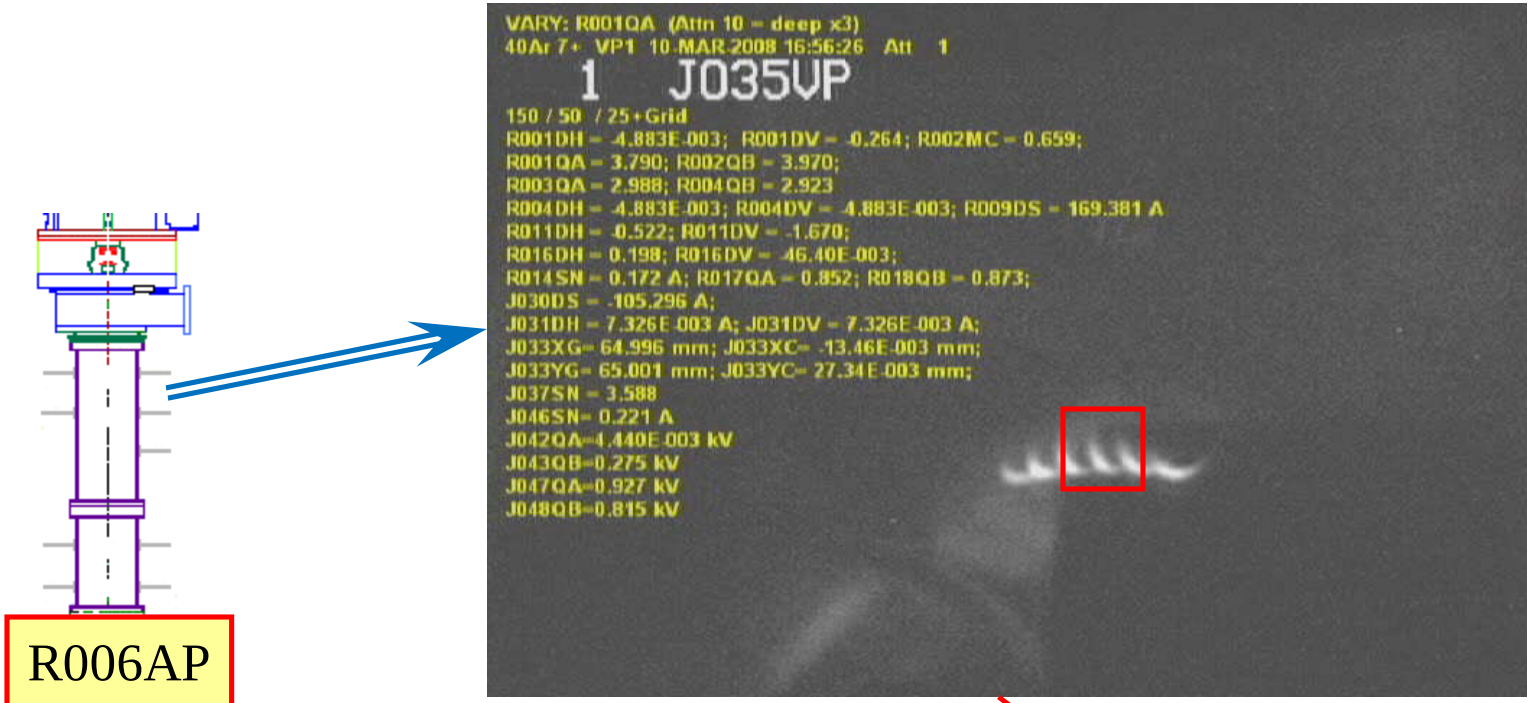


Step 6

If improvement is needed, search for the 'hot spot' in front of R012 with steering and small quadrupole changes, while keeping beam small on J035VP



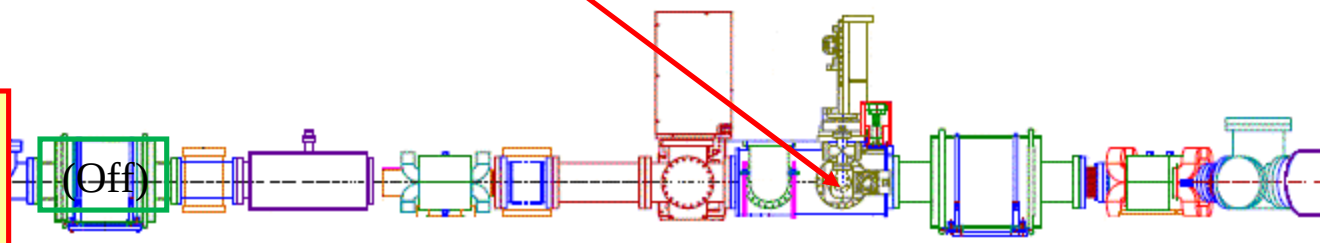
Vary R001QA (Grid at R012)

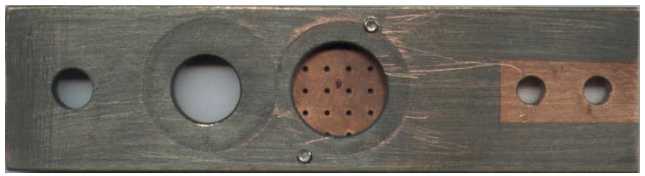


$^{40}Ar^{7+}$

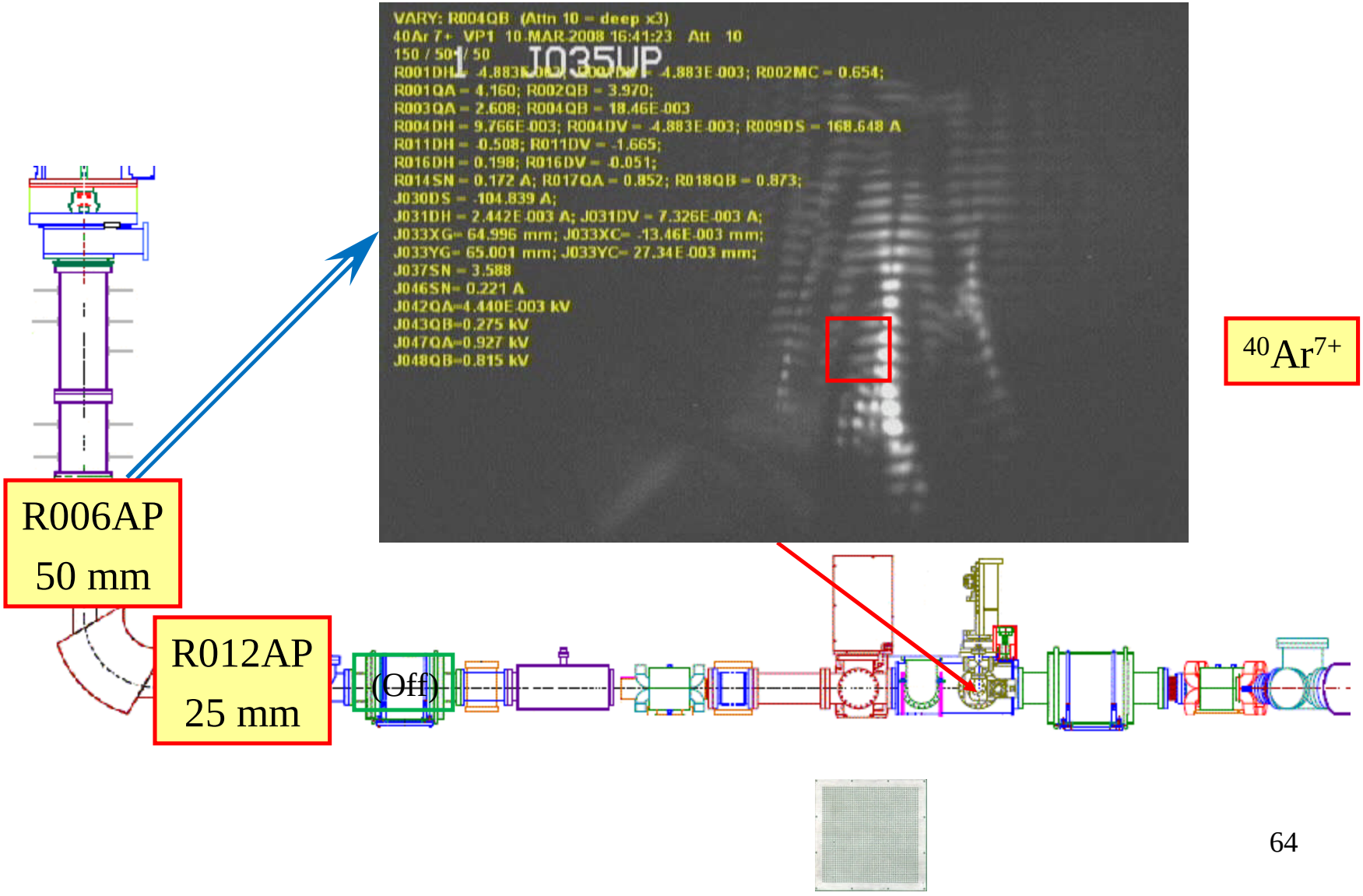
R006AP
50 mm

R012AP
25 mm



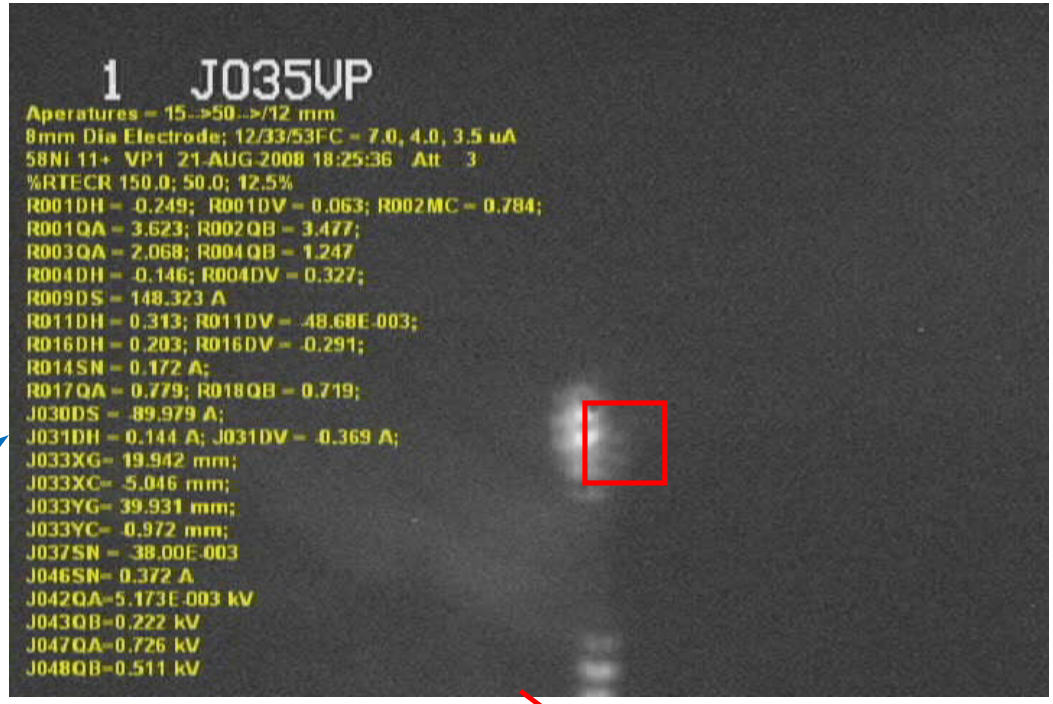


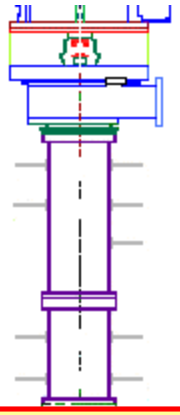
Vary R004QA


VARY: R004QB (Attn 10 = deep x3)
40Ar 7+ VP1 10-MAR-2008 16:41:23 Att 10
150 / 501 / 50
J035VP
R001DH = -4.883E-003; R002DV = -4.883E-003; R002MC = 0.654;
R001QA = 4.160; R002QB = 3.970;
R003QA = 2.608; R004QB = 18.46E-003
R004DH = 9.766E-003; R004DV = -4.883E-003; R009DS = 168.648 A
R011DH = -0.508; R011DV = -1.665;
R016DH = 0.198; R016DV = -0.051;
R014SN = 0.172 A; R017QA = 0.852; R018QB = 0.873;
J030DS = -104.839 A;
J031DH = 2.442E-003 A; J031DV = 7.326E-003 A;
J033XG= 64.996 mm; J033XC= -13.46E-003 mm;
J033YG= 65.001 mm; J033YC= 27.34E-003 mm;
J037SN = 3.588
J046SN= 0.221 A
J042QA=4.440E-003 kV
J043QB=0.275 kV
J047QA=0.927 kV
J048QB=0.815 kV
$^{40}Ar^{7+}$
R006AP
50 mm
R012AP
25 mm
(Off)

Complication: Space Charge in Dipole?

= 1x1 cm



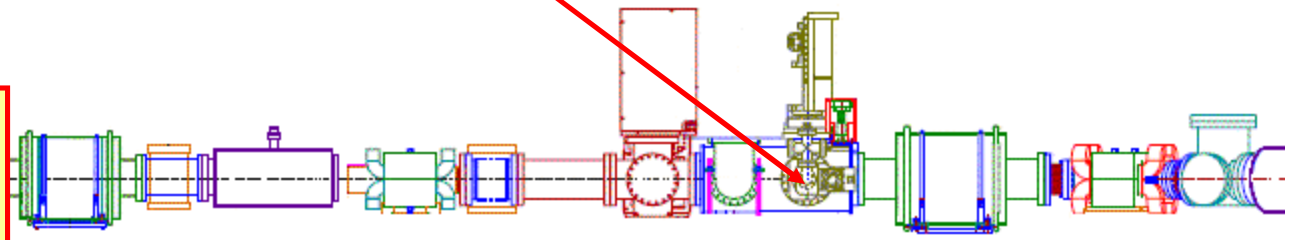


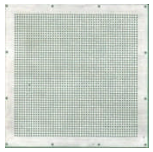
R006AP
15/50 mm

R012AP
12/50 mm

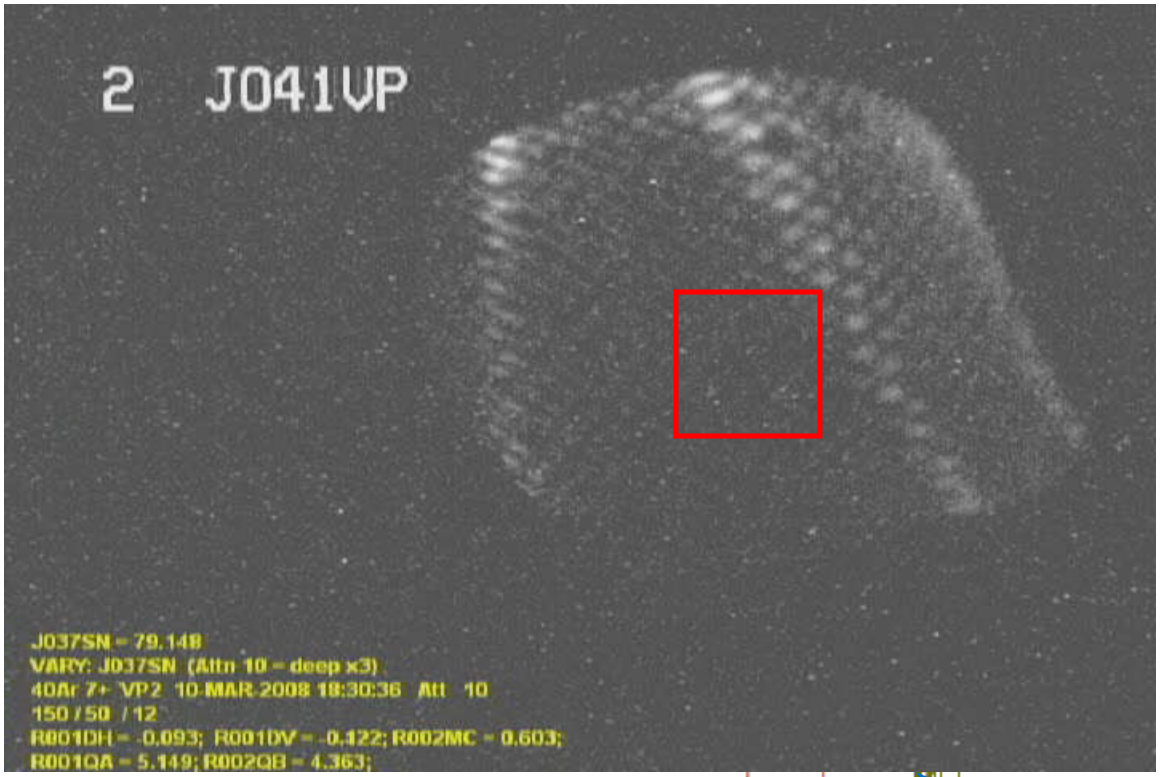
$^{58}Ni^{11+}$

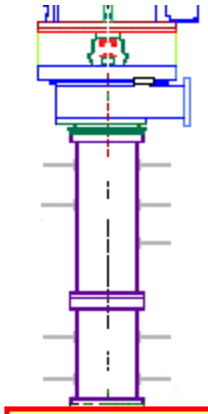
$^{16}O^{3+}$





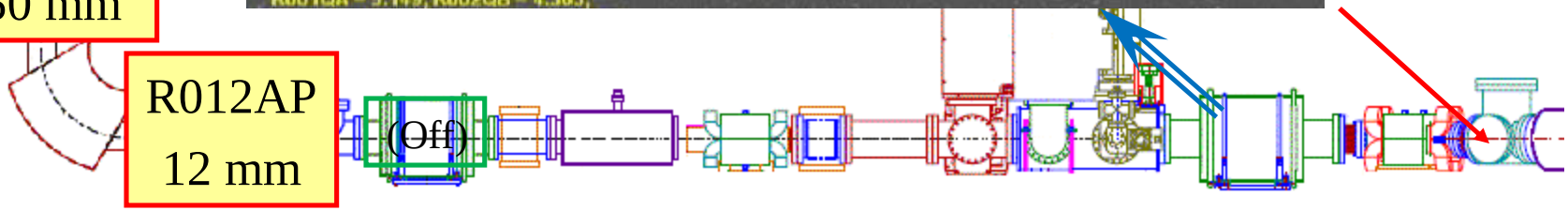
Vary R037SN: Big + Ring-to-Star Tagged (Bad!)





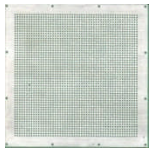
R006AP
50 mm

R012AP
12 mm

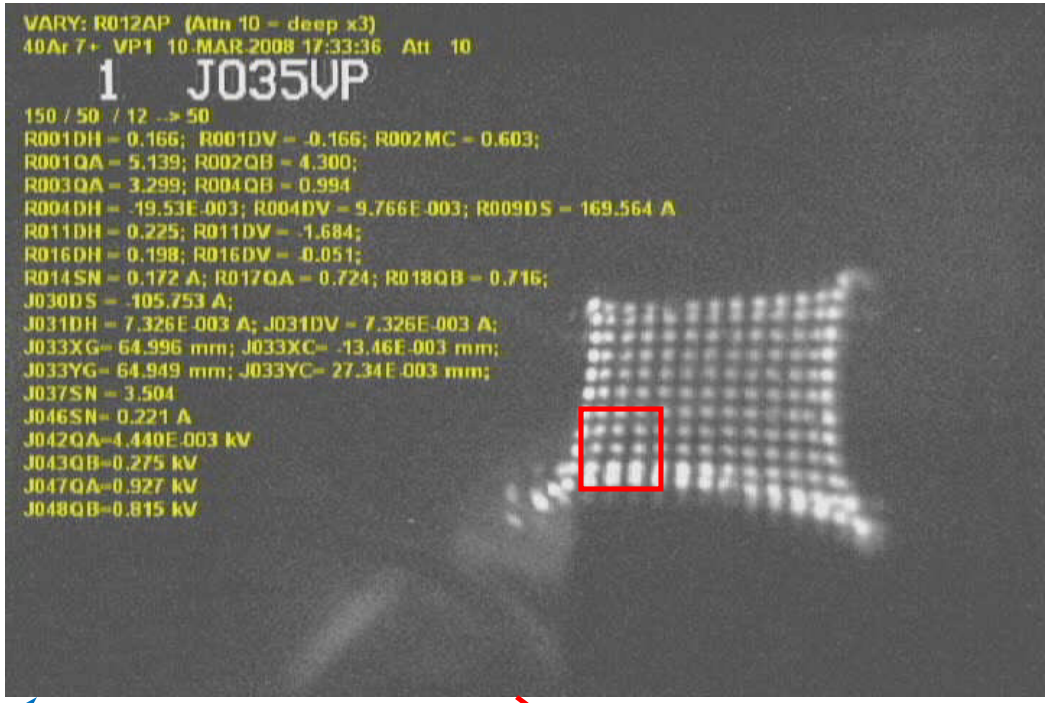


$^{40}Ar^{7+}$

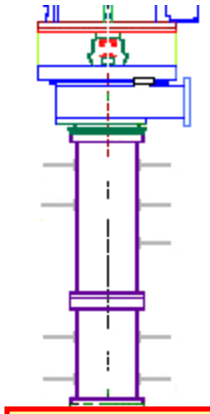
80→120A



(Initially) Better-Looking Tune: Open/Close R012AP

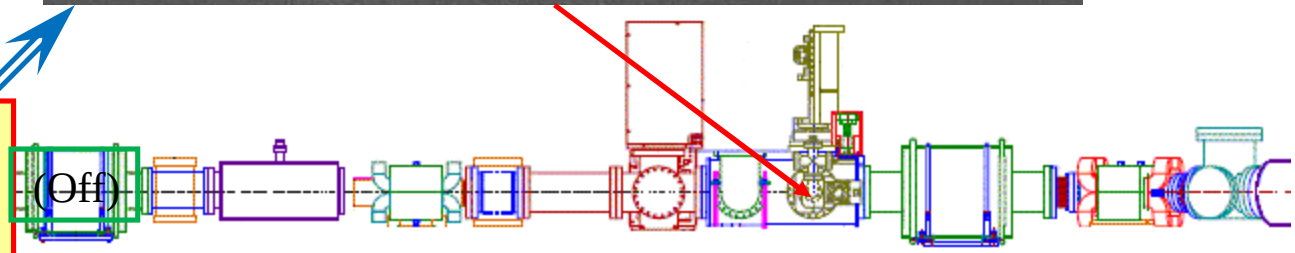


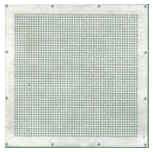
$^{40}Ar^{7+}$



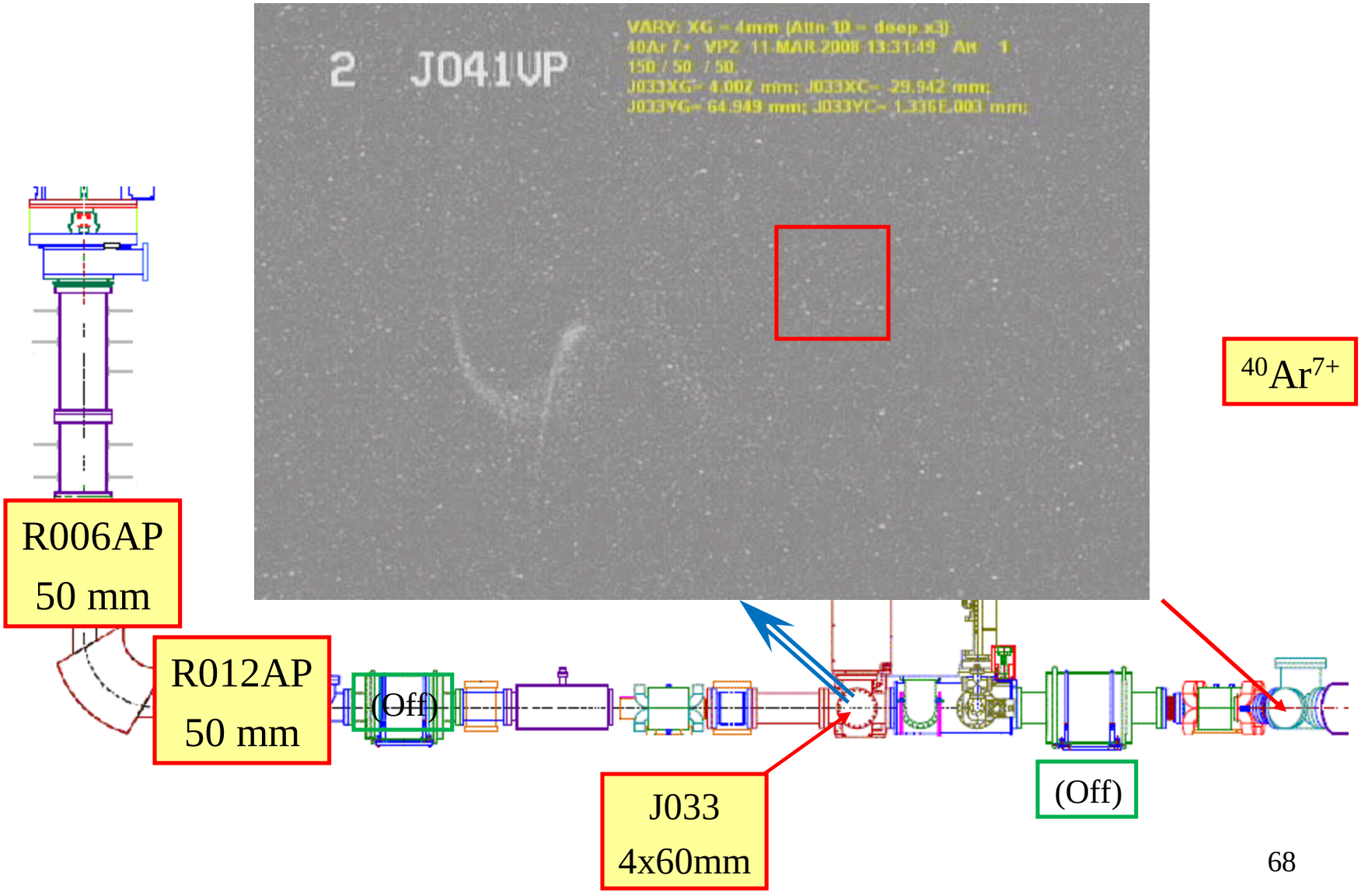
R006AP
50 mm

R012AP
12/50 mm

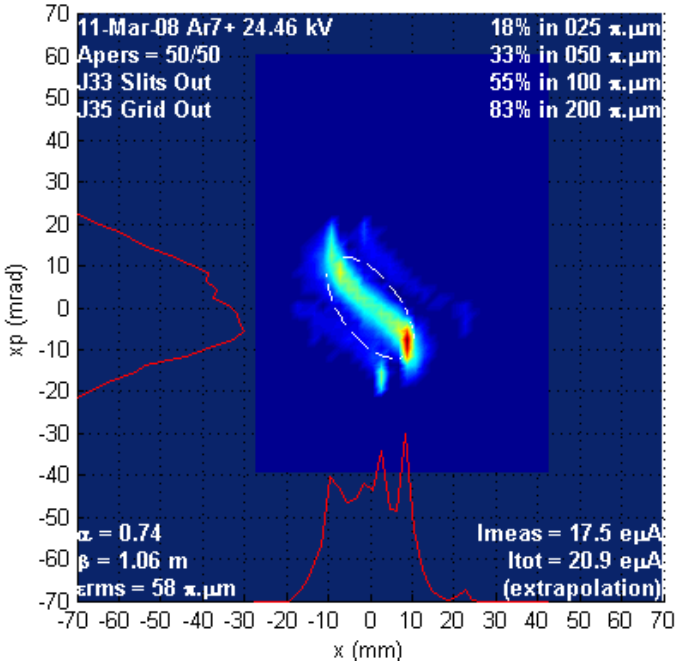


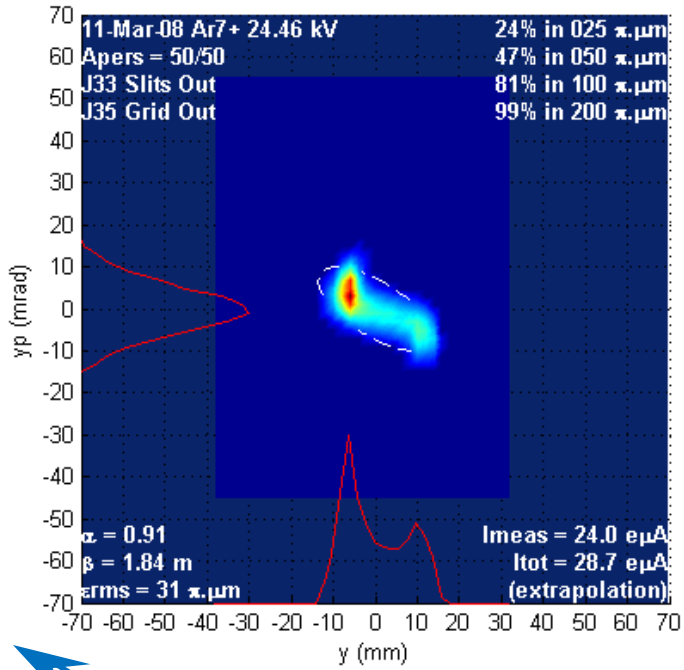


J033 Hz Slit Scan (Width = 4 mm)

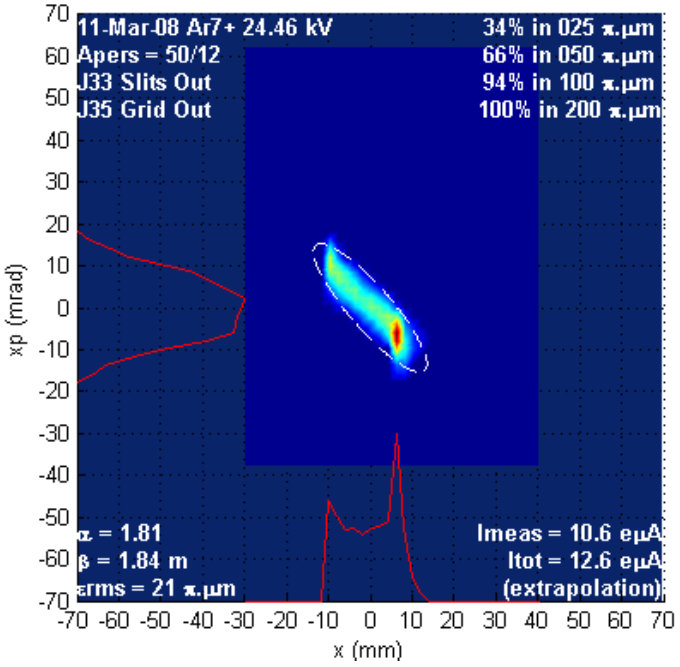


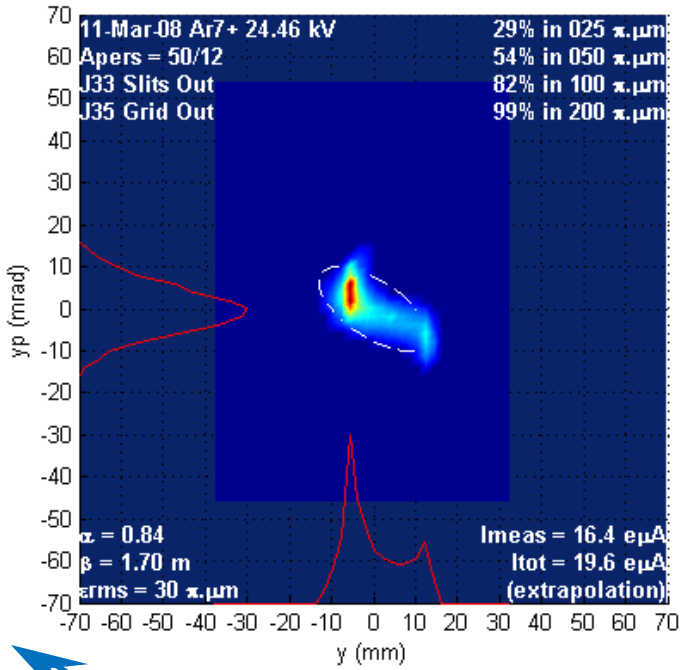
J035 Emittance Scan (Apertures Open)

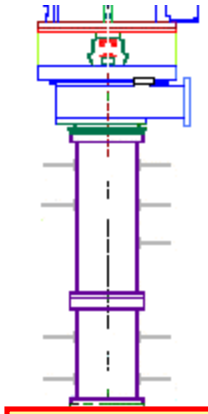




J035 Emittance Scan (R012AP = 12 mm)

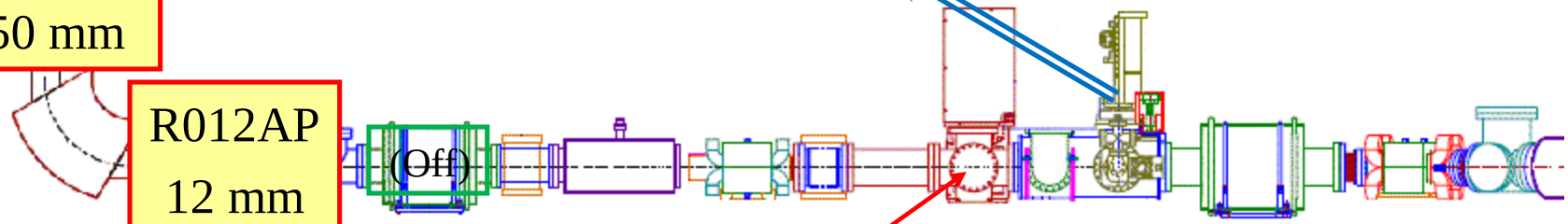






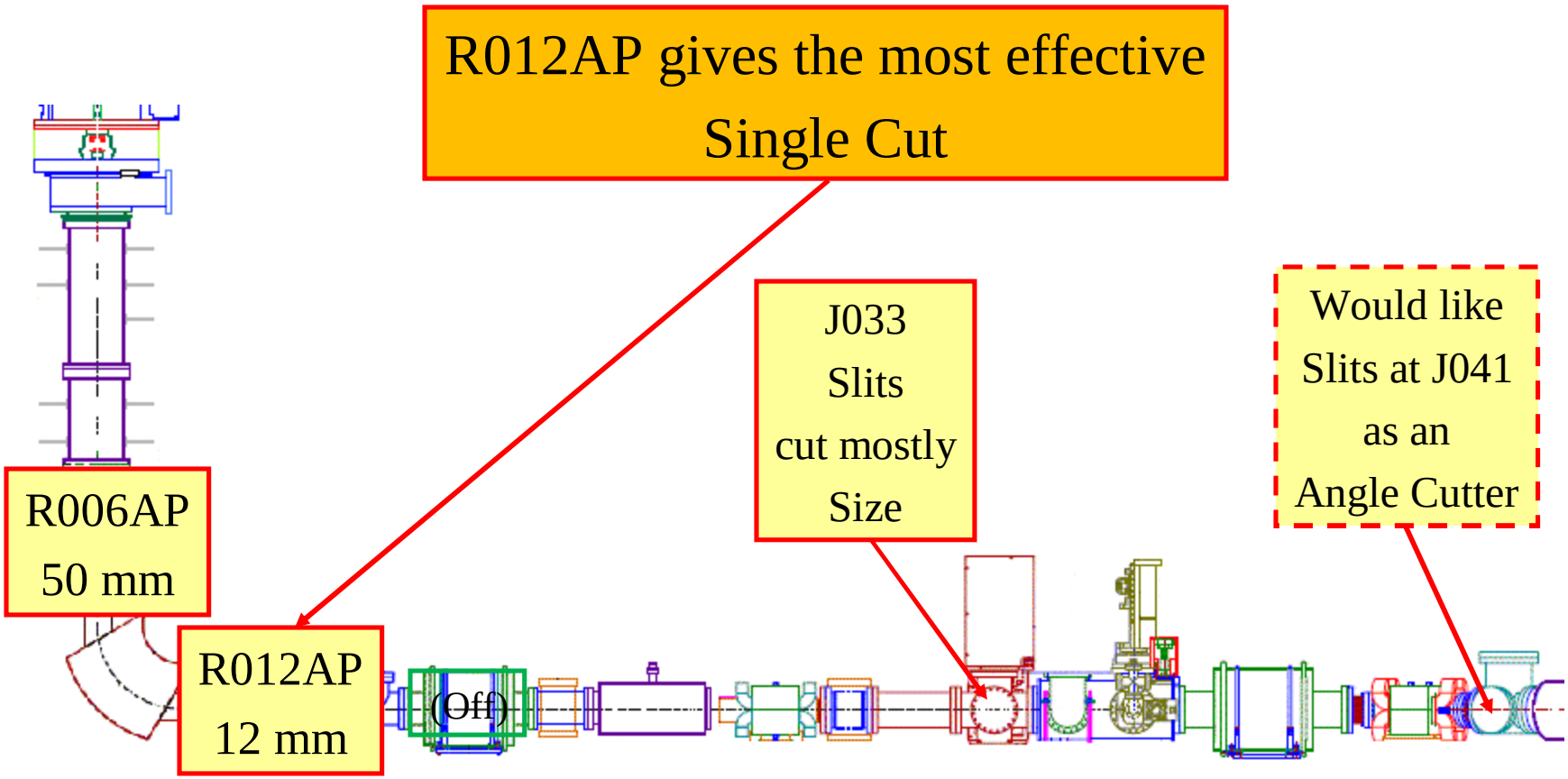
R006AP
50 mm

R012AP
12 mm



J033
60x60mm

Cutting Effectiveness



$^{58}Ni^{11+}$: Normal vs. Low Emittance Tune

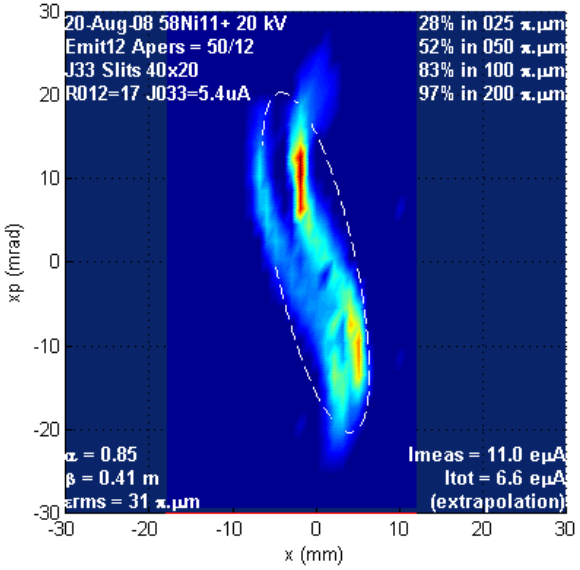
R012 = 17.0 uA; J033 = 5.4 uA

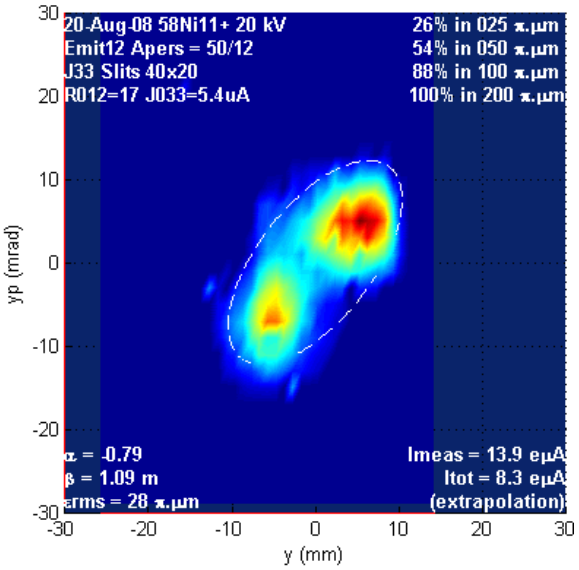
x 2/3

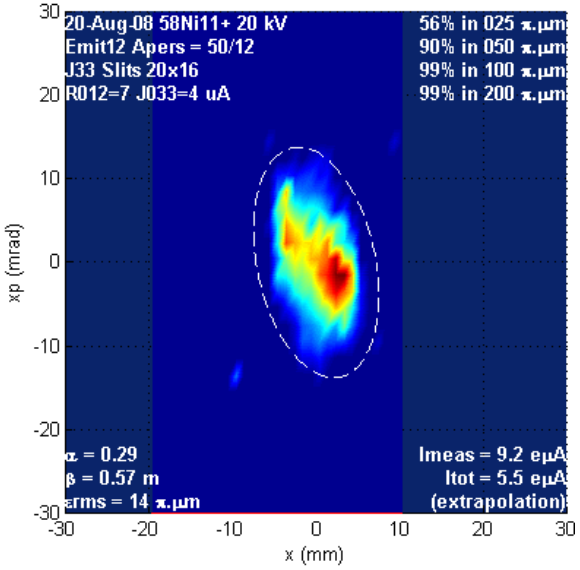
x 1/3

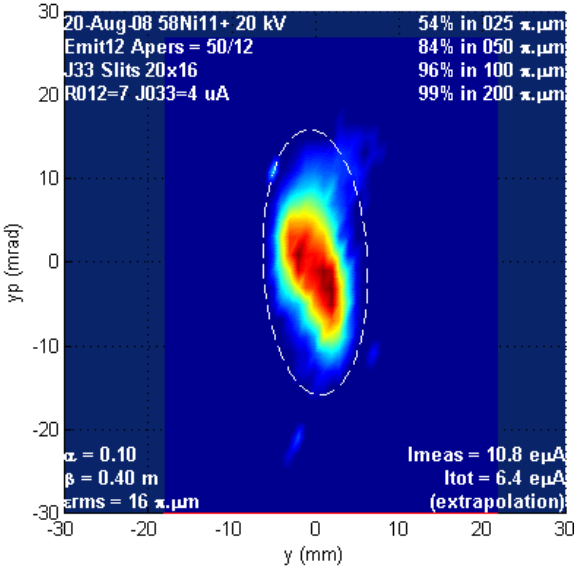
R012 = 7.0 uA; J033 = 4.0 uA

Early Transmission Loss
Tends to be offset by
Later Transmission Gains

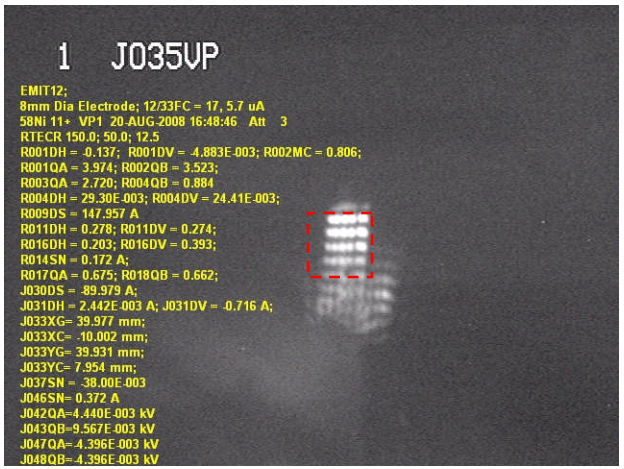


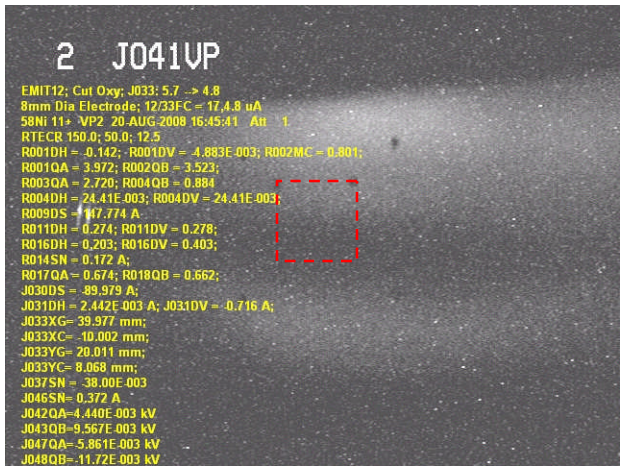


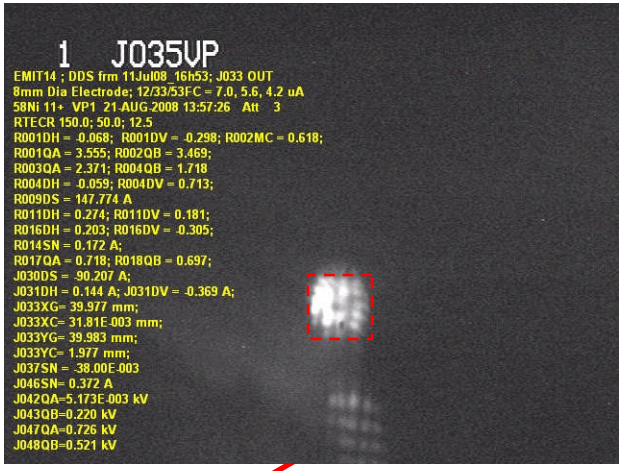


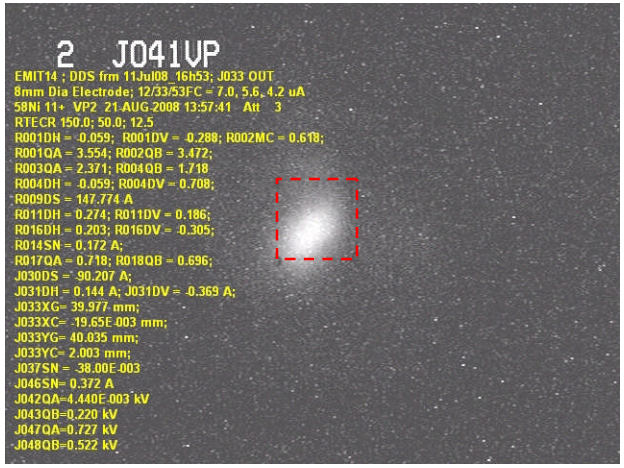


$^{58}Ni^{11+}$: Emittance: High vs. Low





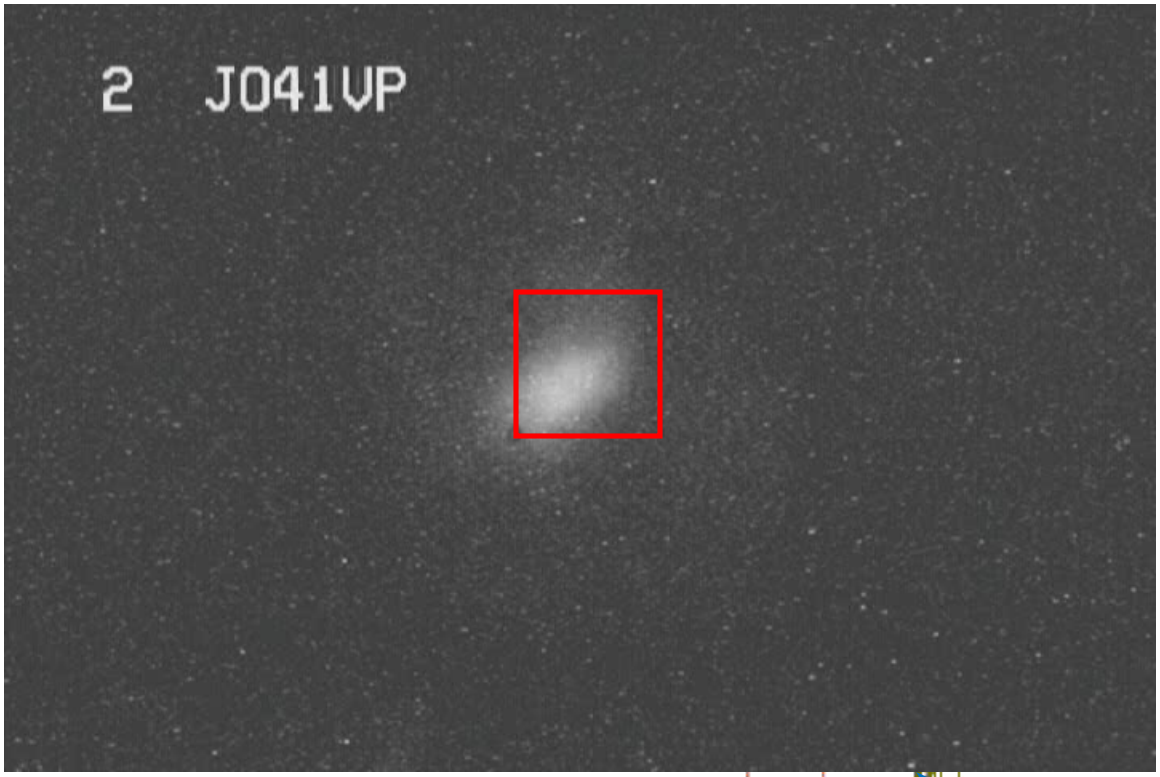




($^{16}O^{3+}$)

In the 2.1 m “almost” free drift between the focus at J035VP and J041VP, the difference in the two emittances is directly observable.

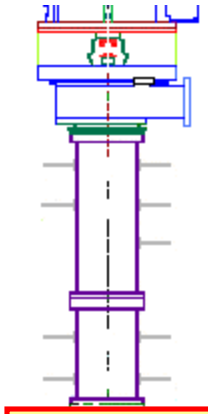
Vary R037SN: Behaves as Desired (no Star/triangles)



$^{58}Ni^{11+}$

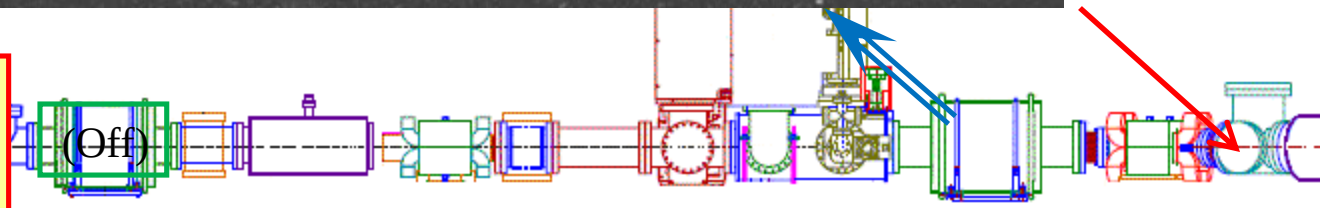
($^{16}O^{3+}$)

(Note the Spherical Aberration characteristic of solenoids)

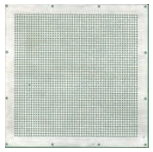


R006AP
50 mm

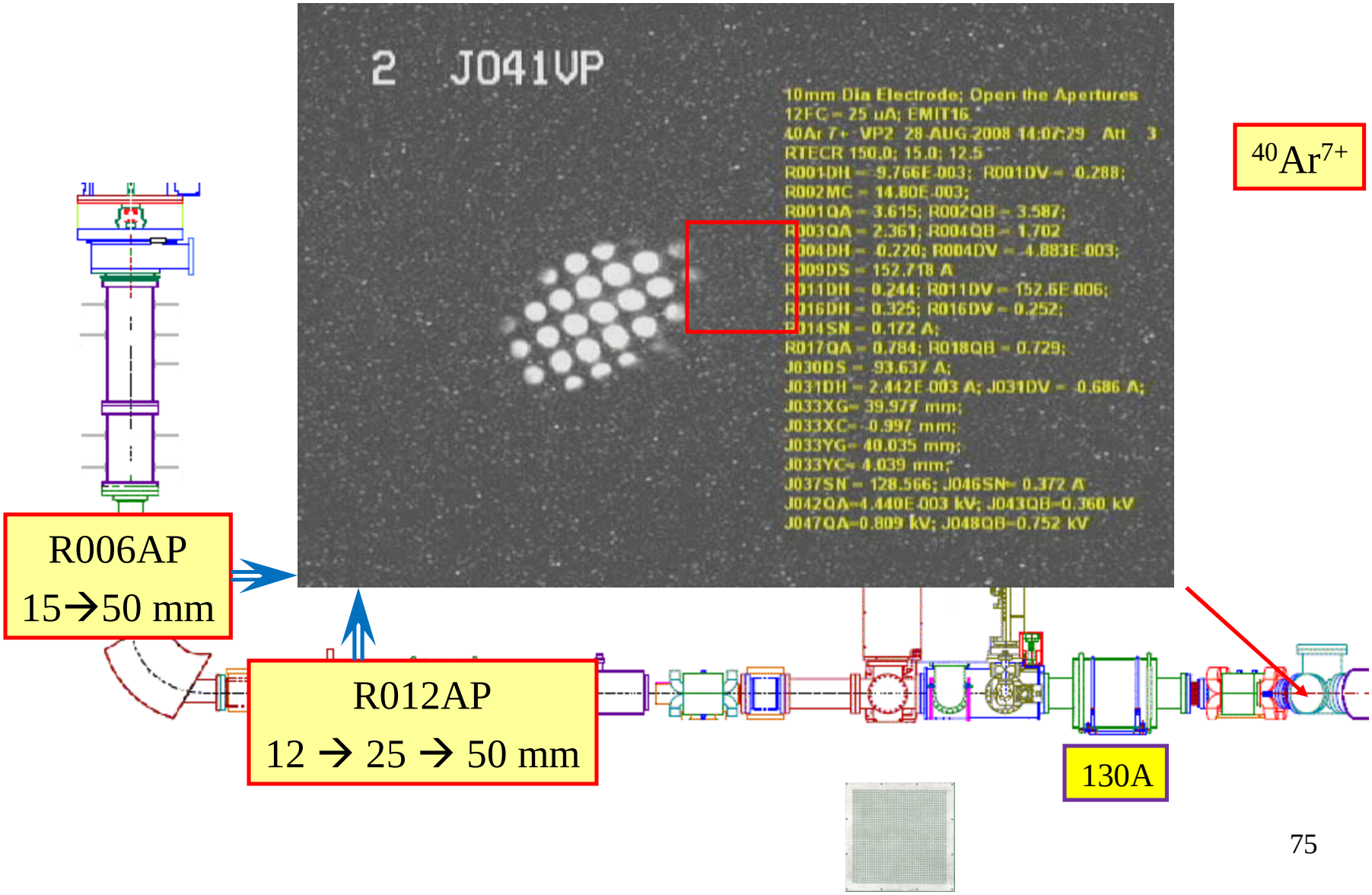
R012AP
12 mm



0→130A

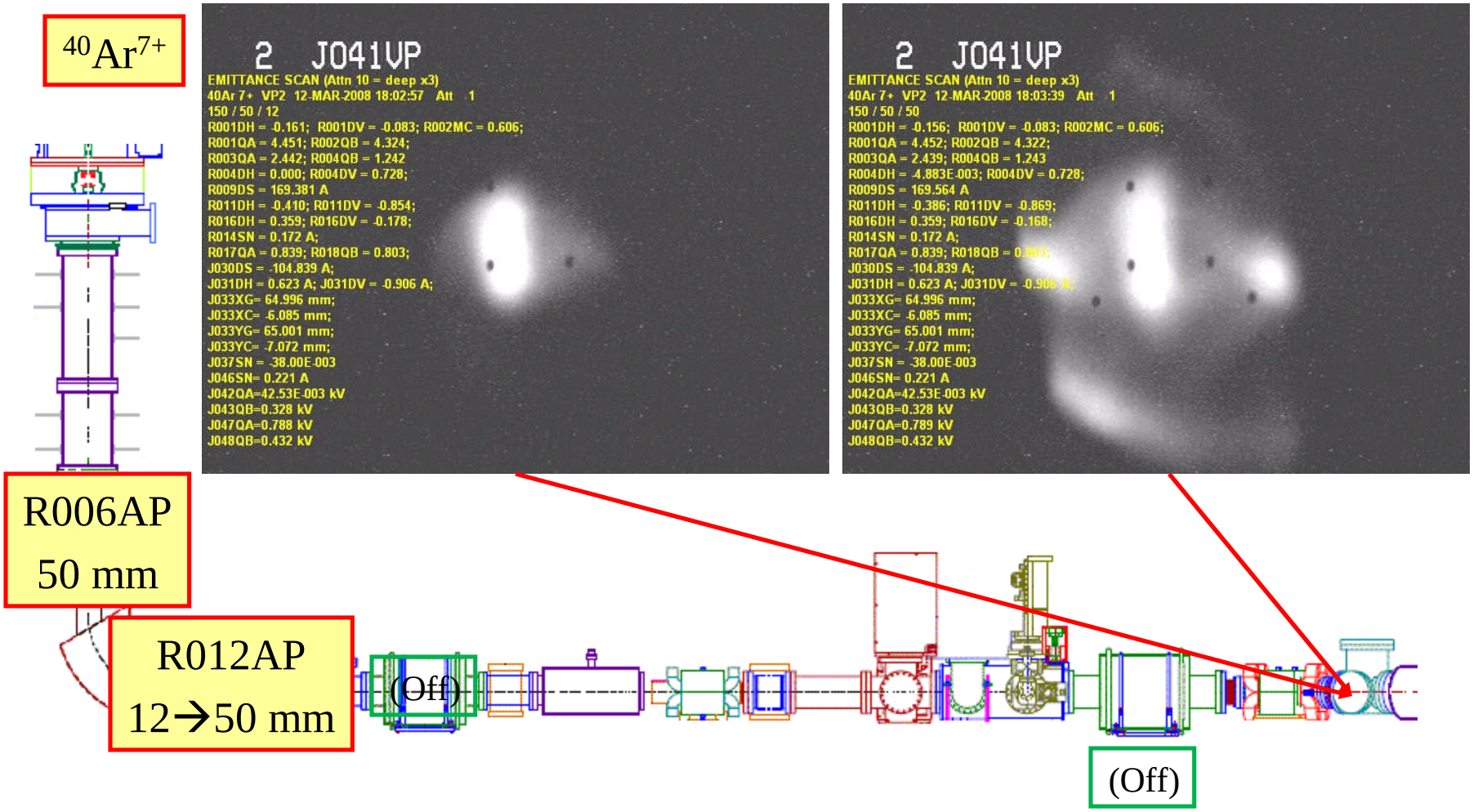


What's Being Cut by Apertures?

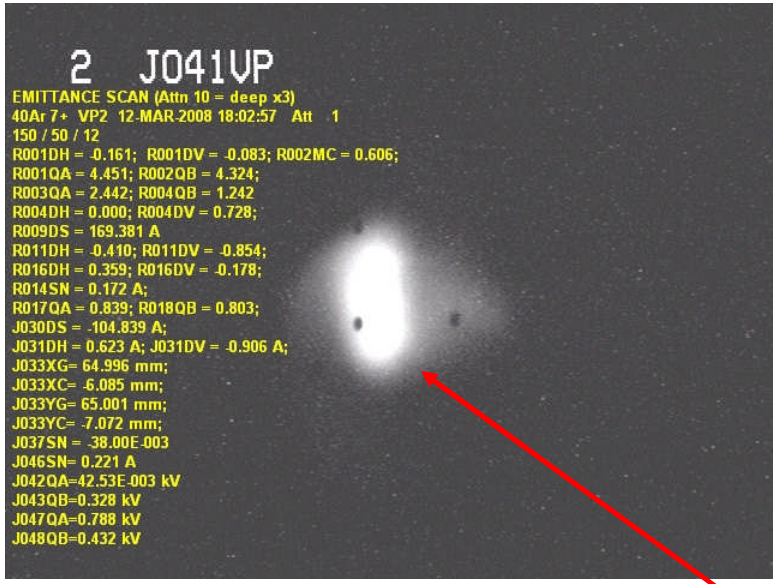


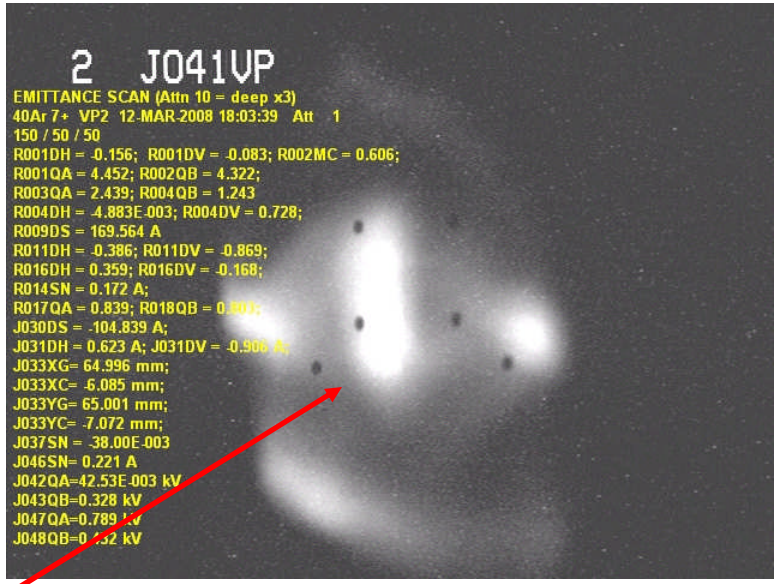
$^{40}Ar^{7+}$

What's Being Imaged / Cut by Apertures?



Note!

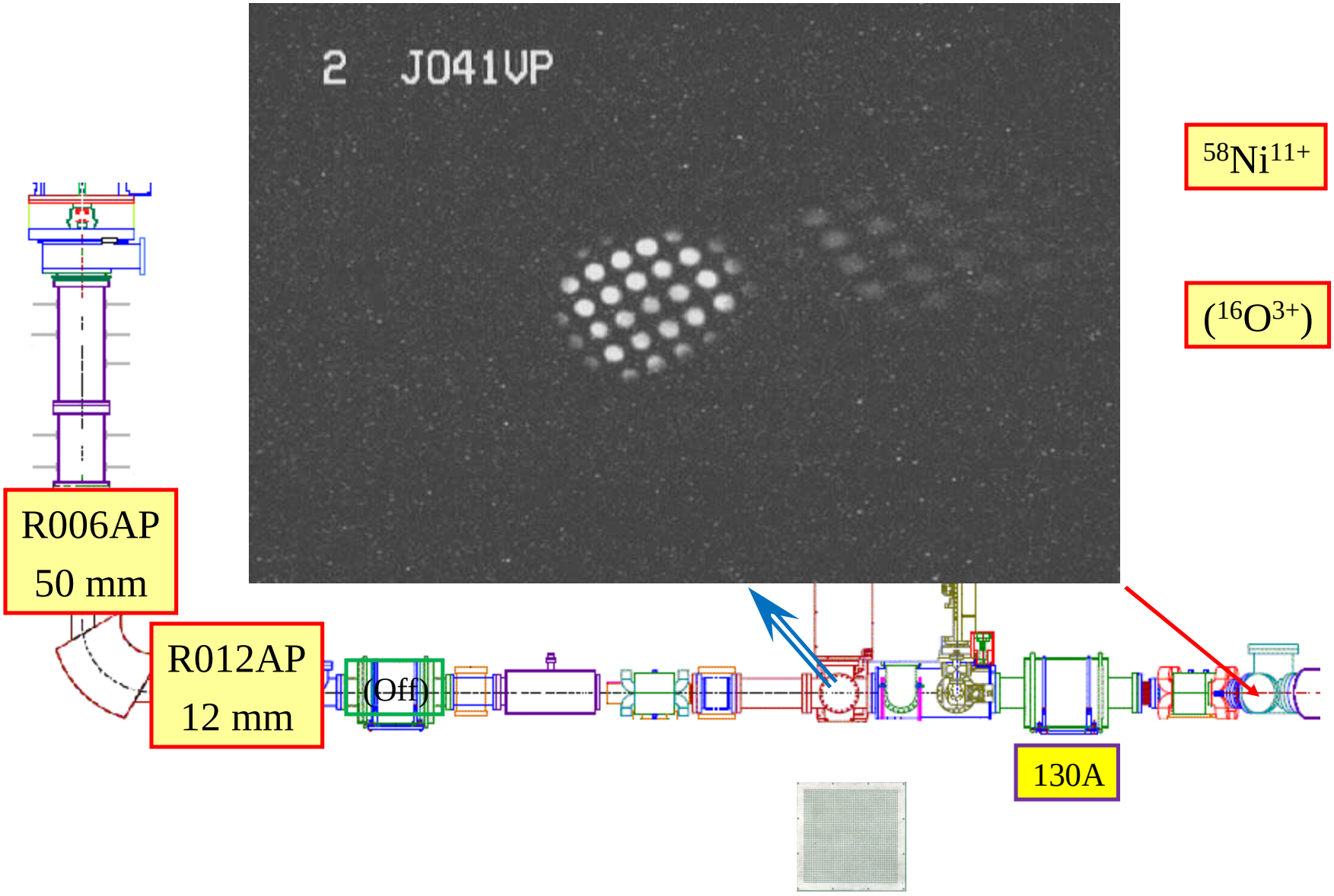




This central piece of beam is

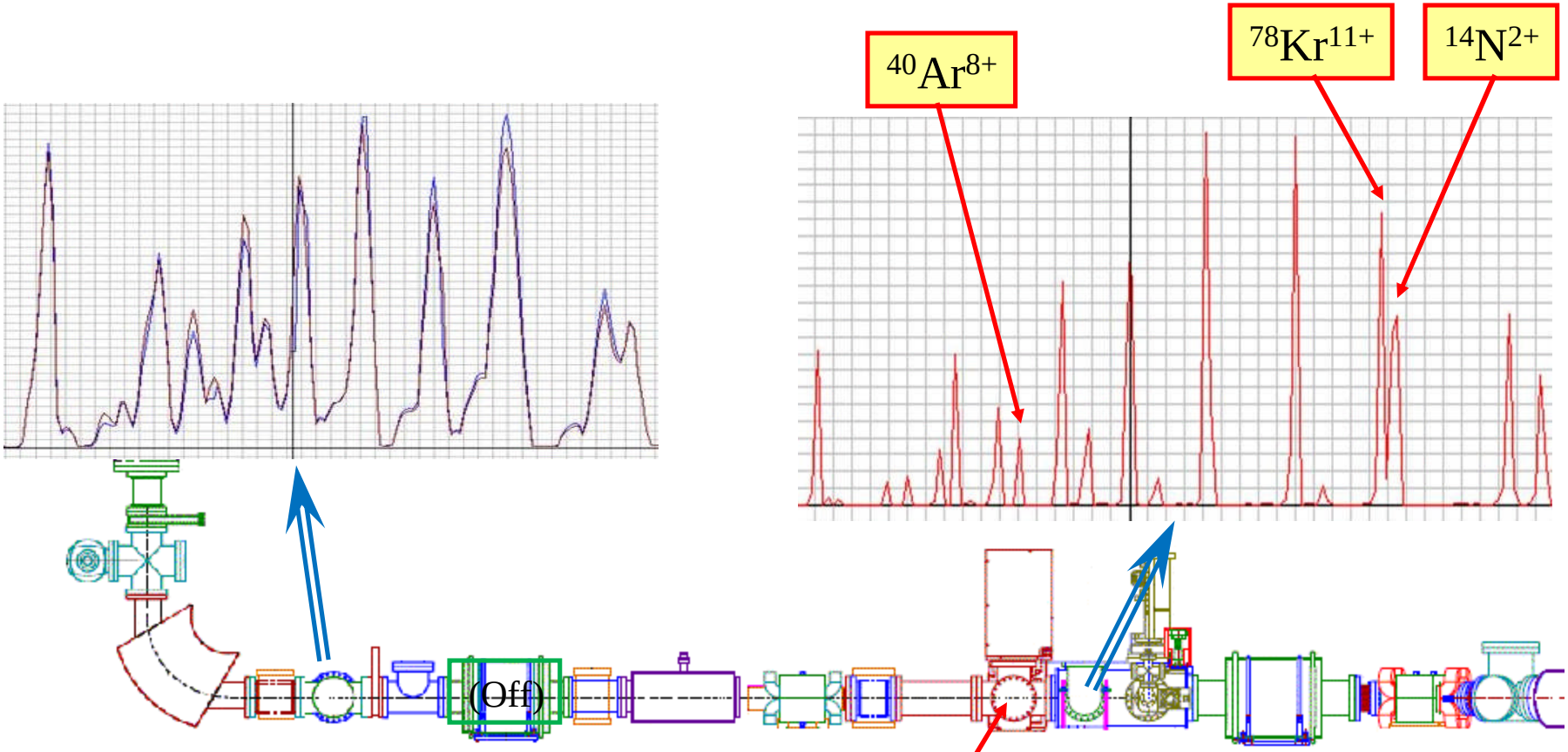
not being significantly cut by apertures. There seem to be 3 similar low-emittance pieces, but on different trajectories. The apertures cut 2 of the 3 (plus a “cloud”) away.

J033 Slit Cut Good

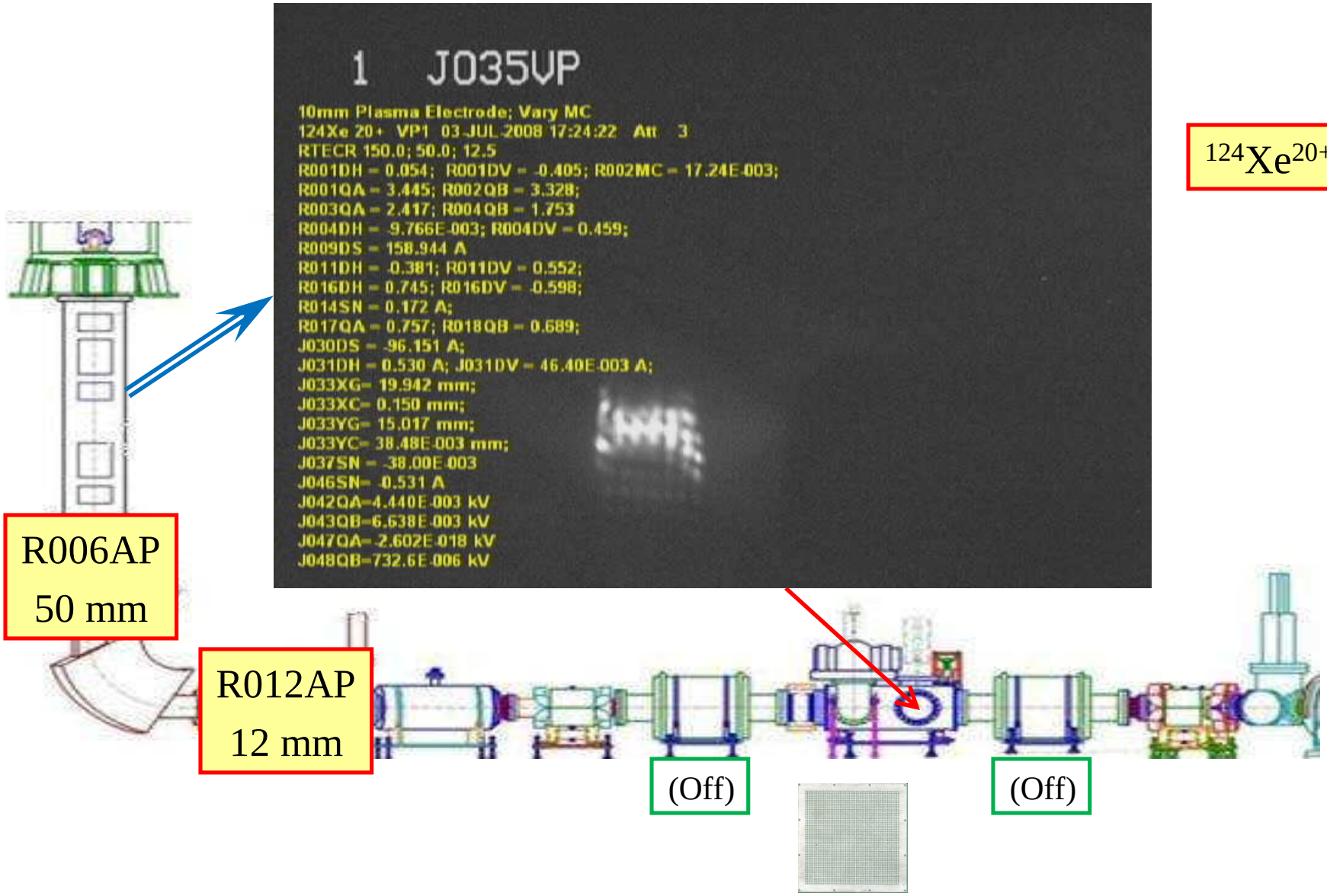


Side Benefit: Better Charge State Resolution (<1%)

(Resolving Power ~ Dispersion/Magnification)



Aside: Yes, the Octupole Works

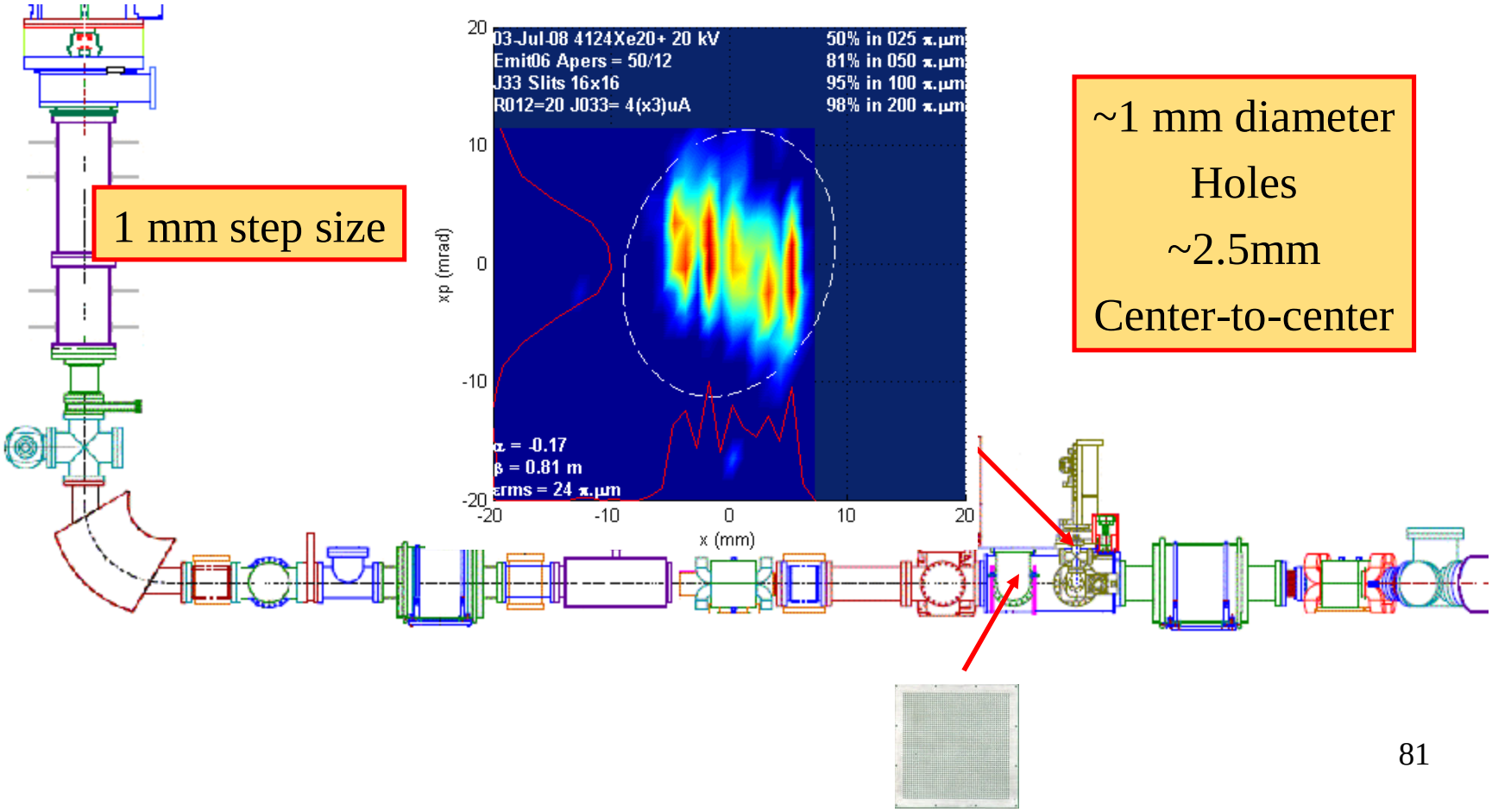


$^{124}Xe^{20+}$

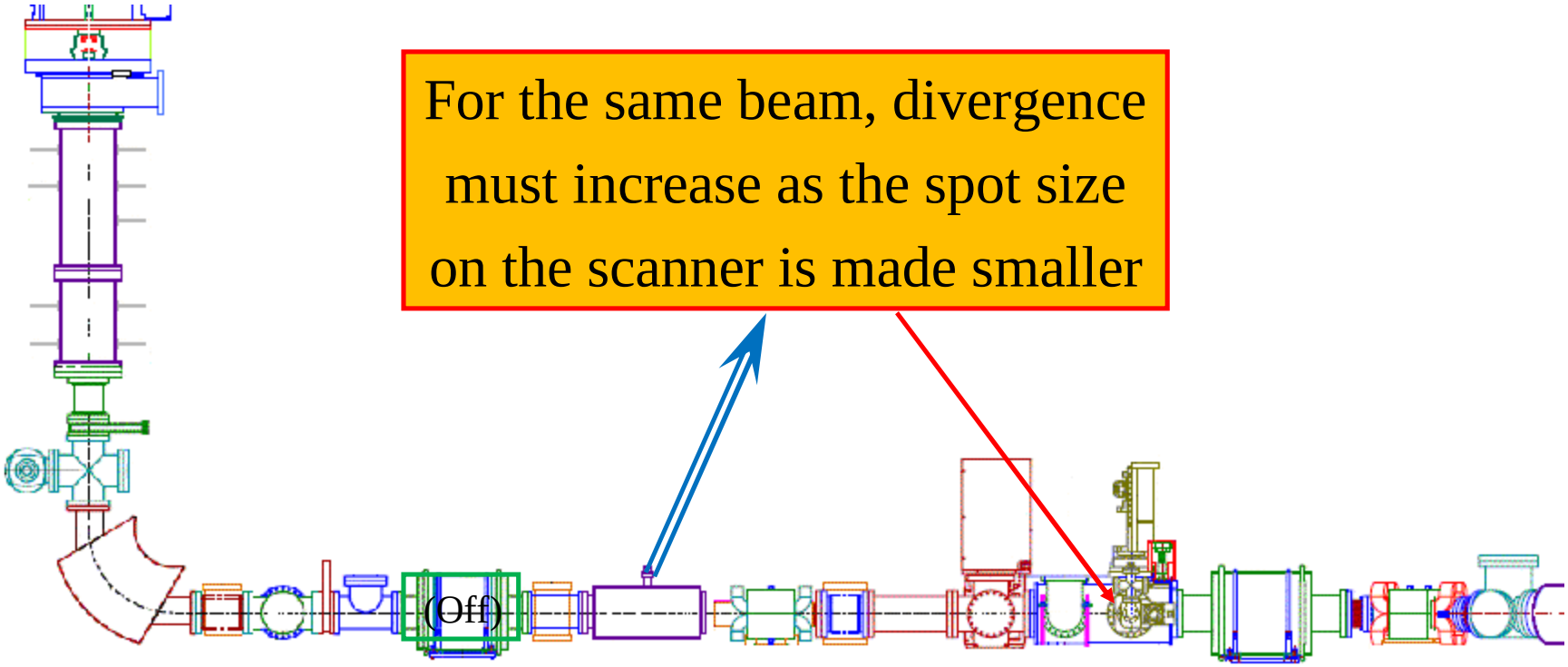
Emittance Scanner Resolution

Position Resolution is ~0.5 mm

Beam Widths > 5 mm → Good



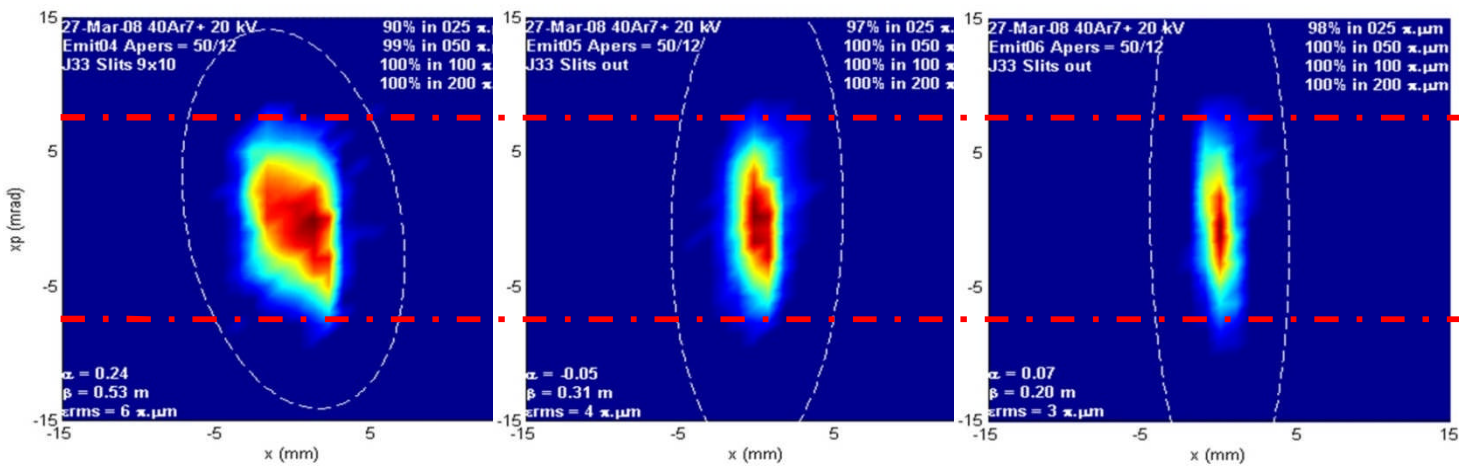
Emittance Scanner Resolution



Emittance Scanner Resolution

Divergence resolution ~ 6.7 mr

10 mr



6*pi*mm*mr

4*pi*mm*mr

3*pi*mm*mr

When divergences < ~10 mr, as they are for many of these measurements, the calculated emittance values depend only on the beam width.

Summary (A) of Low Emittance Tune Tests

$^{40}Ar^{7+}$, $^{58}Ni^{11+}$, $^{78}Kr^{11+}$, and $^{124}Xe^{20+}$ beams were tested and gave very similar optical results.

A bright beam core exists that has minimal, if any, cross-correlations.

This core has about 1/3 of the total beam intensity.

2D rms emittances are reduced by at least a factor of 3-5

The initial focusing element (Double Doublet) settings scale very precisely between beams and extraction HV settings.

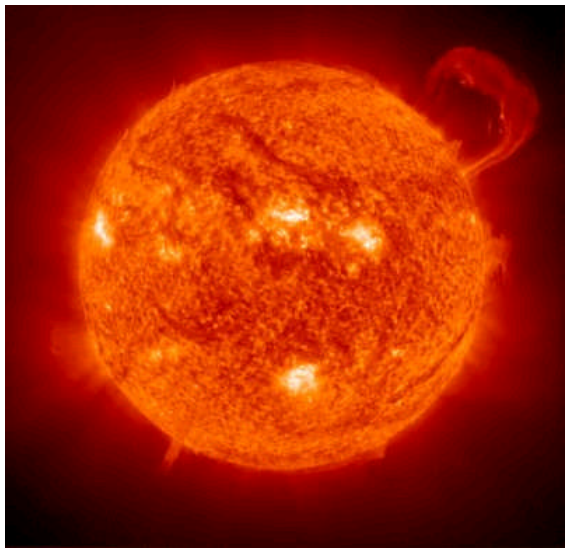
Summary (B) of Low Emittance Tune Tests

Minimal correlations allows clean slit cuts.

Changing the plasma chamber electrode diameter from 8mm to 10mm increased both overall and “low emittance” output by 30-40%, without significantly degrading beam quality.

In the first (and, to-date, only) test with the K500, both injection and extraction efficiency were significantly improved; only 50-60% of the previous injected intensity was needed to achieve the same K500 output current.

Brightness



Intensity On A Faraday Cup
That Cannot Be
Injected, Accelerated, And Extracted
Cleanly Is Useless (Or Worse)

Homework for the Theory Types

Given the complicated nature of the beam structure from an ECR ion source ….

… how is it even remotely possible to organize (de-correlate) this beam using linear, first order, optical focusing elements?

It’s not!

So it already exists (focusing and steering merely select), But Why?

?

Can the “core” be separated in systems
Using solenoid or other focusing?

Can the “core” be separated by
“processing”
after the analysis magnet only?

An NSCL World Record?

Operating ECR Ion Sources = 4

Ion Source Group Members = 3

Sources per Sorcerer = 1.333

One Very Over-Worked Group

So, In Particular

Thanks for letting me play with Your Toys!

The Cast (*Lord(s) of the Rings IV*)

BEAM PHYSICS

- Felix Marti
- Marc Doleans
- Xiaoyu Wu
- Q. Zhao

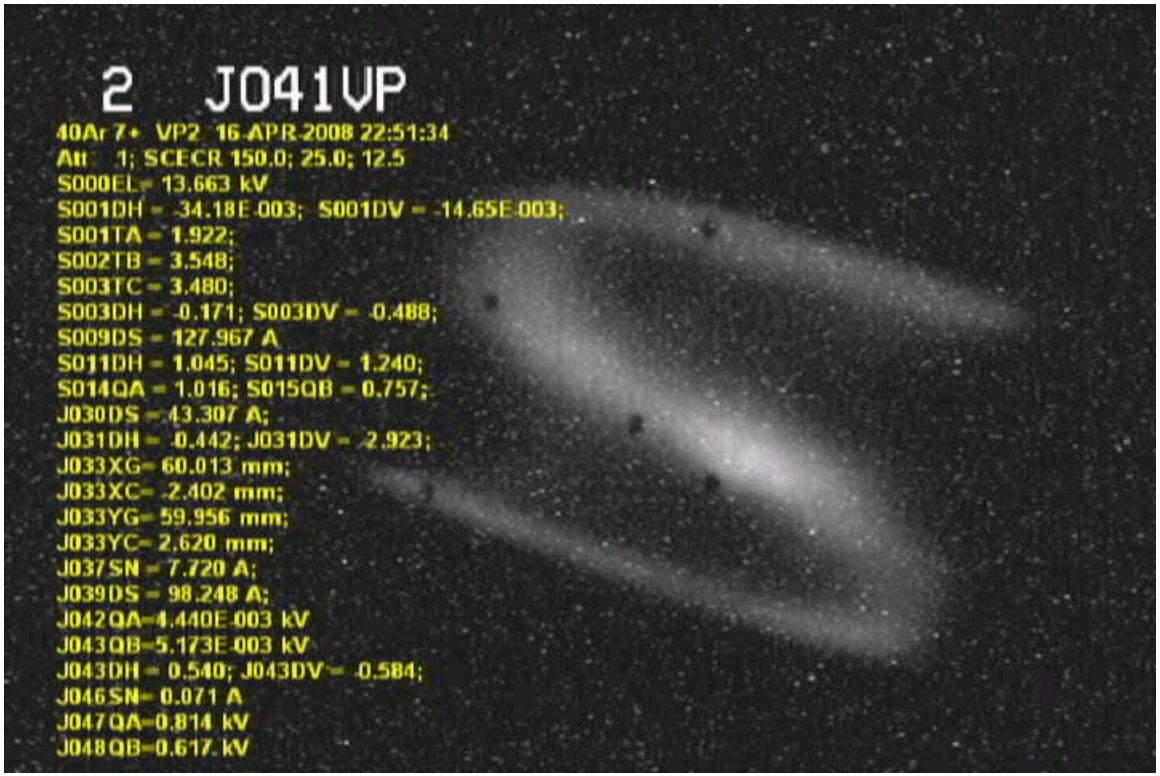
ION SOURCE

- Peter Zavodszky
- G. Machicoane
- Dallas Cole
- Larry Tobos

GSI

- Peter Spaedtke

For fun, raise R037SN: What will it do?



$^{40}Ar^{7+}$

SCECR


NSCL
