The role of EBIT in X-ray laser research

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Thank my colleagues for helpful information on the past and present

Dan Dietrich - GSI, EBIT, EBIS

Pat Egan - GSI

Ross Marrs - EBIT

K. T. Cheng - EBIT, atomic physics

Peter Beiersdorfer - EBIT

Walter Johnson - Average Atom Code

Jorge Filevich - Interferometer measurements

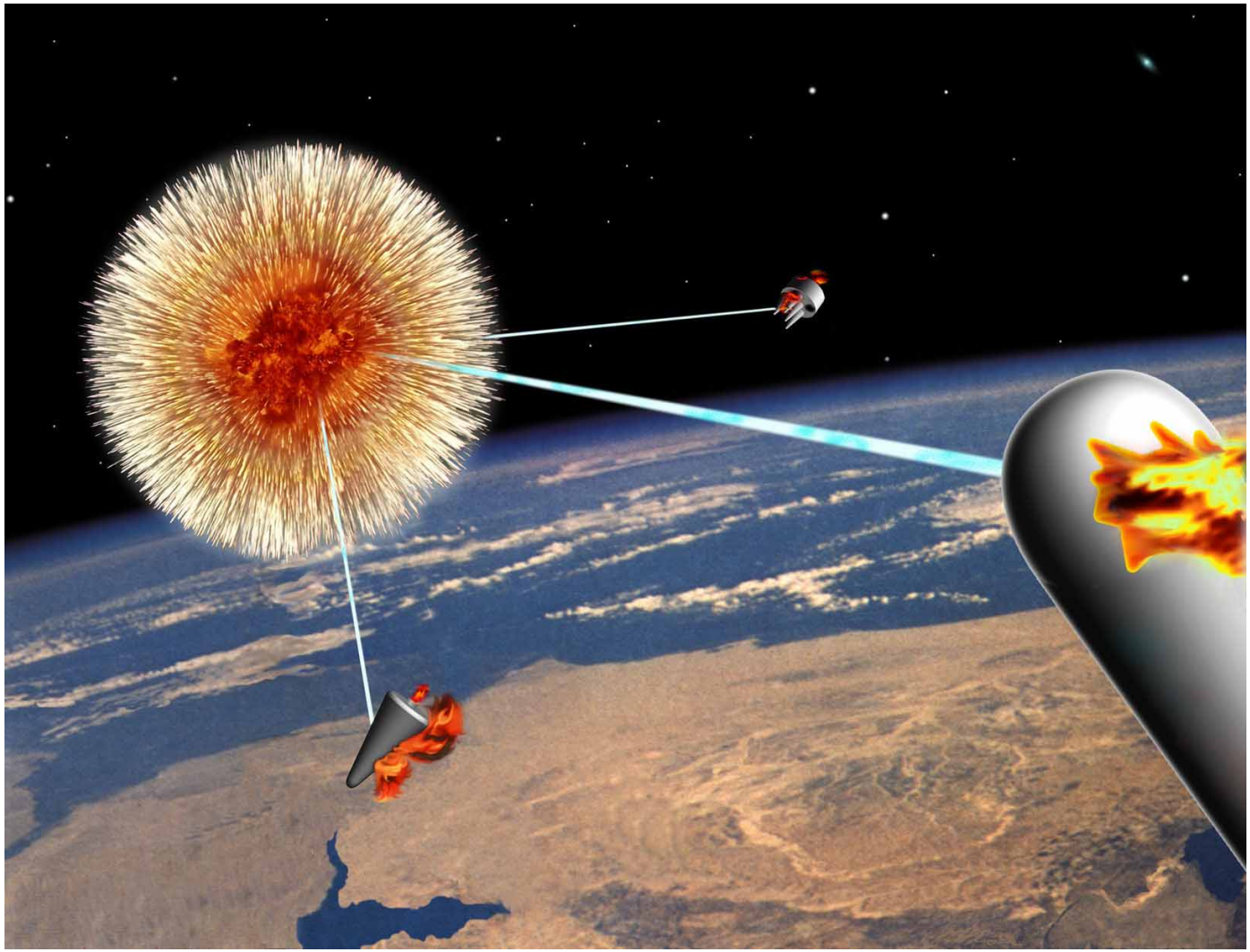
Jim Dunn - COMET

EBIT was developed as a tool to help the X-ray laser program better understand atomic physics

- X-ray laser program made atomic physics a national priority
- Competition with the Soviets played an important role
- Early GSI experiments showed need for a facility like EBIT
- Soviet EBIS work of Donets motivated research in this field
- EBIT brought us new capabilities in multi-electron QED
- EBIT used to evaluate proposals for new laboratory X-ray lasers
- Current X-ray laser research and the need for more atomic data

The nuclear pumped X-ray laser program drove the need for atomic data of highly ionized ions in the 1980's

First X-ray lasers demonstrated by LLNL in early 1980's were nuclear pumped



Competition with the Soviets made the X-ray laser program a national priority and made EBIT possible

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Review of theoretical works on X-ray laser research performed at RFNC—VNIITF

By E.N. AVRORIN, V.A. LYKOV, P.A. LOBODA, AND V.YU. POLITOV
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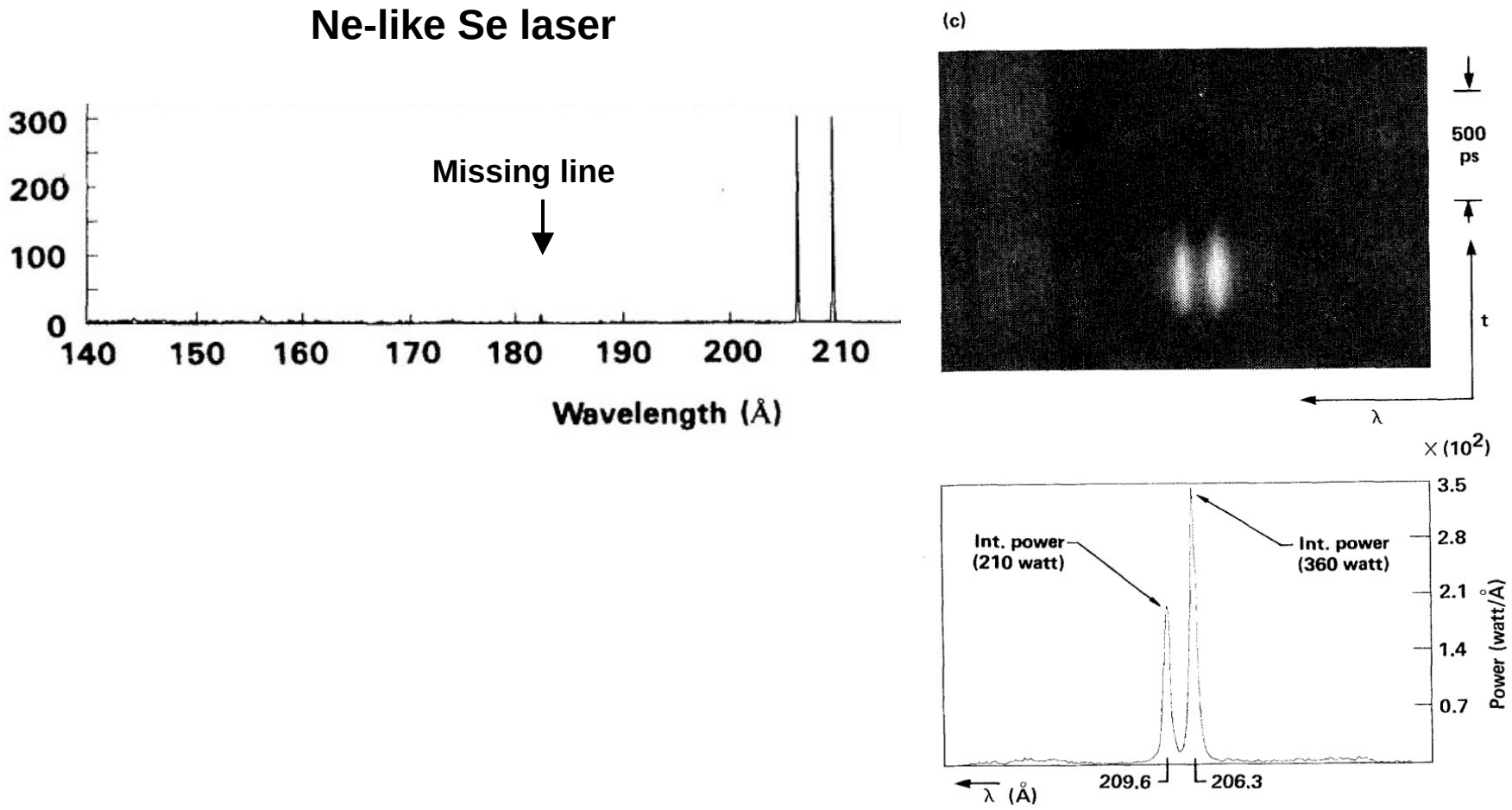
Research works on nonequilibrium plasma physics had a significant place in fundamental studies pursued at RFNC—VNIITF in 1980s with underground nuclear explosions. These works got under way after the XRL radiation with the wavelength $\lambda \approx 14$ Å and laser beam energy of about 100 kJ had been registered at an underground nuclear explosion (*Aviation Week and Space Technology* 1981). The goal of investigations conducted at VNIITF at that period was to verify the basic physical principles of XRL operation and evaluate the feasibility of attaining the reported parameters of XRL radiation (Aviation Week and Space Technology 1981).

Theoretical and experimental works on XRL problems resulted in the full-scale VNIITF experiment carried out in 1987. In this experiment X-ray pumping spectra and XRL radiation with the parameters close to calculated values were registered. Laser radiation energy measurements gave $E \approx 10$–20 kJ at $\lambda \approx 39$ Å and $E \approx 100$ kJ at $\lambda \approx 28$ Å.

The experiment confirmed the validity of theoretical concepts on various XRL schemes and demonstrated experimentally the fundamental feasibility of creating such lasers using the energy of nuclear explosion.

Used by permission of Peter Loboda

First laboratory X-ray laser at LLNL in 1984 did not lase on predicted line at 182 Å and highlighted our need for better physics understanding



Courtesy of D. L. Matthews et al., PRL 54, 110 (1985)

Prior to EBIT researchers were going to large facilities such as GSI UNILAC to measure high-Z line positions to study multi-electron QED effects

- July 1985 - July 1986 - Dan Dietrich does GSI experiments
- November 1985 - measured Bi at GSI UNILAC
- January 1986 - Pat Egan does Bi experiments at GSI
  1. G.A. Chandler et al. ,"Precision x-ray crystal spectroscopy of neon-like gold," Phys. Rev. A 39, 565 (1989).
  2. D. D. Dietrich et al., "Beam foil spectroscopy of n=3 to n=2 transitions in highly stripped bismuth," Phys. Rev. A 41, 1450 (1990).
- GSI experiments had large Doppler shifts to deal with
- GSI experiments set precedent for publishing atomic data
- 1985 - Beiersdorfer does Ag spectoscopy at PLT Tokamak
  1. P. Beiersdorfer et al., “High-resolution n=3 to n=2 neonlike spectra of neonlike Ag,” Phys. Rev. A 34, 1297 (1986).
  2. P. Beiersdorfer et al., ”X-ray transitions in highly charged neonlike ions,” Phys. Rev. A 37, 4153 (1988).

LLNL researchers went to large facilities such as GSI Darmstadt UNILAC to measure high-Z line positions to understand multi-electron QED

Doppler shift and noise were major challenges

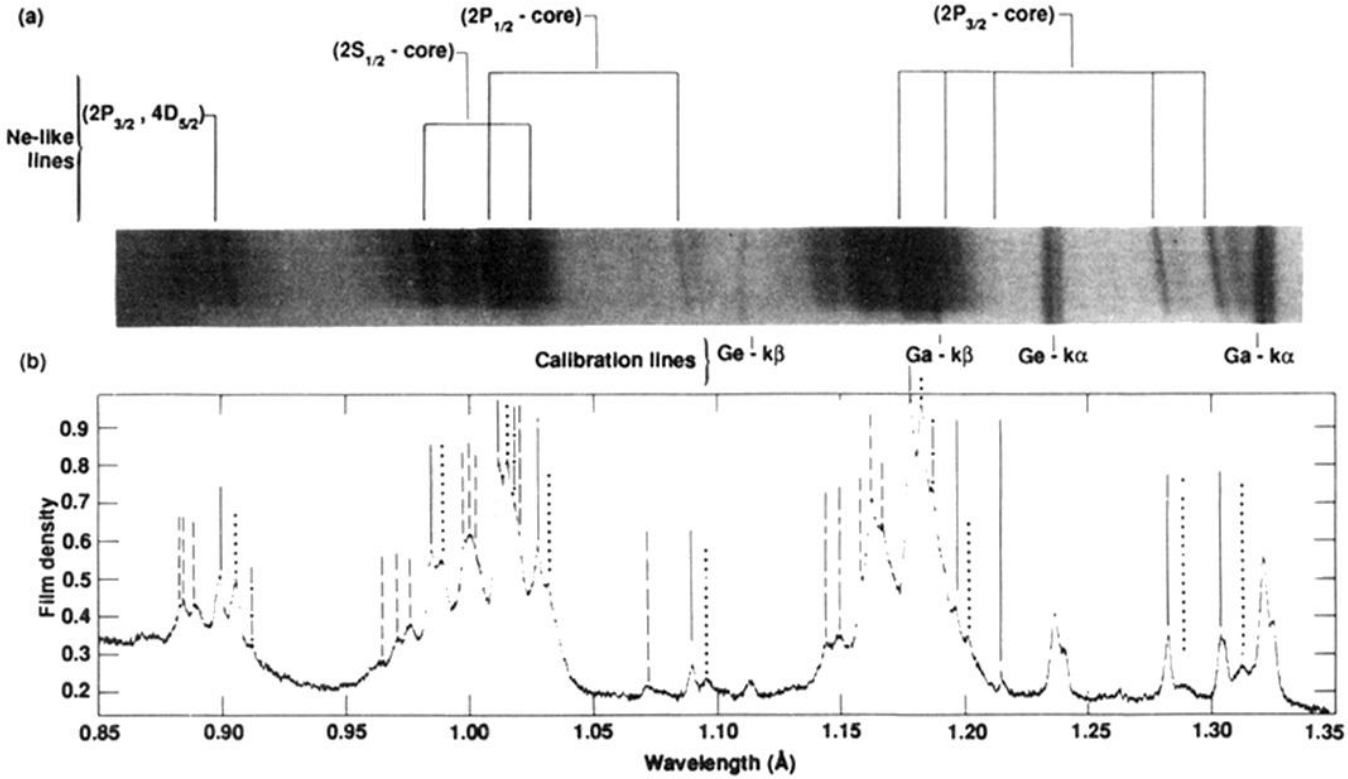


FIG. 3. (a) Raw film data of a gold x-ray spectrum taken with an indium antimony 220 crystal. (b) A densitometer trace of the spectrum formed by averaging densitometer scans along the gold x-ray lines. The lines are identified from a given charge state in the spectra as follows: ——, Ne-like; · · · ·, Na-like, —·—·—·, Mg-like; — — —, F-like; -----and O-like.

"Precision x-ray crystal spectroscopy of neon-like gold", G.A. Chandler et al. Phys. Rev. A 39, 565 (1989).

Energies of Au lines had experimental uncertainties comparable to the calculated differences due to beam foil and Doppler shifts from accelerator beam at GSI

TABLE I. Neonlike gold transition energies to the ground state (in eV).

Upper level	Measured[a]	Calculated	Difference	Rel. int.	$(2J+1)R_b$ [b]	gf
$(2p_{3/2},3s_{1/2})_1$	9506.5(4.5)	9 505.3	1.2	0.41	3.0	$1.50E-1$
$(2p_{3/2},3p_{1/2})_2$	9666.7(4.5)	9 663.6	3.1	0.34	4.9	$1.70E-3$
$(2p_{3/2},3p_{3/2})_2$	10 190.0(4.9)	10 193.6	−3.6	0.02	1.5	$1.50E-3$
$(2p_{3/2},3d_{3/2})_1$	10 357.9(5.2)	10 363.7	−5.8	0.09	3.0	$8.90E-3$
$(2p_{3/2},3d_{5/2})_1$	10 519.7(5.4)	10 527.7	−8.0	1.00	3.0	$2.26E+0$
$(2p_{1/2},3s_{1/2})_1$	11 374.8(6.2)	11 377.5	−2.7	0.04	3.0	$2.70E-2$
$(2p_{1/2},3d_{3/2})_1$	12 260.8(7.1)	12 268.5	−7.7	0.26	3.0	$9.53E-1$
$(2s_{1/2},3p_{1/2})_1$	12 071.6(6.9)	12 081.4	−9.8	0.15	2.8	$3.43E-1$
$(2s_{1/2},3p_{3/2})_1$	12 600.2(7.5)	12 608.6	−8.4	0.06	2.8	$2.42E-1$
$(2s_{1/2},3d_{5/2})_2$	12 909.6(7.8)	12 915.8	−6.1	0.04	1.6	$1.25E-2$
$(2p_{3/2},4d_{5/2})_1$	13 802.8(8.9)	13 809.7	−6.9	0.14	1.3	$4.84E-1$

[a]Numbers in parentheses are the experimental errors.

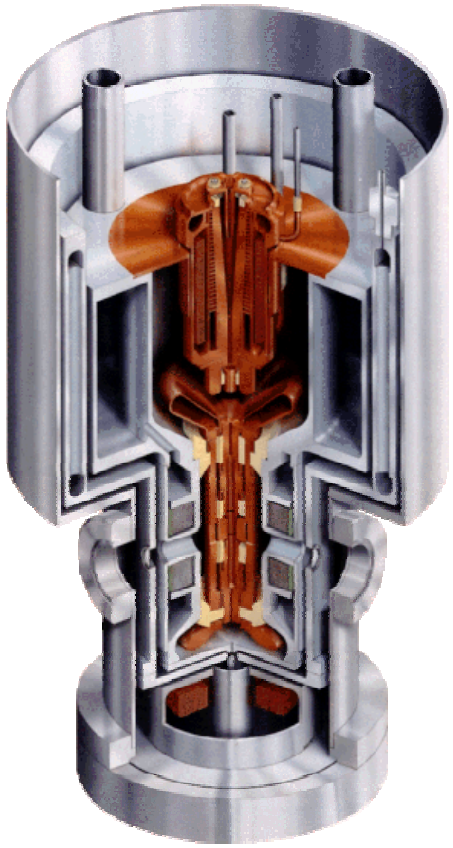
[b]$(2J+1)R_b$ repres

TABLE II. Sources of measured energy errors for neonlike gold transitions (in eV).

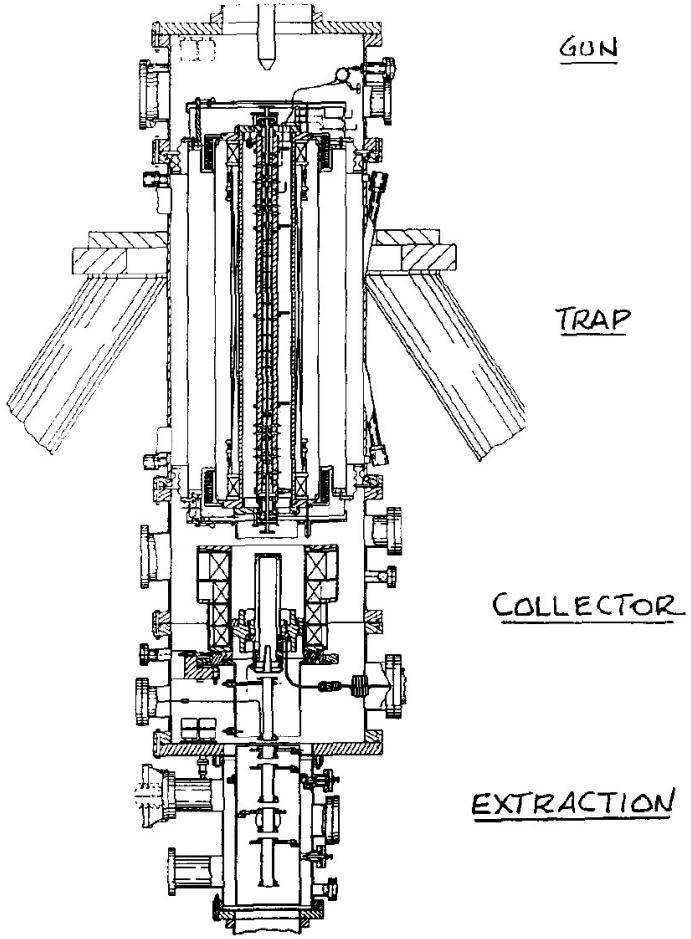
Upper level	Statistical	Foil location (∓0.5 mm)	Crystal alignment (∓1 mrad)	Beam energy (∓1.4%)
$(2p_{3/2},3s_{1/2})_1$	1.46	2.35	0.24	1.87
$(2p_{3/2},3p_{1/2})_2$	1.51	2.43	0.24	1.72
$(2p_{3/2},3p_{3/2})_2$	1.67	2.71	0.24	1.81
$(2p_{3/2},3d_{3/2})_1$	1.73	2.81	0.24	2.04
$(2p_{3/2},3d_{5/2})_1$	1.79	2.90	0.24	2.07
$(2p_{1/2},3s_{1/2})_1$	2.09	3.40	0.24	2.24
$(2p_{1/2},3d_{3/2})_1$	2.42	3.97	0.24	2.42
$(2s_{1/2},3p_{1/2})_1$	2.35	3.85	0.24	2.38
$(2s_{1/2},3p_{3/2})_1$	2.56	4.20	0.24	2.48
$(2s_{1/2},3d_{5/2})_2$	2.69	4.51	0.25	2.29
$(2p_{3/2},4d_{5/2})_1$	3.07	5.18	0.29	2.72

"Precision x-ray crystal spectroscopy of neon-like gold", G.A. Chandler et al. Phys. Rev. A 39, 565 (1989).

To address the need for atomic data the X-ray laser program funded EBIT and EBIS as alternatives to large accelerators: motivated by Donets' EBIS research in USSR

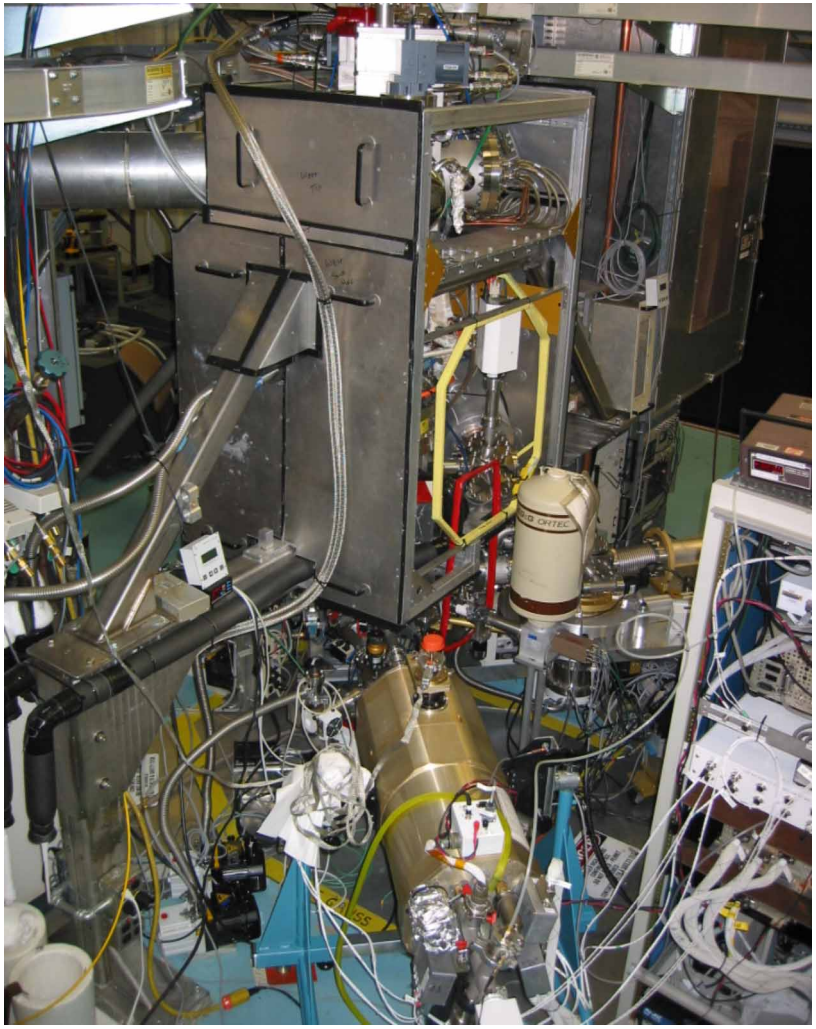


EBIT - compact
Ross Marrs LLNL

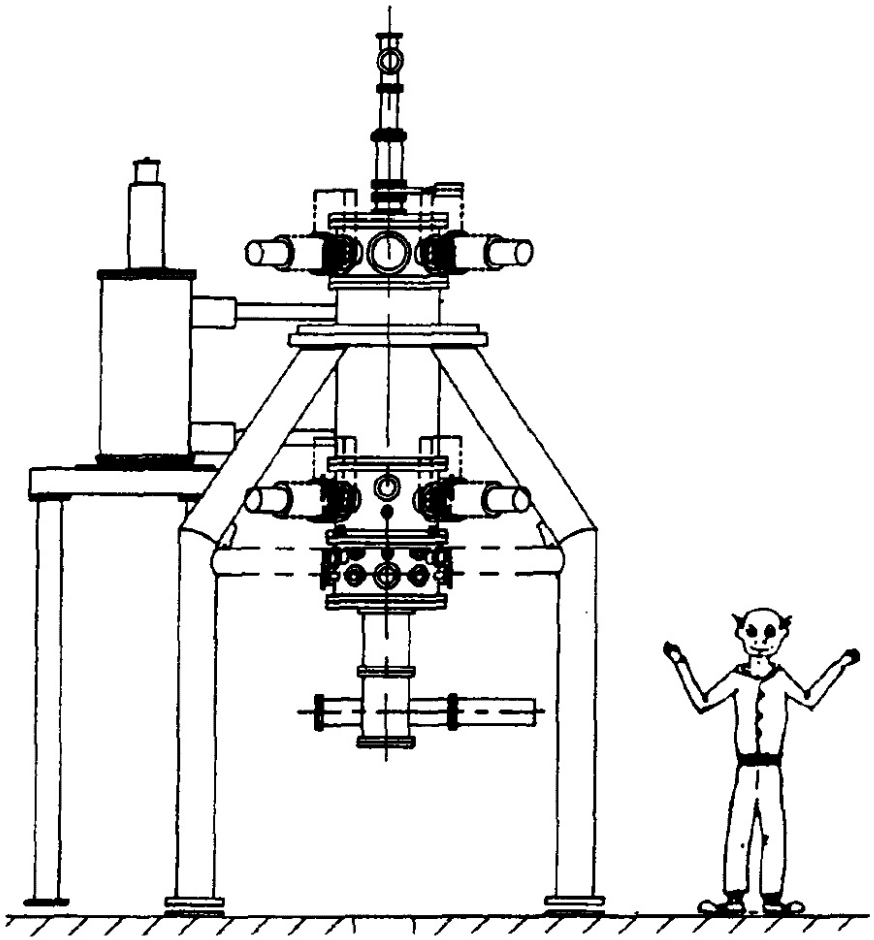


EBIS - large 1m - 10^2 more ions
Bob Schmeider SNL

EBIT was more compact than the EBIS planned at Sandia and ions were viewed directly in the trap

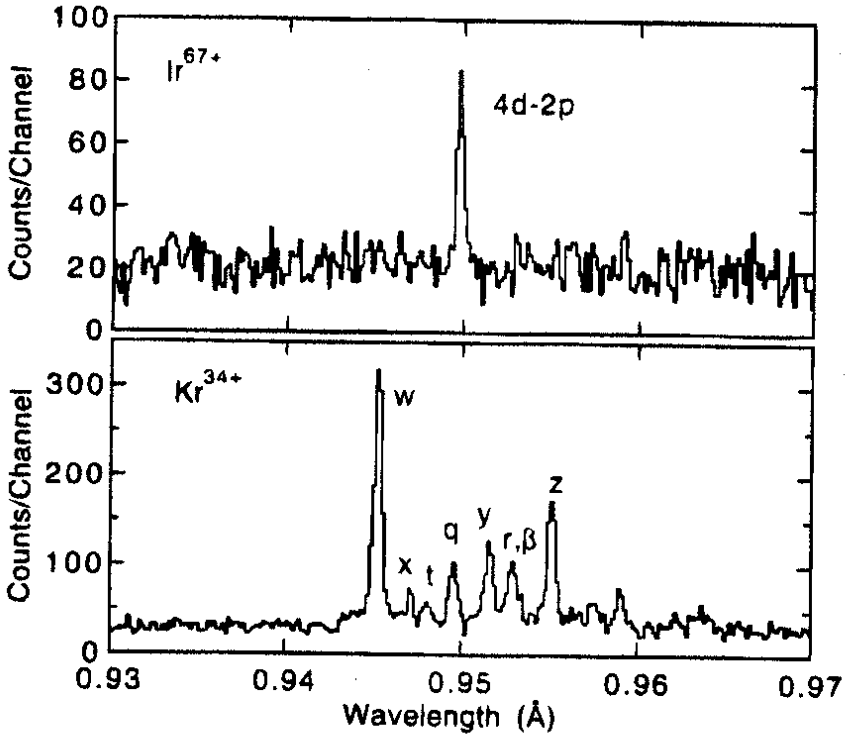


EBIT

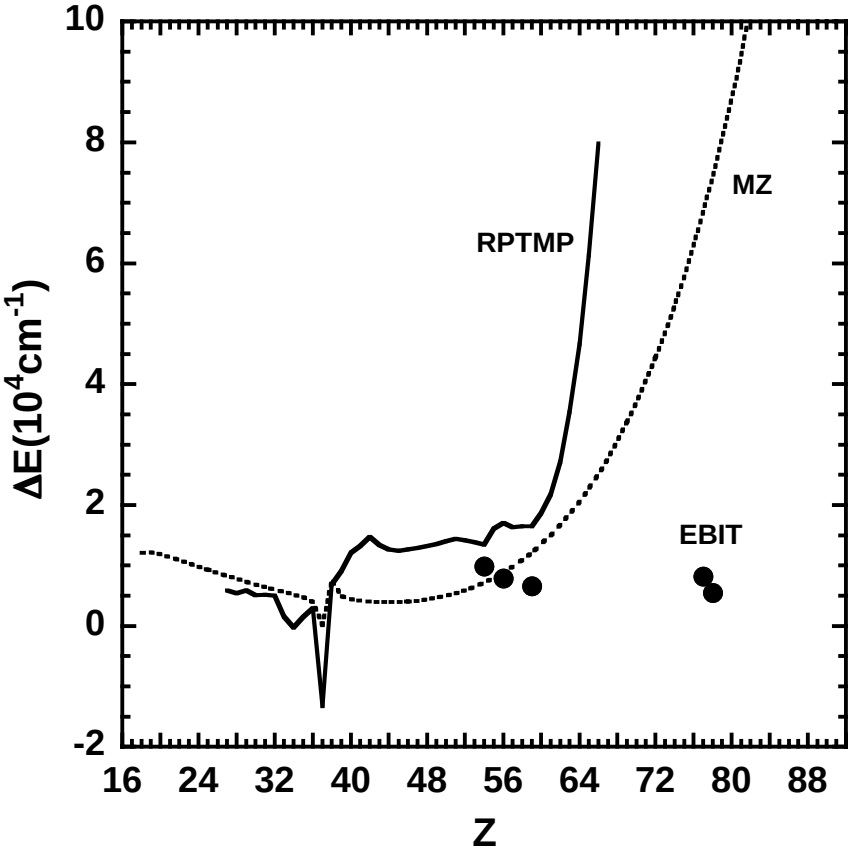


EBIS

EBIT measured high Z spectra to very high accuracy to distinguish between atomic physics calculations



EBIT spectra of Ne-like Ir 4D line calibrated with He-like Kr lines
von Hamos LiF(200) crystal spectrometer R=30 cm
Uncertainty is .27 x 10^4 cm^{-1} (0.33 eV)

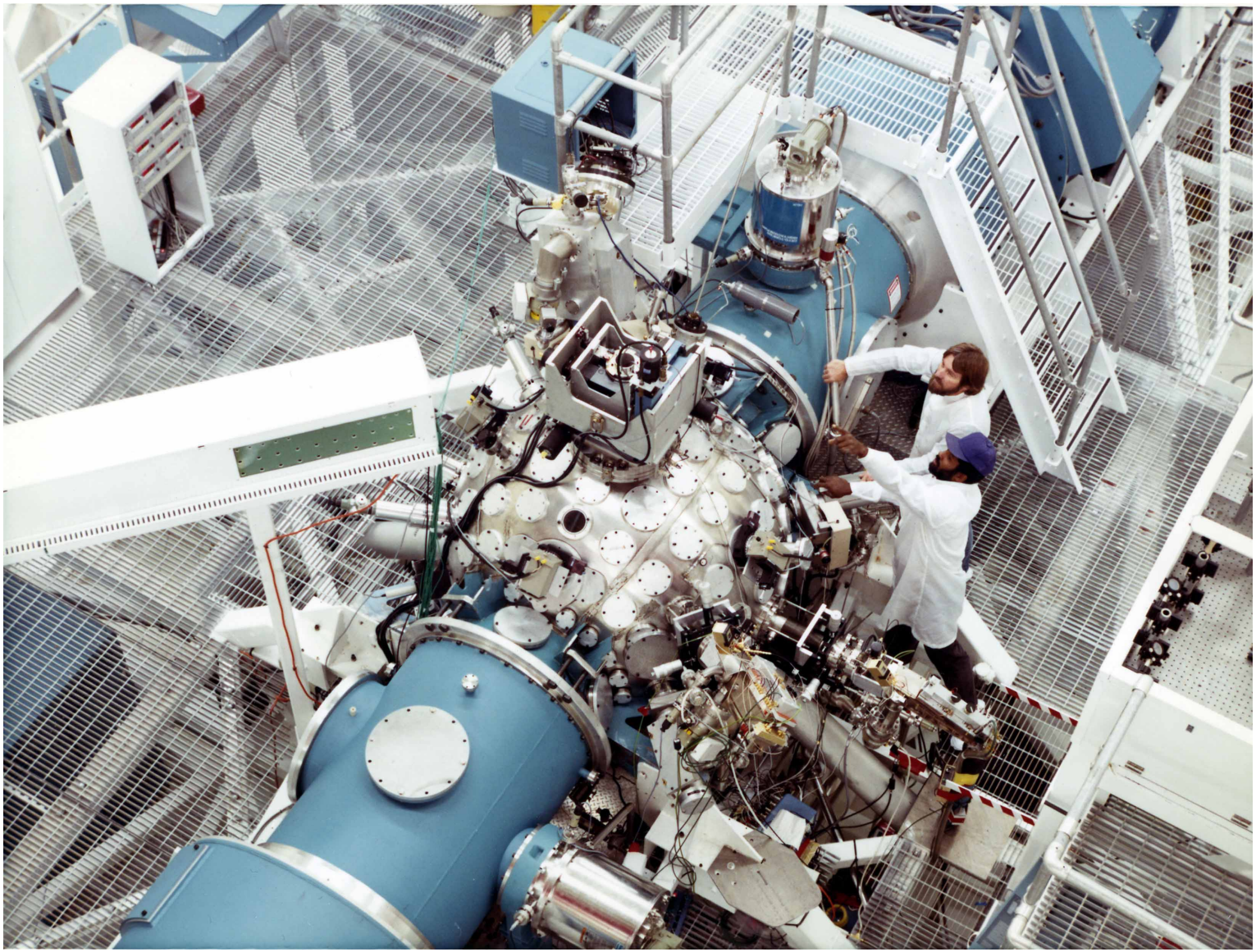


Energy difference of codes and EBIT data from MCDF calculation vs Z for Ne-like 4D line

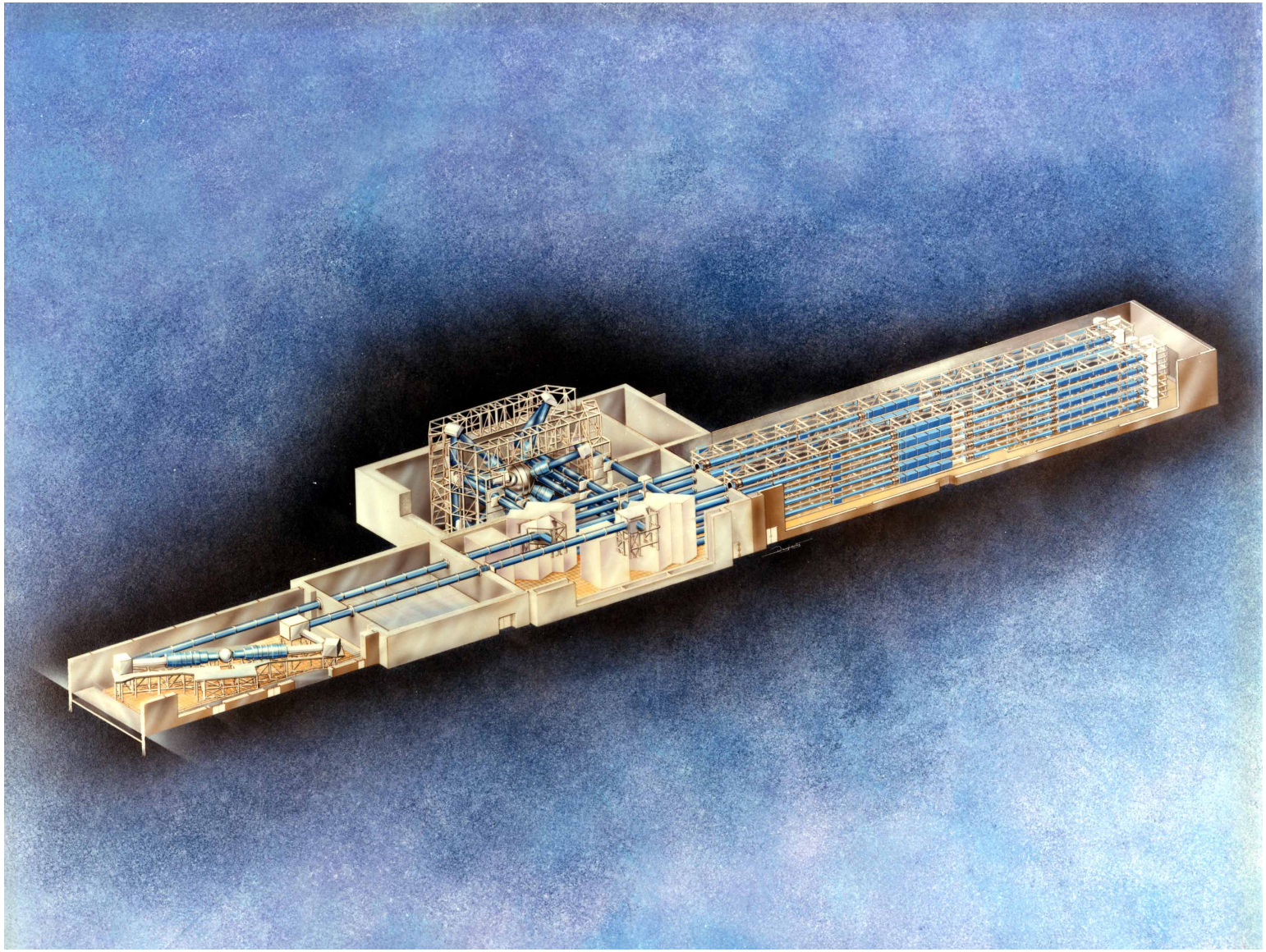
EBIT became an important tool for the X-ray laser program

- EBIT enabled rapid response to important questions
- Experimentalists no longer had to travel to GSI and schedule beam time
- EBIT allowed one to select a particular ionization stage to study
- EBIT was used to measure cross sections
- EBIT did high resolution spectroscopy of high Z ions
- EBIT greatly improved our understanding of multi-electron QED
- EBIT was limited to excitation from the ground state

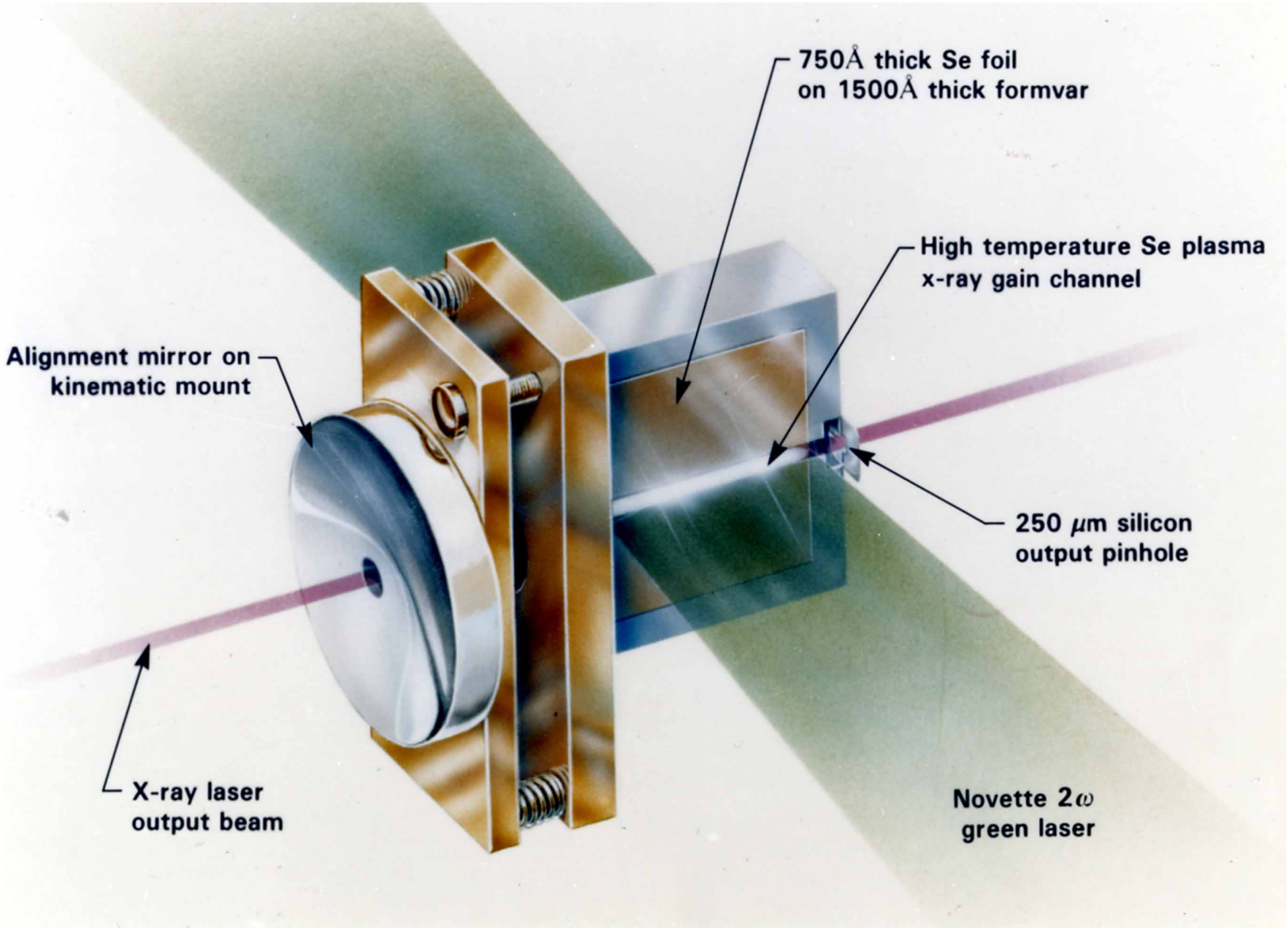
Nova 2-beam target chamber was built for X-ray laser research



From 1985 to 1996 the Nova 2-beam facility was used to conduct X-ray laser experiments



X-ray laser plasma was created by illuminating exploding foil target from both sides by 2.5 kJ, 500 ps beams of green Nova light focused to 120 μm by 2 cm line

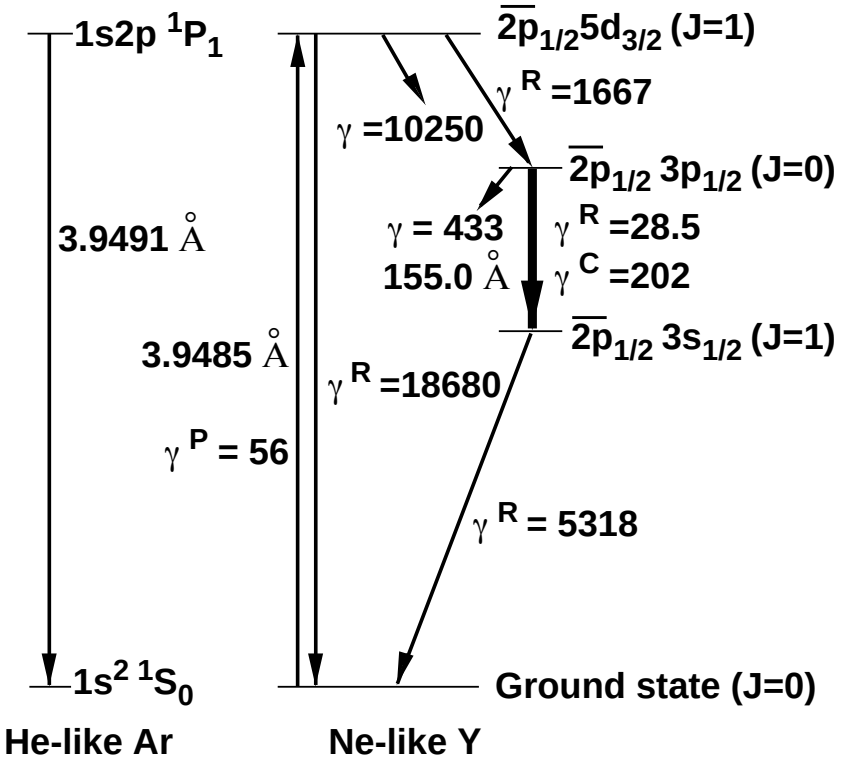


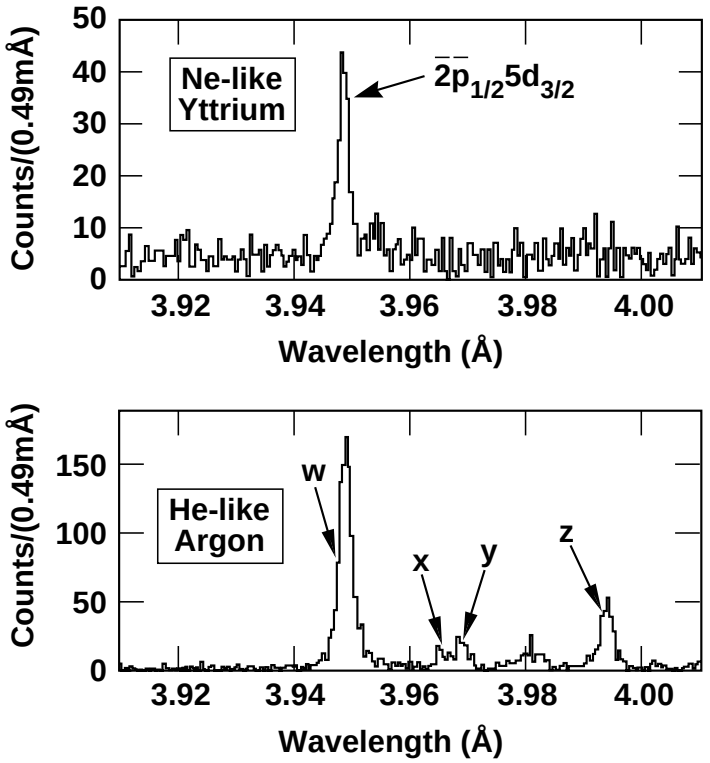
Collaborated with Peter Beiersdorfer, Steve Elliott, and EBIT group on many experiments to support the laboratory X-ray laser effort and improve our atomic physics capability

1. "Measurements of line overlap for resonant photopumping of 4 - 4 transitions in highly charged nickel-like ions," Phys. Rev. A 46, R25 (1992).
2. "An argon-pumped yttrium X-ray laser," Physica Scripta 47, 42 (1993).
3. "Measurement of Line Overlap for Resonant Photo-Pumping of Transitions in Neon-like Ions by Nickel-like Ions," Phys. Rev. A 47, 1403 (1993).
4. "Measurements of 3d - 5f and 3d - 6f transition energies in nickel-like ions for resonant photopumping by helium-like ions," Physica Scripta 49, 556 - 560 (1994).
5. "Resonant-line overlap for photopumping and spoiling of X-ray lasing transitions in neonlike Fe XVII and Cu XX," Phys. Rev. A 49, 3123 - 3126 (1994).
6. "Measurement of the Ly-a Mg resonance with the 2s - 3p Ne-like Ge line," Phys. Rev. A 50, 2143 - 2149 (1994).
7. "Resonant photo-pumping of neon-like cobalt with sodium Ly-a radiation," J. Phys. B 27, 4523 - 4529 (1994).
8. "Photo-pumping resonance for modifying the kinetics of a neonlike La47+ laser," Physica Scripta 51, 322 - 325 (1995).
9. "Measurement of the 3d - 4f transition in Ni-like Er for use in a photo-pumped X-ray laser scheme," Phys. Rev. A 51, 1683 - 1686 (1995).
10. "Measurements of line overlap for resonant spoiling of X-ray lasing transitions in nickel-like tungsten," Phys. Rev. A 52, 2689 - 2692 (1995).
11. "Energies of neon-like n = 4 to n = 2 resonance lines," Physica Scripta 54, 183 - 187 (August 1996).
12. "High-resolution measurement, line identification, and spectral modeling of the Kb spectrum of heliumlike argon emitted by a laser-produced plasma using a gas puff target," Phys. Rev. E 55, 3773 - 3776 (March 1997).

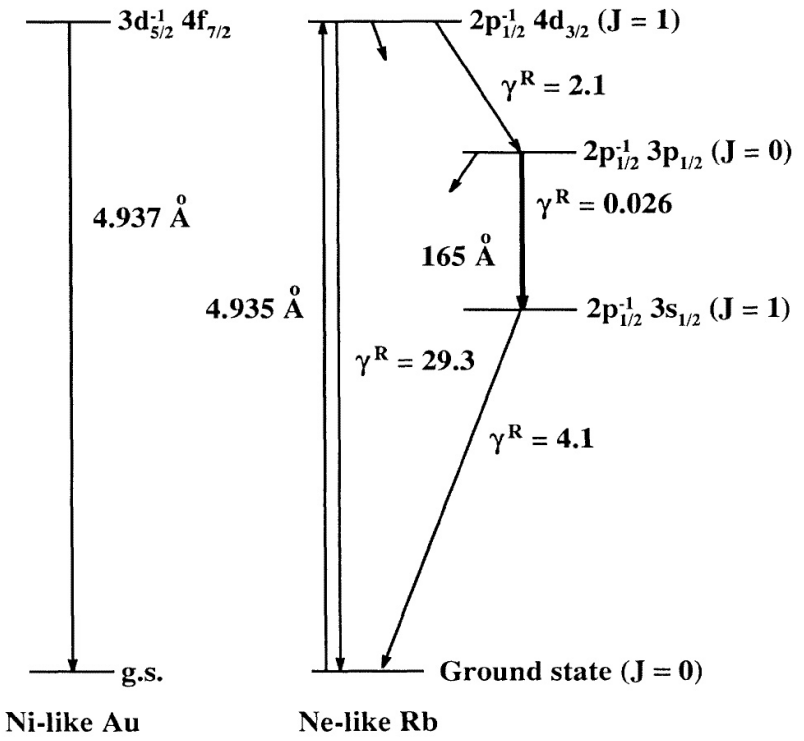
Resonance for photo-pumped scheme such as He-α Ar pumping Ne-like Y was verified by using EBIT

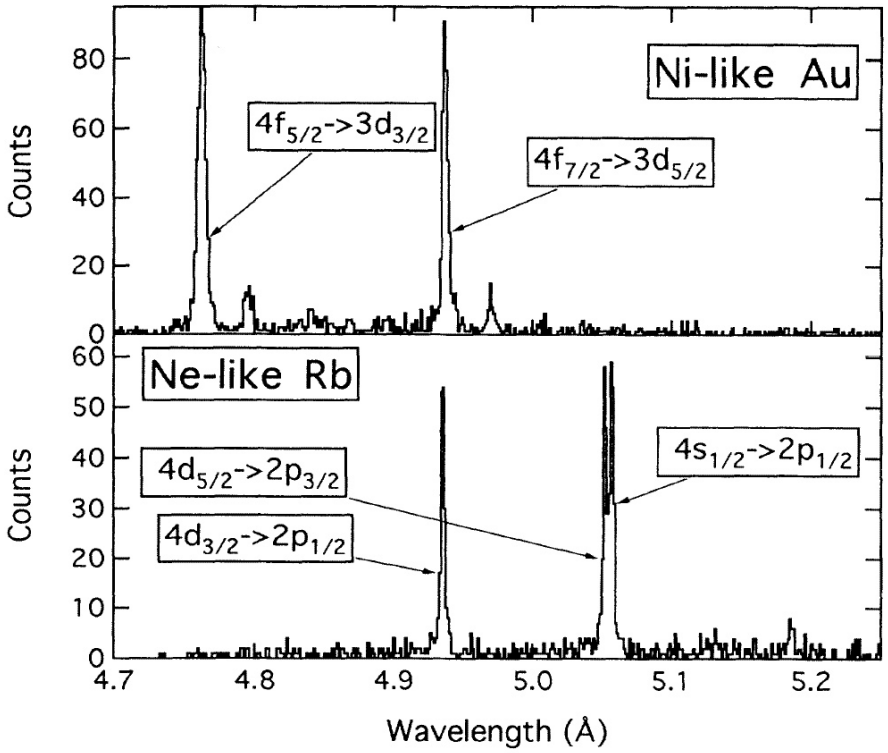
Code calculations not sufficient to verify resonances





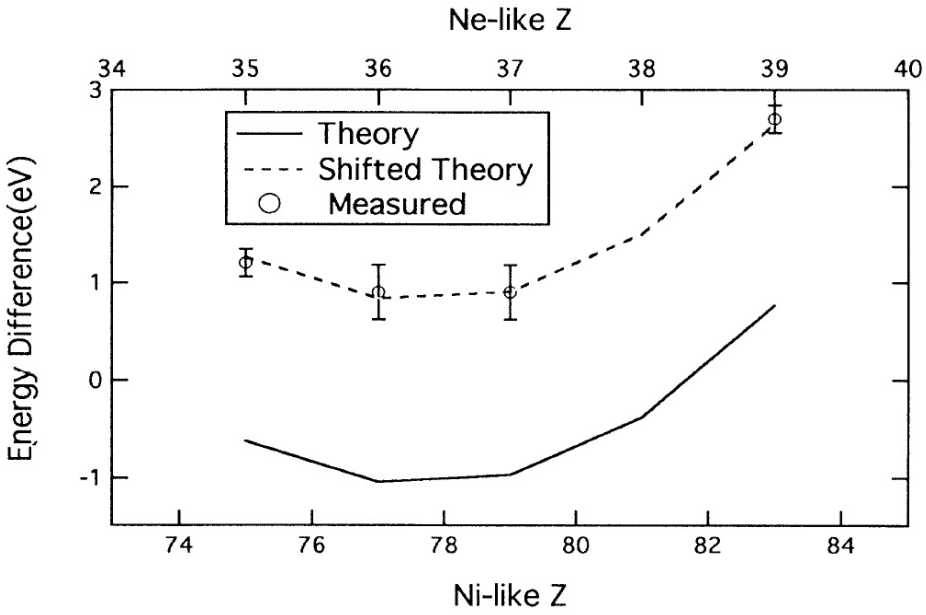
X-ray laser scheme using Ni-like Au to photo-pump Ne-like Rb was tried on Nova and the resonance was verified on EBIT

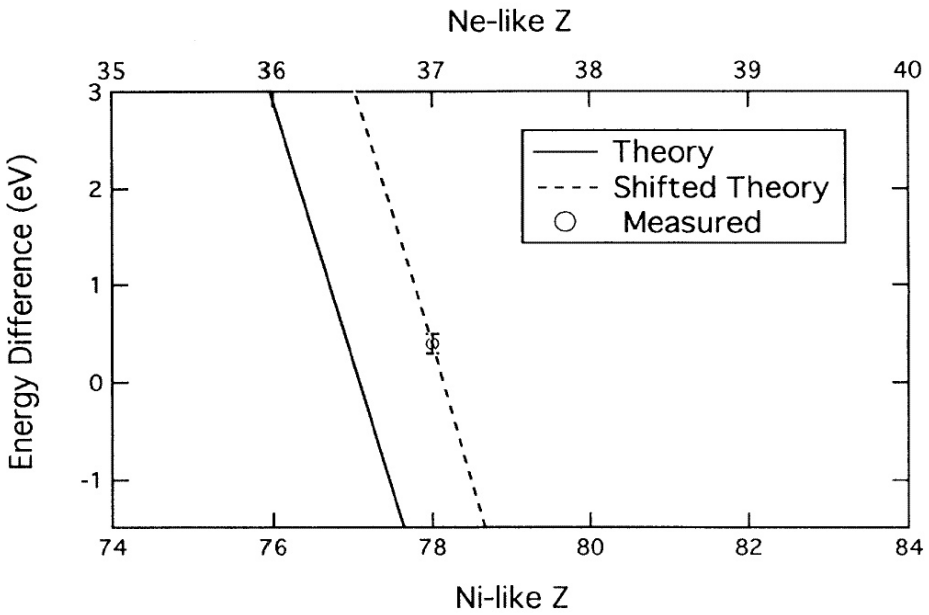




Flat Ge(111) crystal spectrometer
5 keV e-beam for Au, 3 keV for Rb

EBIT showed that the X-ray laser scheme using Ni-like Pt to photo-pump Ne-like Rb had an even better resonance than the Au pumped Rb



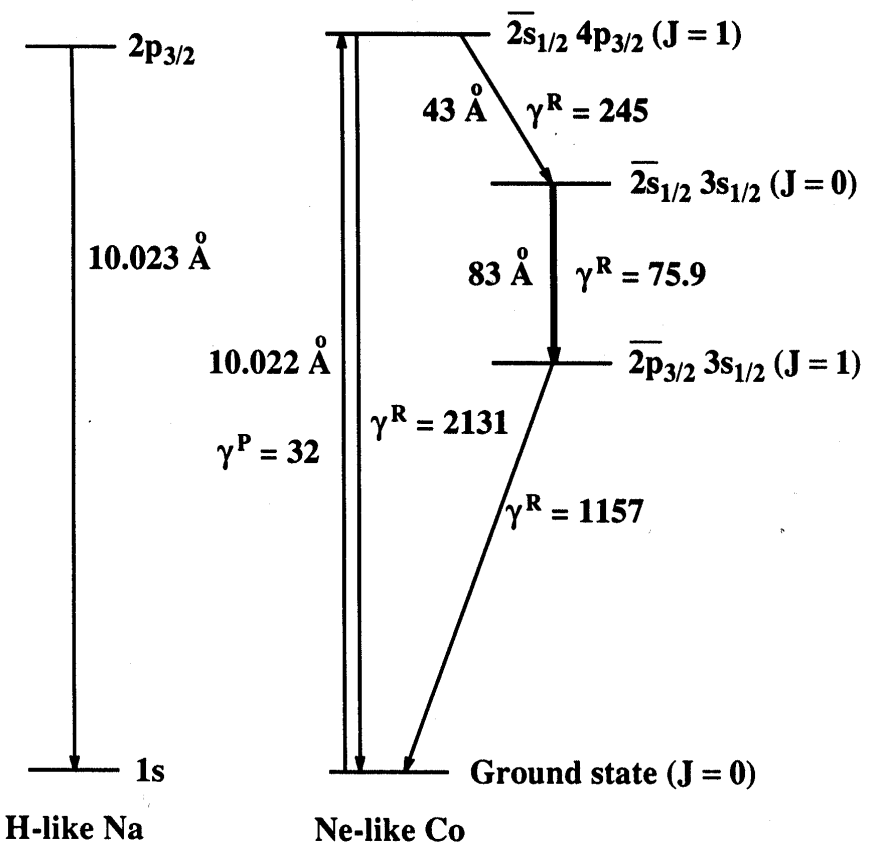


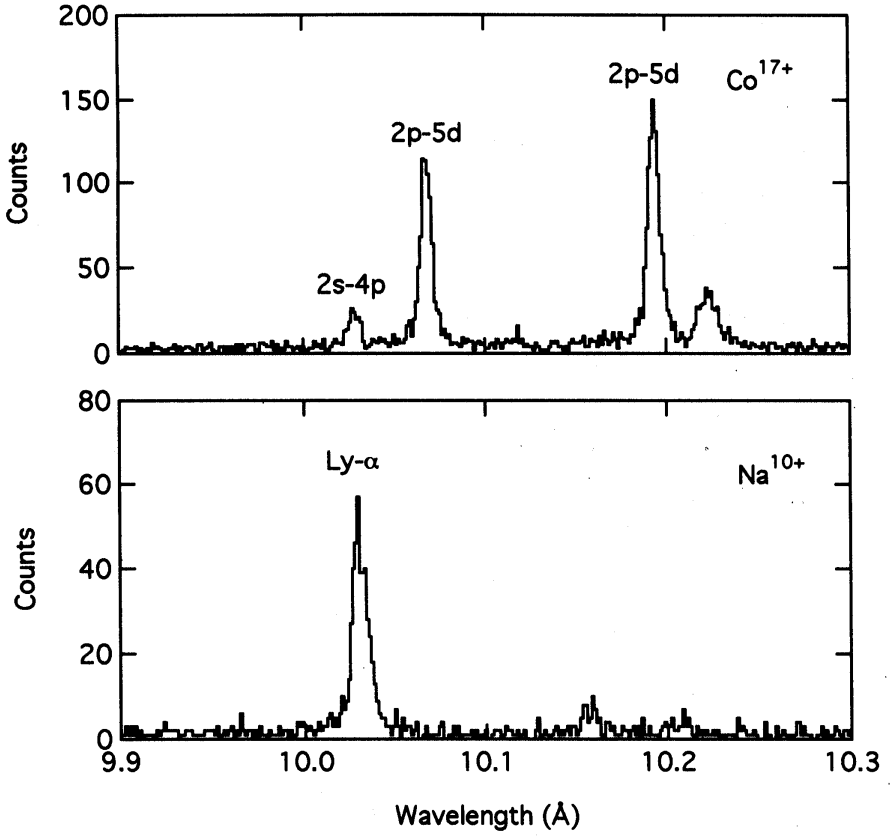
Energy difference of Ne-like $(\underline{2p}_{1/2}\ 4d_{3/2})_1$ and Ni-like $(\underline{3d}_{5/2}\ 4f_{7/2})_1$ lines
Theory is shifted by 1.88 eV to match data
$Z_{Ni} = 2\ Z_{Ne} + 5$

Energy difference of Ne-like $(\underline{2p}_{1/2}\ 4d_{3/2})_1$ and Ni-like $(\underline{3d}_{3/2}\ 4f_{5/2})_1$ lines
Theory is shifted by 2.86 eV to match data
$Z_{Ni} = 2\ Z_{Ne} + 4$

2511.4(5) eV - 4.9369(10) Å - Ni-like Au $(\underline{3d}_{5/2}\ 4f_{7/2})_1$ line
2511.9(5) eV - 4.9359(10) Å - Ni-like Pt $(\underline{3d}_{3/2}\ 4f_{5/2})_1$ line
2512.3(5) eV - 4.9351(10) Å - Ne-like Rb $(\underline{2p}_{1/2}\ 4d_{3/2})_1$ line

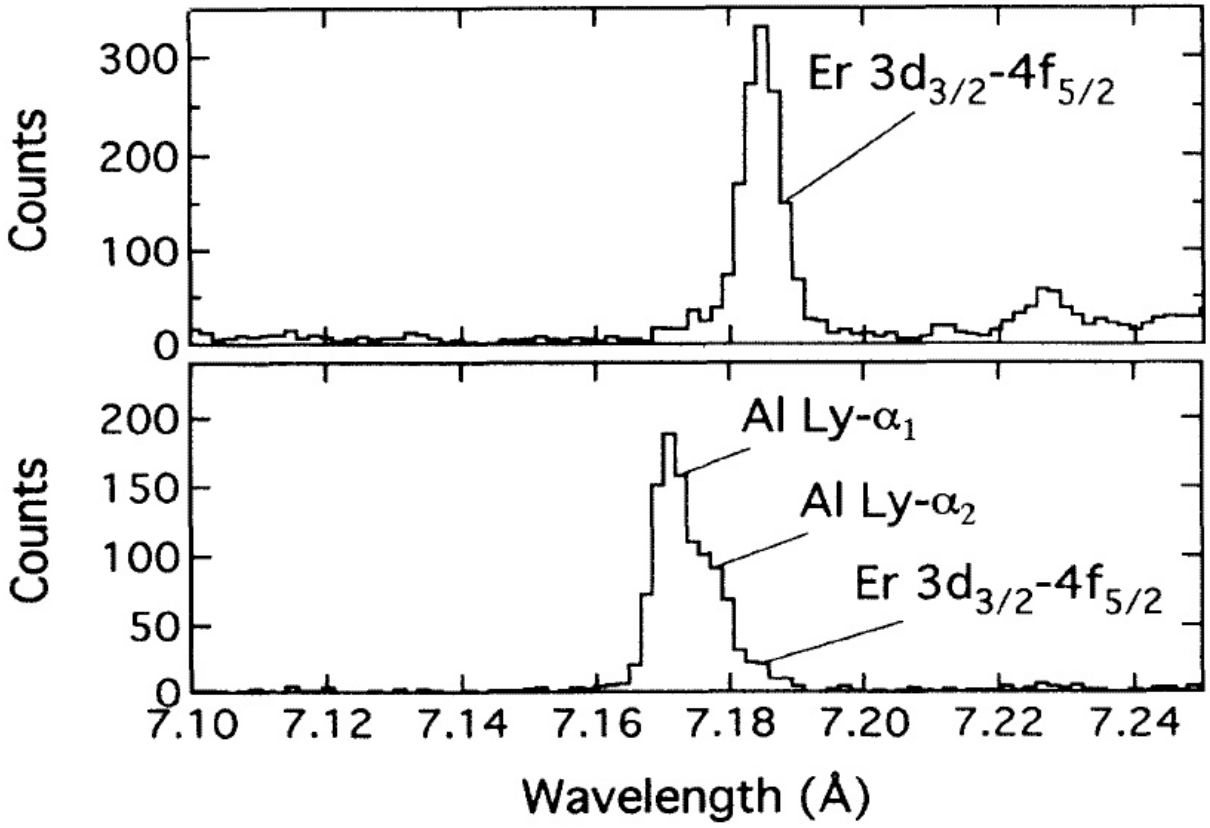
EBIT verified that Ly-α Na has excellent resonance to photo-pump Ne-like Co and potentially lase at 83 Å





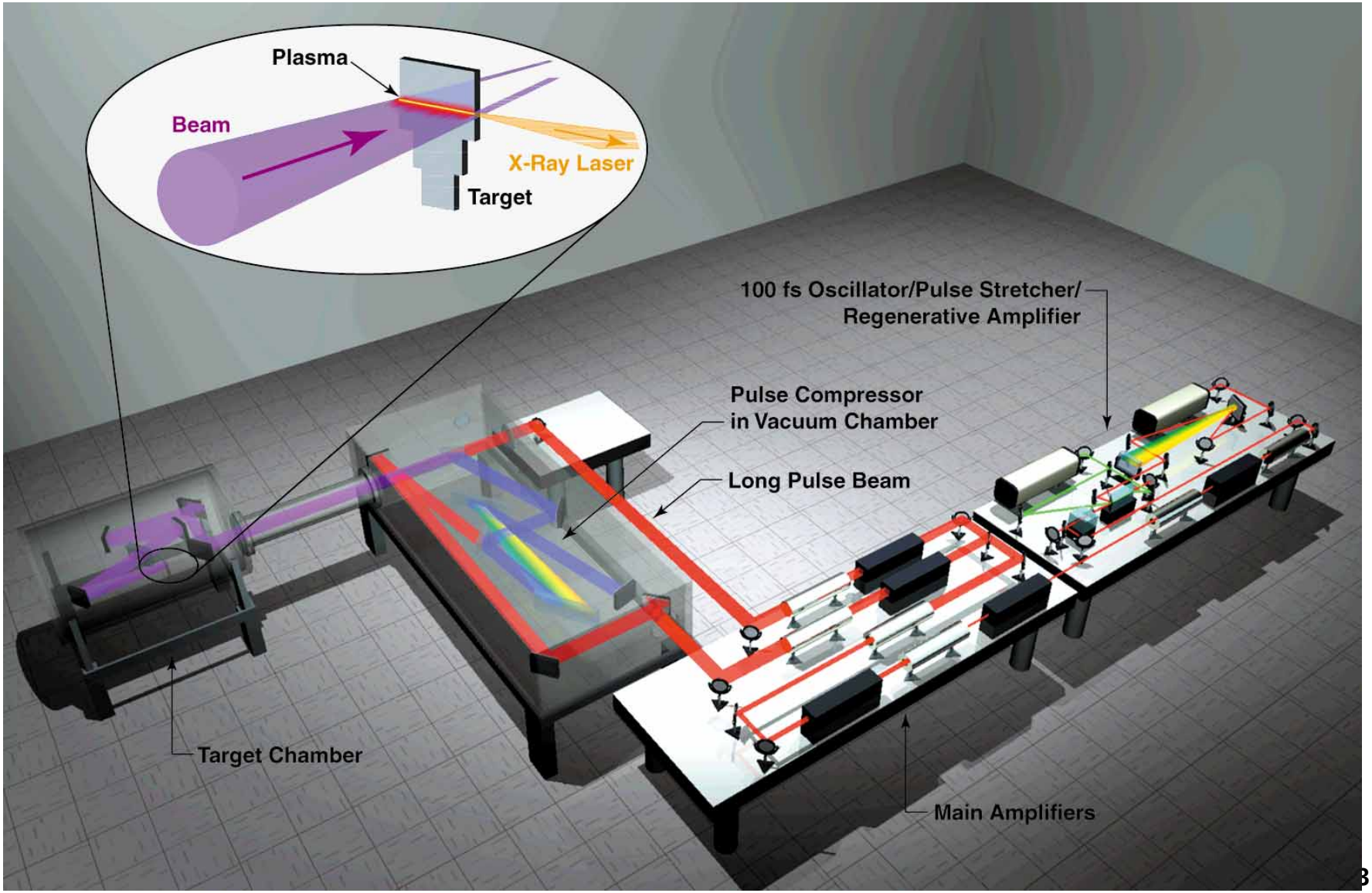
10.0222 (11) Å Ne-like Co 2s-4p line
10.0232 Å Ly-α_1 Na line
SNL Saturn machine is strong source of Ly-α Na (8 kJ)

EBIT used to verify that Ly-α Al does not have a good resonance to photo-pump Ni-like Er

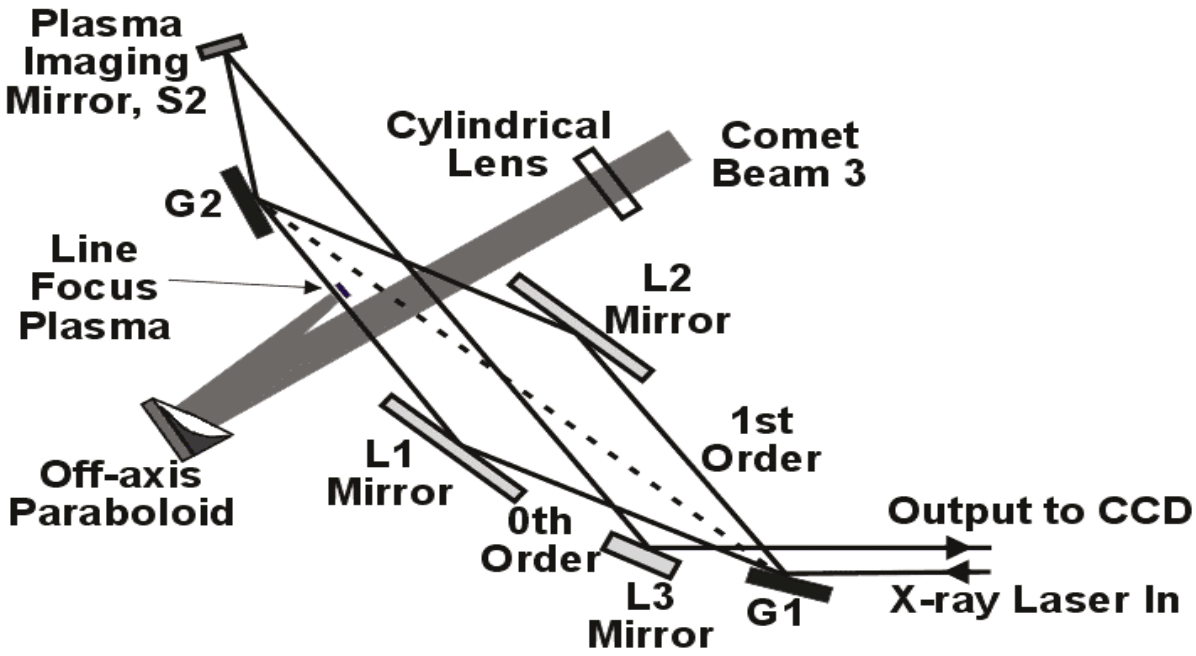


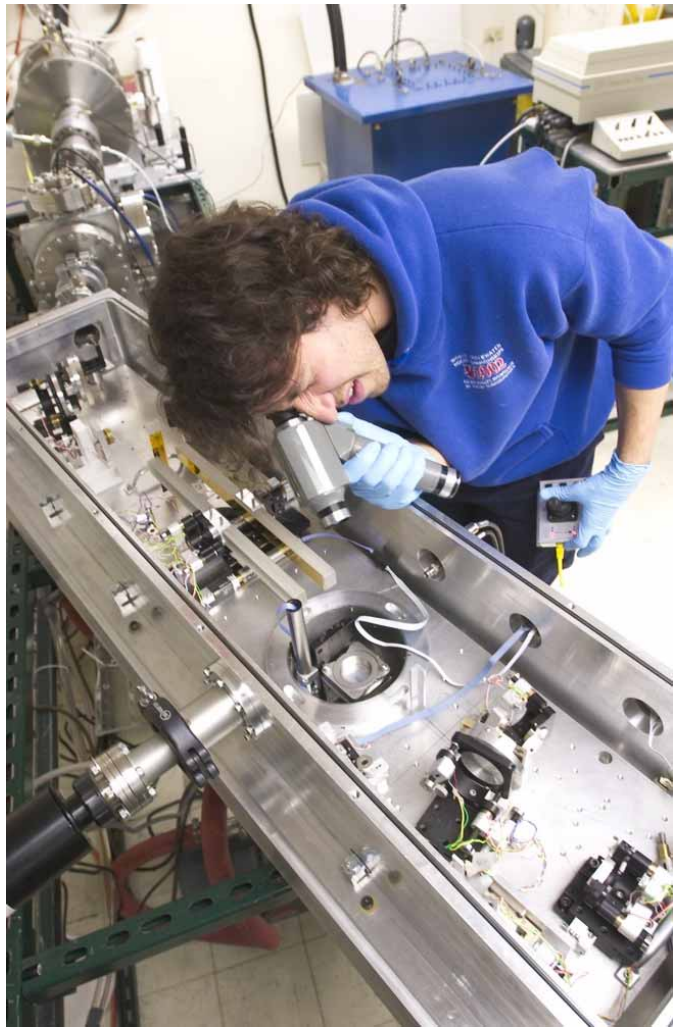
7.1763 Å - Ly-α_2 Al line
7.176 Å MCDF calculation of Ni-like Er 3d3/2 - 4f5/2 line
7.178 Å Estimate from nearby elements of Ni-like Er 3d3/2 - 4f5/2 line
7.1837(13) Å - EBIT measurement

With the advent of psec lasers X-ray laser experiments can be done every 3 minutes at the COMET laser facility at LLNL using less than 10 J of energy



Combining X-ray laser and X-ray optics the X-ray laser interferometer is used to measure the 2D electron density profile of plasmas

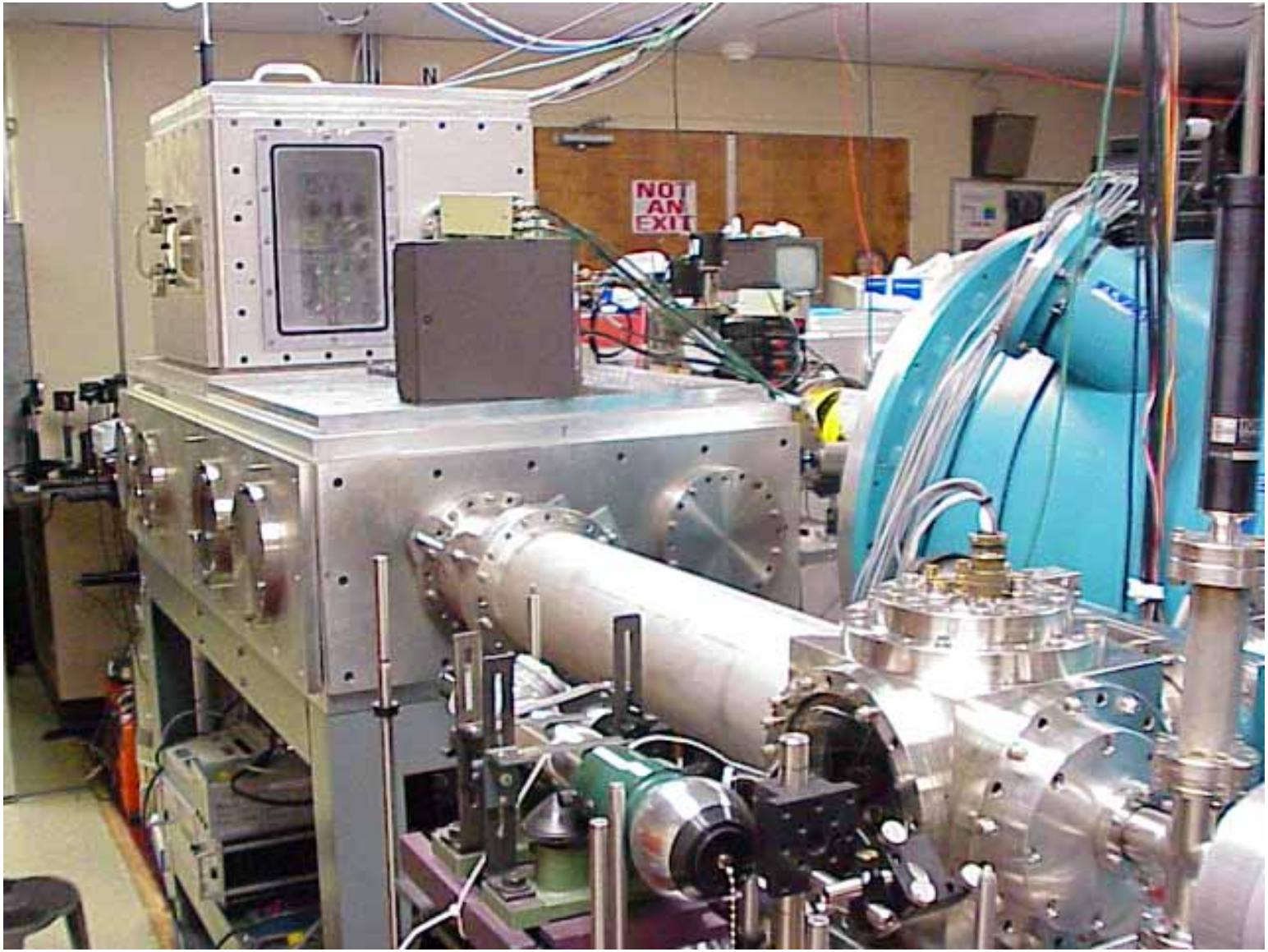




Pd XRL at 14.7 nm (84.5 eV)
Ar XRL at 46.9 nm (26.4 eV)

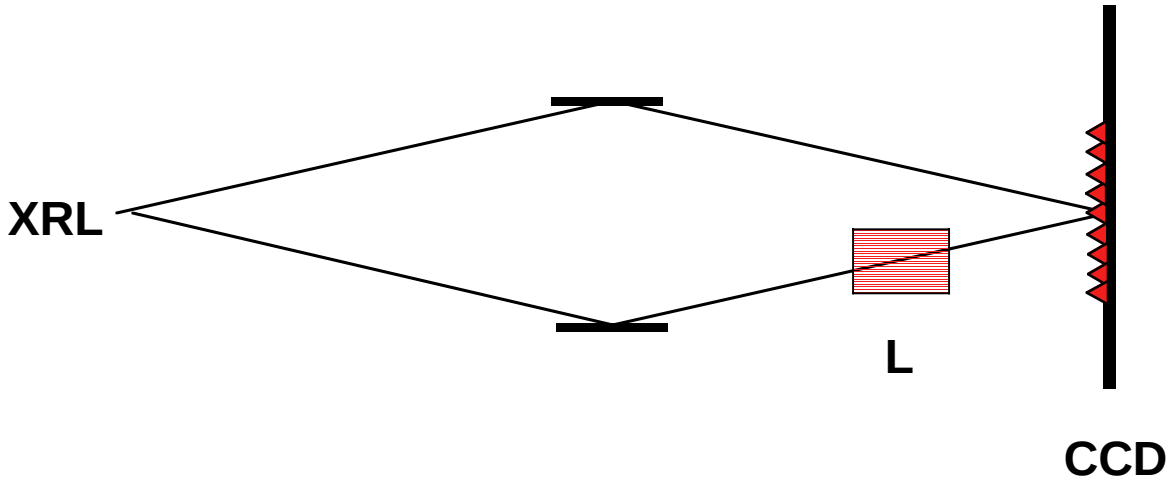
Jorge Filevich at CSU

Interferometer chamber is attached to main target chamber (blue) where XRL is produced at LLNL



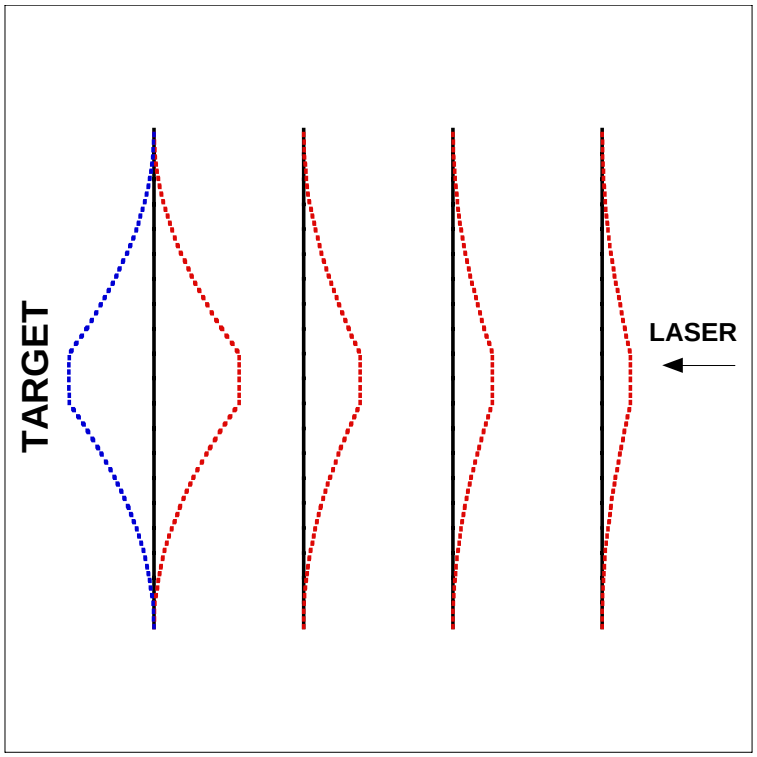
Interferometer measures the plasma electron density by counting the number of fringe shifts

Assume index of refraction $n = [\ 1 - (n_e / n_{crit})\ ]^{1/2} \cong 1 - (n_e / (2\ n_{crit}\ ))$



$N_{fringe} = (1 - n)\ L / \lambda \cong n_e\ L / (2\ n_{crit}\ \lambda)$

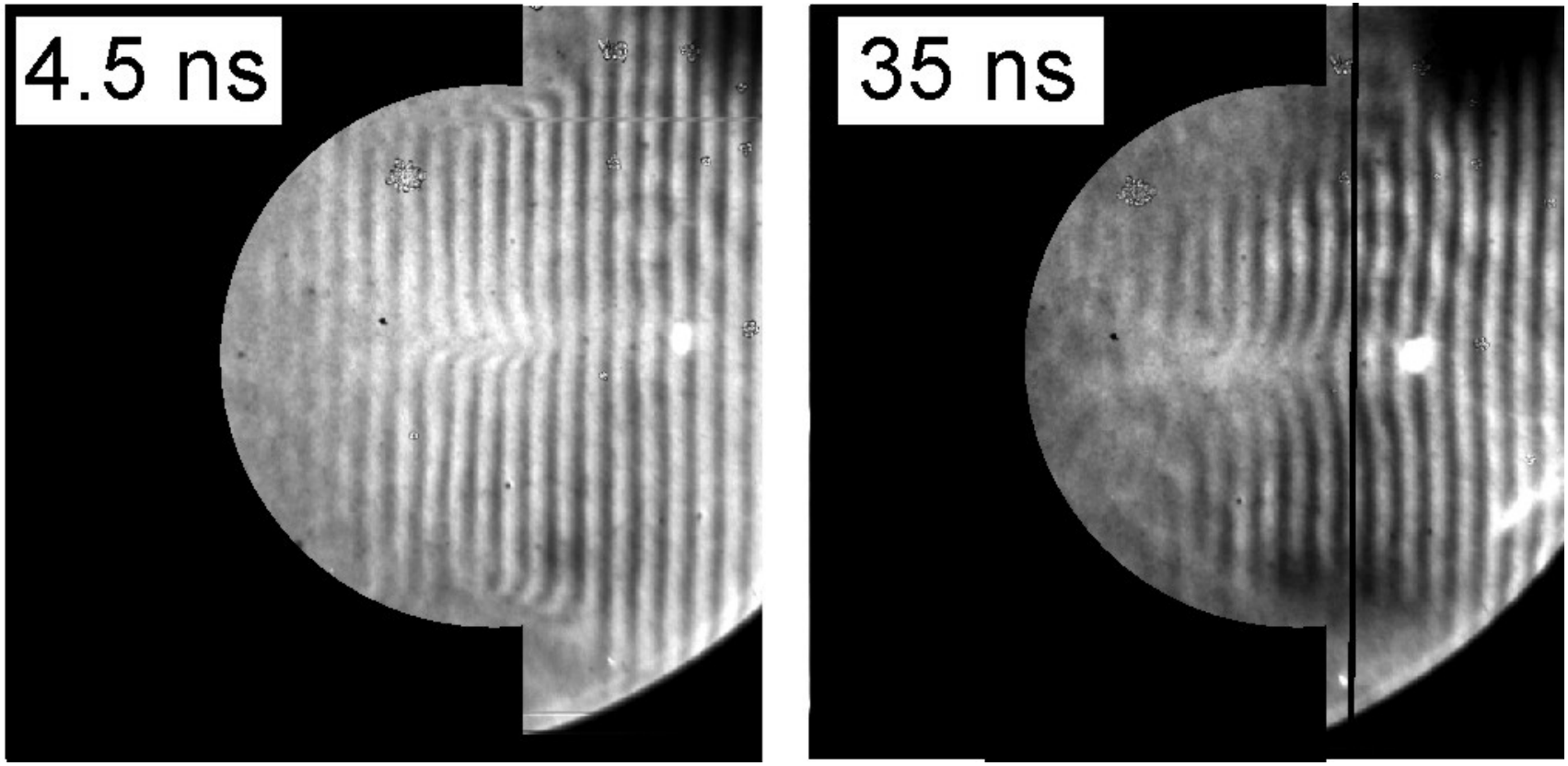
Recent interferometer experiments with Sn, Ag, and C plasmas measured an index of refraction greater than one



$N_{fringe} = n_e L / (4.8 \times 10^{18}/cm^2)$ for Ne-like Ar laser at 46.9 nm (26.44 eV) assumes only free electrons contribute to index of refraction

Anomalous index change can cause fringe lines to bend toward target surface and also cause X-ray laser to bend toward target surface

Interferograms of Ag plasma taken using Ar XRL at 46.9 nm (26.44 eV) show index of refraction greater than one at late time when plasma near Ag^{2+}



Data taken by Jorge Filevich of Colorado State University
Presented at 10th ICXRL in Berlin in August 2006
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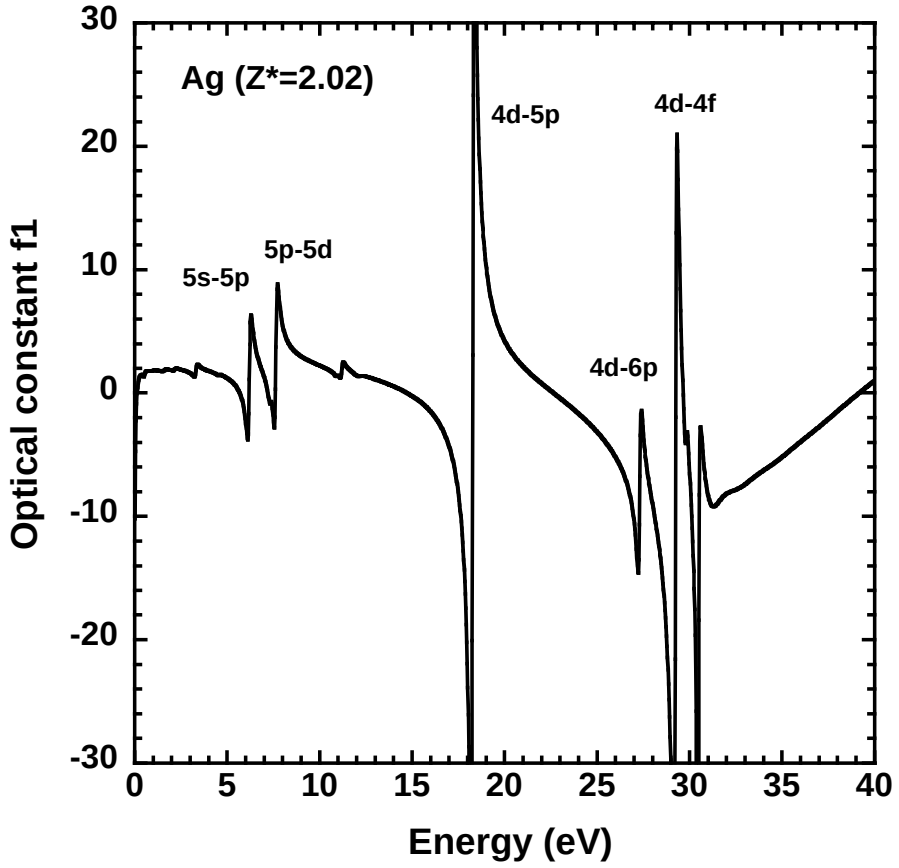
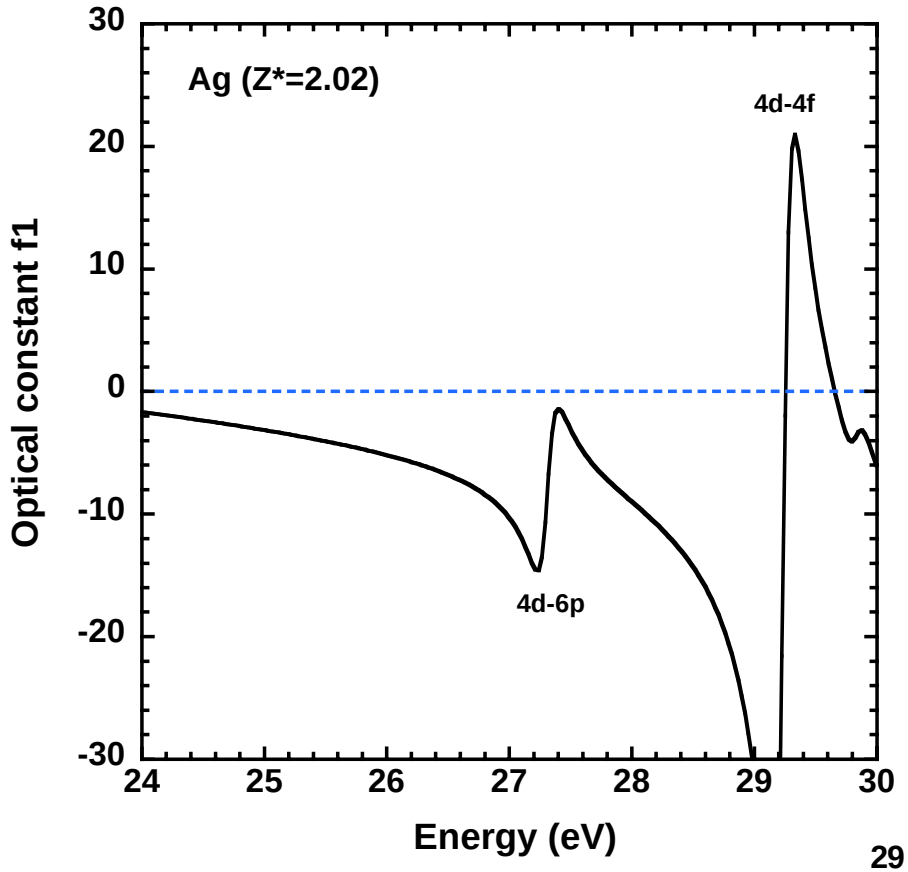
Ionization Potential

Ag^{0+} = 6.9 eV
Ag^{1+} = 20.8 eV
Ag^{2+} = 35.0 eV

Ag^{2+} has large anomalous dispersion that makes index of refraction greater than one but we need atomic data to calculate f1 accurately

Ave Atom calculations show 4d-4f line near 29.3 eV
MCDF code has 4d-4f line at 25.5 eV but 3 eV shift needed for Sn^{2+}
f1 = -6.6 at 26.44 eV $\quad n \cong 1 - (f1 * n_{ion} / (2\, n_{crit}))$





EBIT was developed as a tool to help the X-ray laser program better understand atomic physics

- Before EBIT experimentalists did experiments at GSI UNILAC
- EBIT enabled rapid response to important questions
- EBIT allowed one to select a particular ionization stage to study
- EBIT was used to measure cross sections
- EBIT did high resolution spectroscopy of high Z ions
- EBIT greatly improved our understanding of multi-electron QED
- EBIT continues to be an invaluable tool for atomic physics
- GSI using XRL to excite Li-like 2s-2p lines to study hyperfine structure