Plasma Wakefield Acceleration Experiment at PITZ

- Introduction
- PWFA principles
- Motivation
- Lithium plasma cell
- Summary

Osip Lishilin, Research Seminar,
Zeuthen, 2016-07-01

Particle accelerators are part of modern life

- About 30 000 around the world
- Industrial
  - Cutting/welding
  - Polymerization
  - Sterilization
  - Semiconductor manufacturing
  - Defectoscopy
- Medical
  - Cancer treatment
  - Isotope production
- Security

Photo: wikipedia/Ikiwaner CC BY-SA 3.0

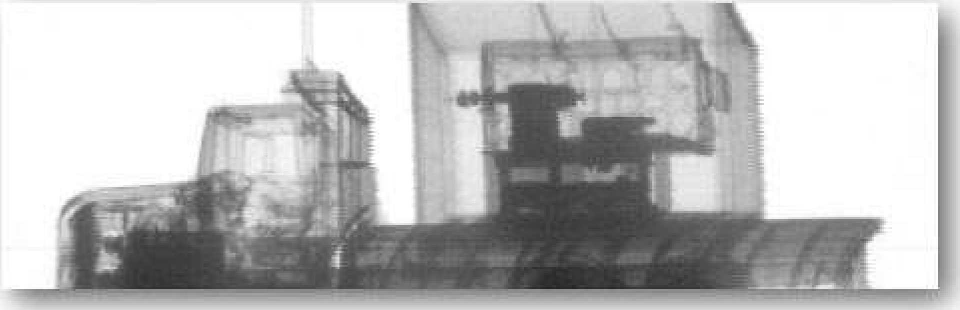


Photo: United States Department of Energy

But they are expensive

- Heidelberg Ion-Beam Therapy Center ~ €119M

http://medicalphysicsweb.org/cws/article/research/51684
https://www.klinikum.uni-heidelberg.de/About-us.124447.0.html?&L=1

- Minimum cost medical system is about €2M

Big scale science

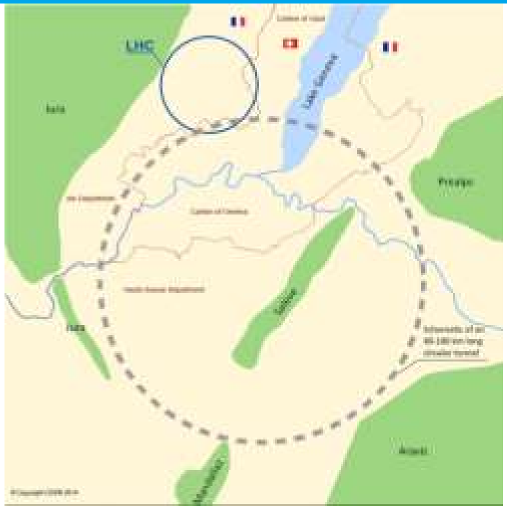


Image: CERN

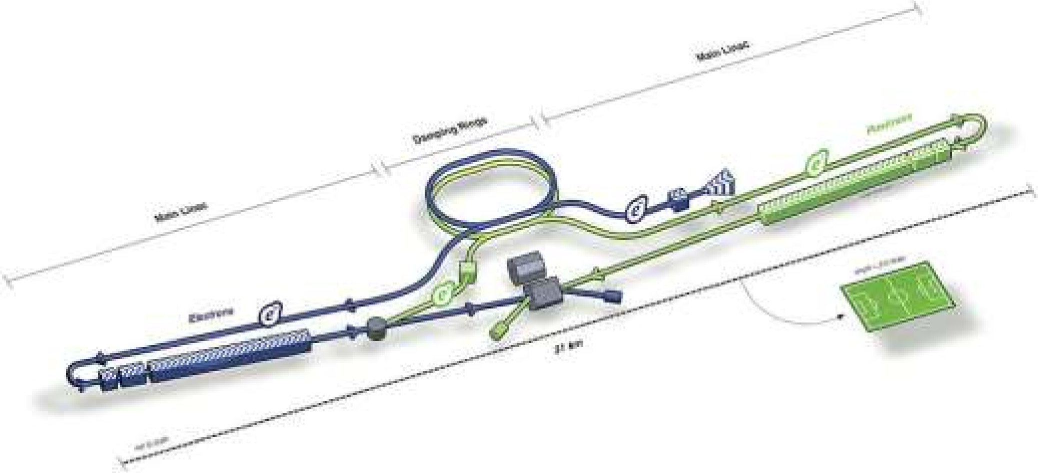
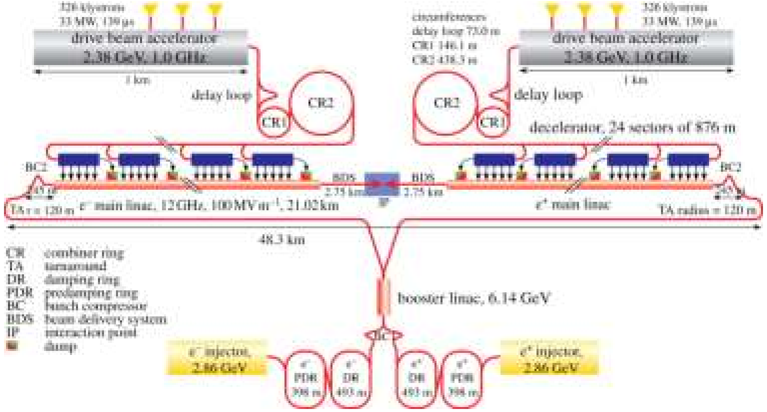


Image: ILC Comms/CC BY-SA 3.0

LHC: $10B
FCC: $?

ILC: $8B - $20B



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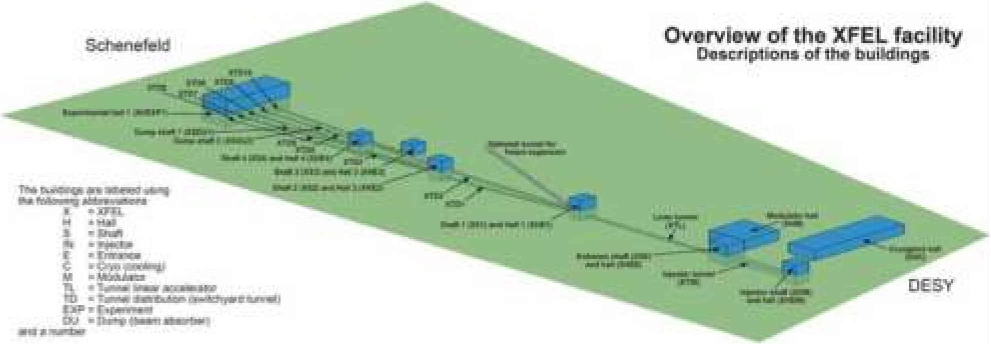


Image: xfel design report

CLIC: $?B

European XFEL: $850M

Why so big?

- Limitations of accelerating gradient
  - Electric field < 100 MV/m
- Synchrotron radiation
  - Energy loss per turn:

$$\Delta\varepsilon_T = \frac{4\pi}{3}\beta^3\gamma^4 mc^2 \frac{r_{cl}}{\rho_L}$$

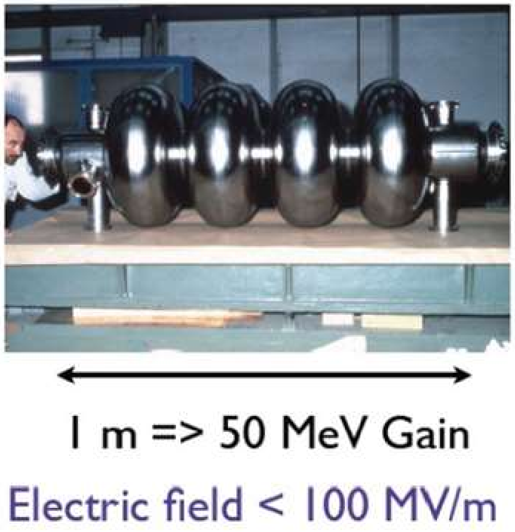


Image from http://dx.doi.org/10.5170/CERN-2016-001.1 /CC BY 4.0

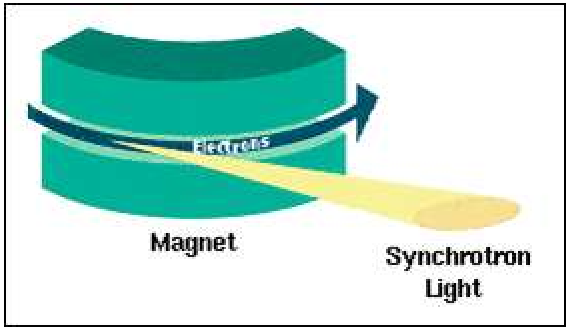
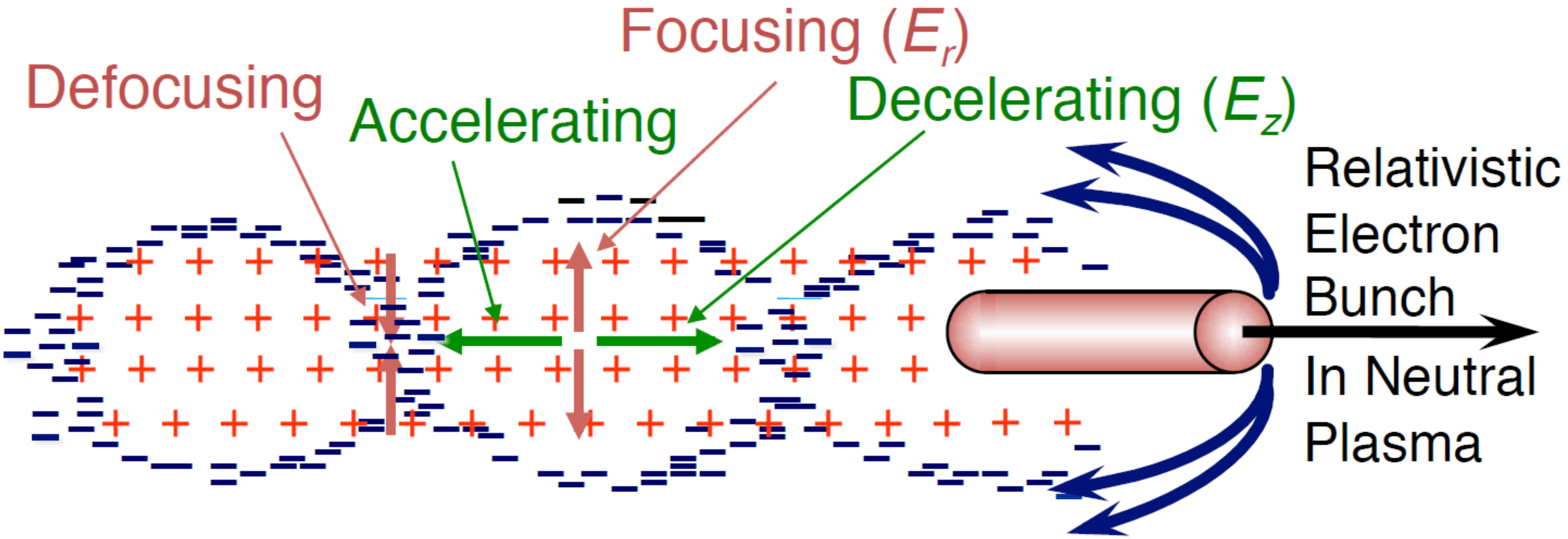


Image: John Adams Institute/ CC BY-SA 3.0

Plasma Wakefield acceleration

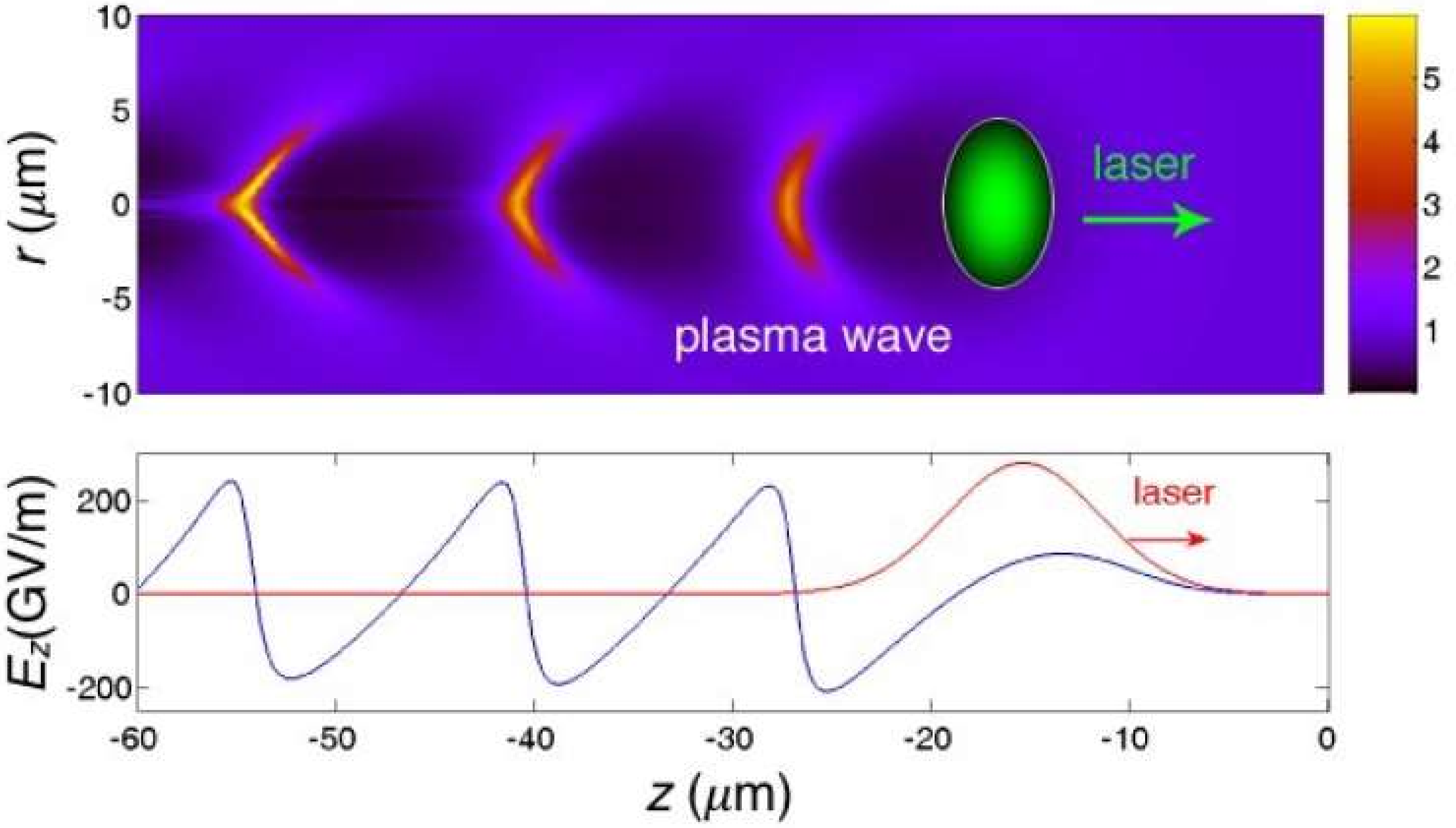
Image from http://dx.doi.org/10.5170/CERN-2016-001.119 /CC BY 4.0



- A single bunch drives a large plasma wave which accelerates and focuses particles

Laser Wakefield Acceleration

Image from http://dx.doi.org/10.5170/CERN-2016-001.1 /CC BY 4.0

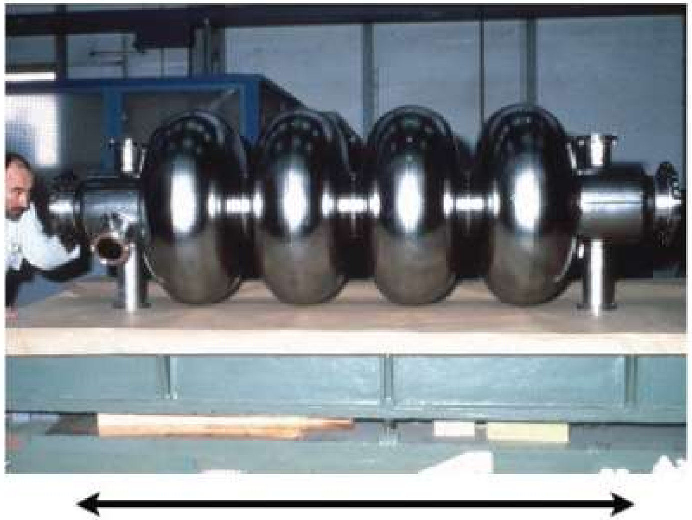


- A laser pulse drives a plasma wave through the ponderomotive force

Plasma Wakefield Acceleration

Image from http://dx.doi.org/10.5170/CERN-2016-001.1 /CC BY 4.0

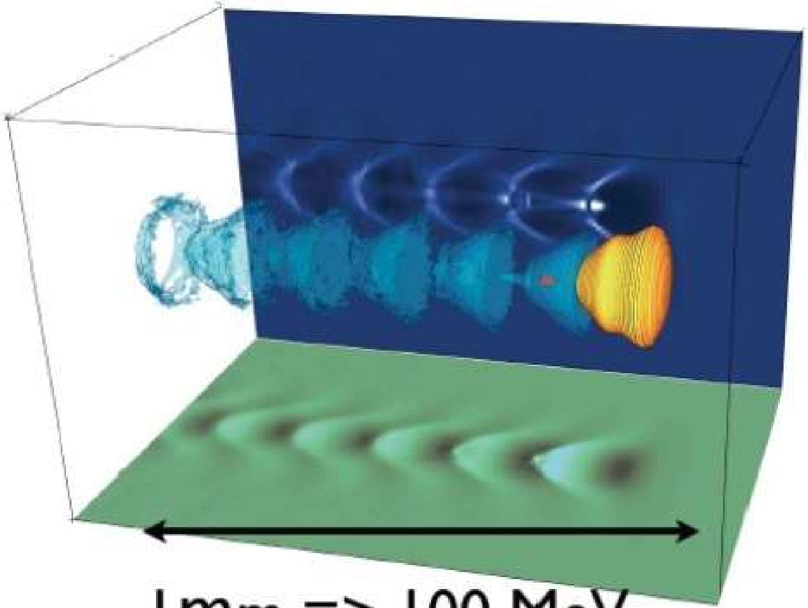
RF Cavity



1 m => 50 MeV Gain

Electric field < 100 MV/m

Plasma Cavity

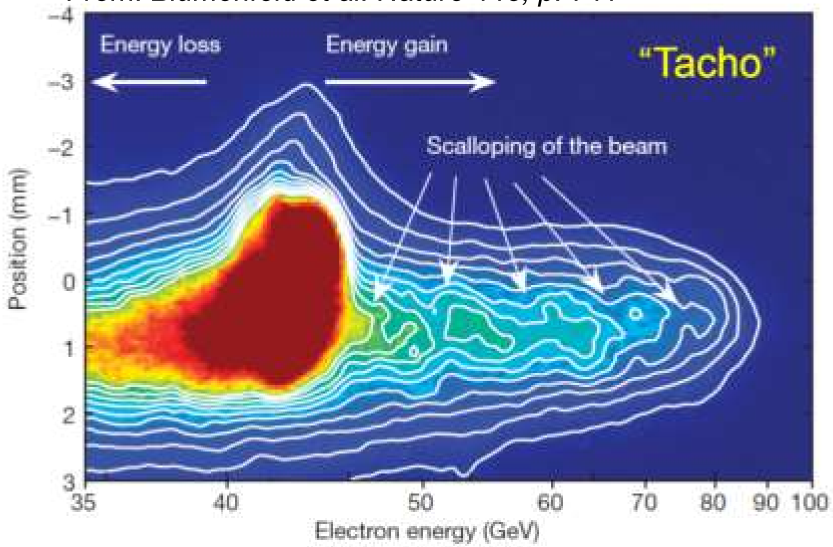


1mm => 100 MeV

Electric field > 100 GV/m

Some examples of plasma and laser wakefield acceleration

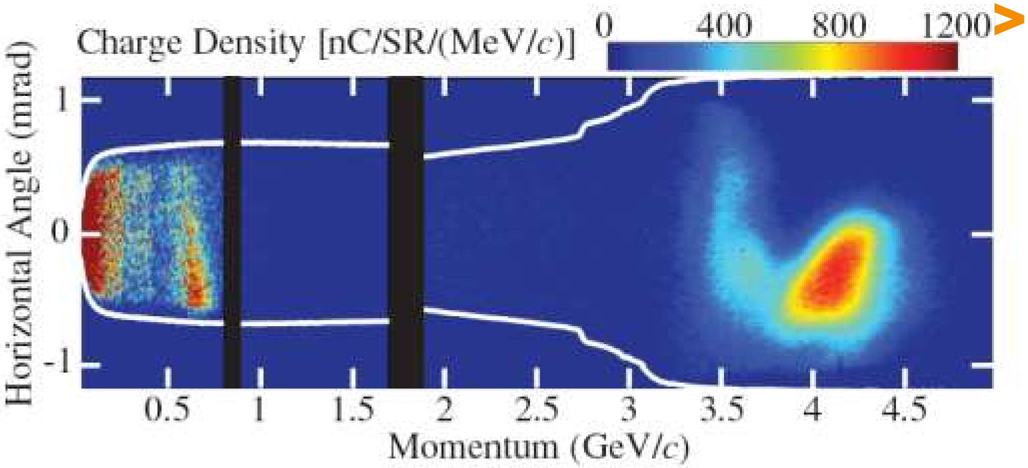
From: Blumenfeld et al. Nature 445, p. 741



> Beam-driven PWFA at SLAC:

- Initial beam energy 42 GeV (after 3 km of the accelerator)
- Increase of energy up to 84 GeV after passing 85 cm of plasma for a fraction of the beam

From: W. Leemans et al., PRL 113, 245002 (2014)



> Laser-driven PWFA at Berkeley

- 4.2 GeV beam
- 9 cm of gas discharge plasma

Concept for a linear staged plasma accelerator

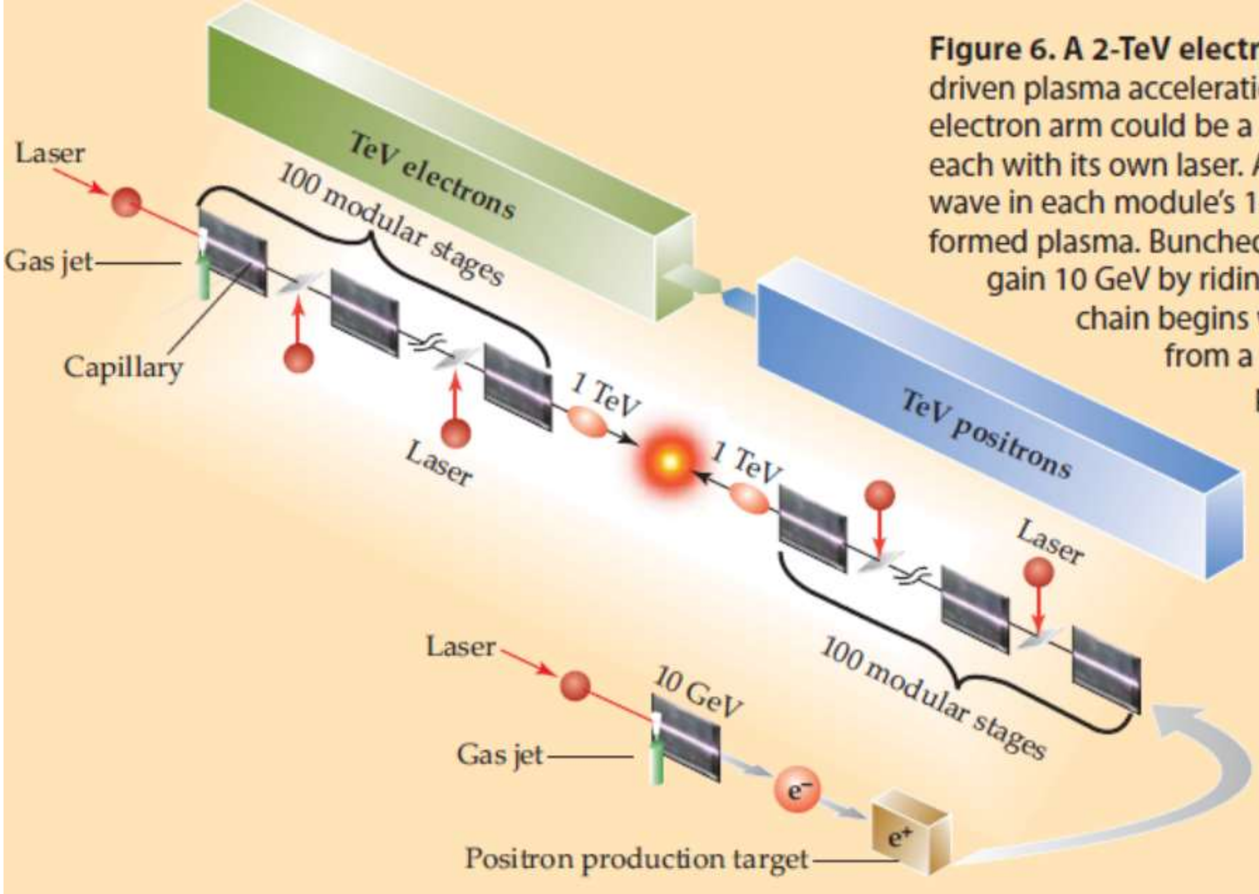
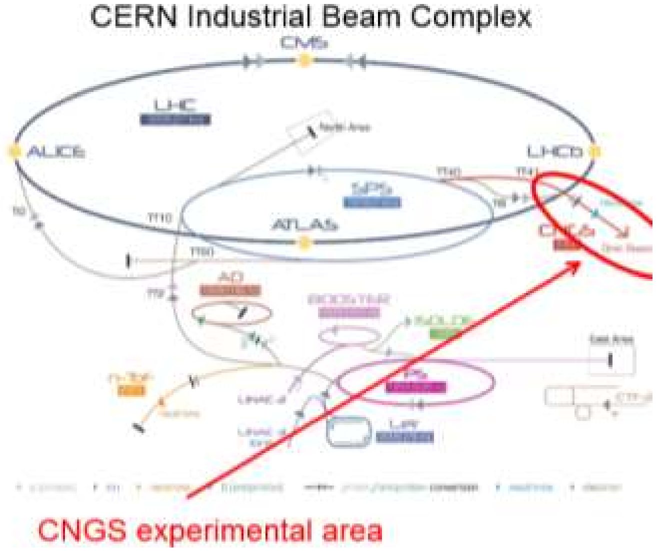


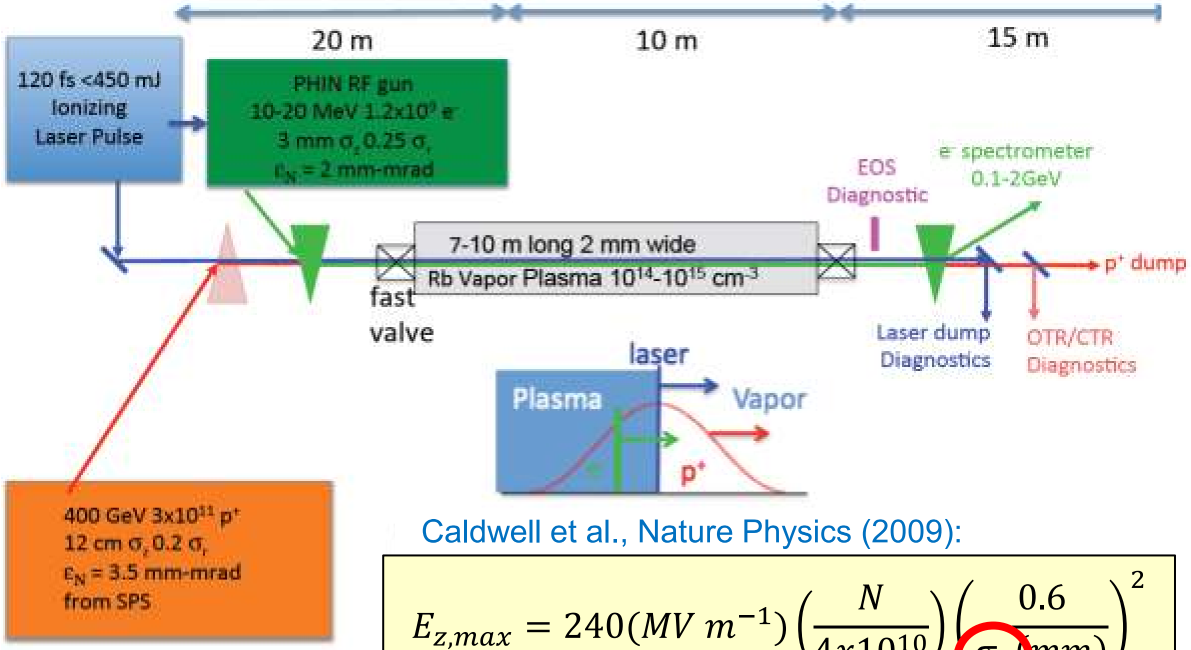
Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of preformed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

From: Leemans et al., Physics today, March 2009, p.44

EAAC Workshop 2013: Patric Muggli, AWAKE: A Proton-Driven Plasma Wakefield Experiment at CERN

- Use high energy proton beams from SPS to drive plasma wave
- Convert proton beam energy to accelerate electron beam in single stage





Caldwell et al., Nature Physics (2009):

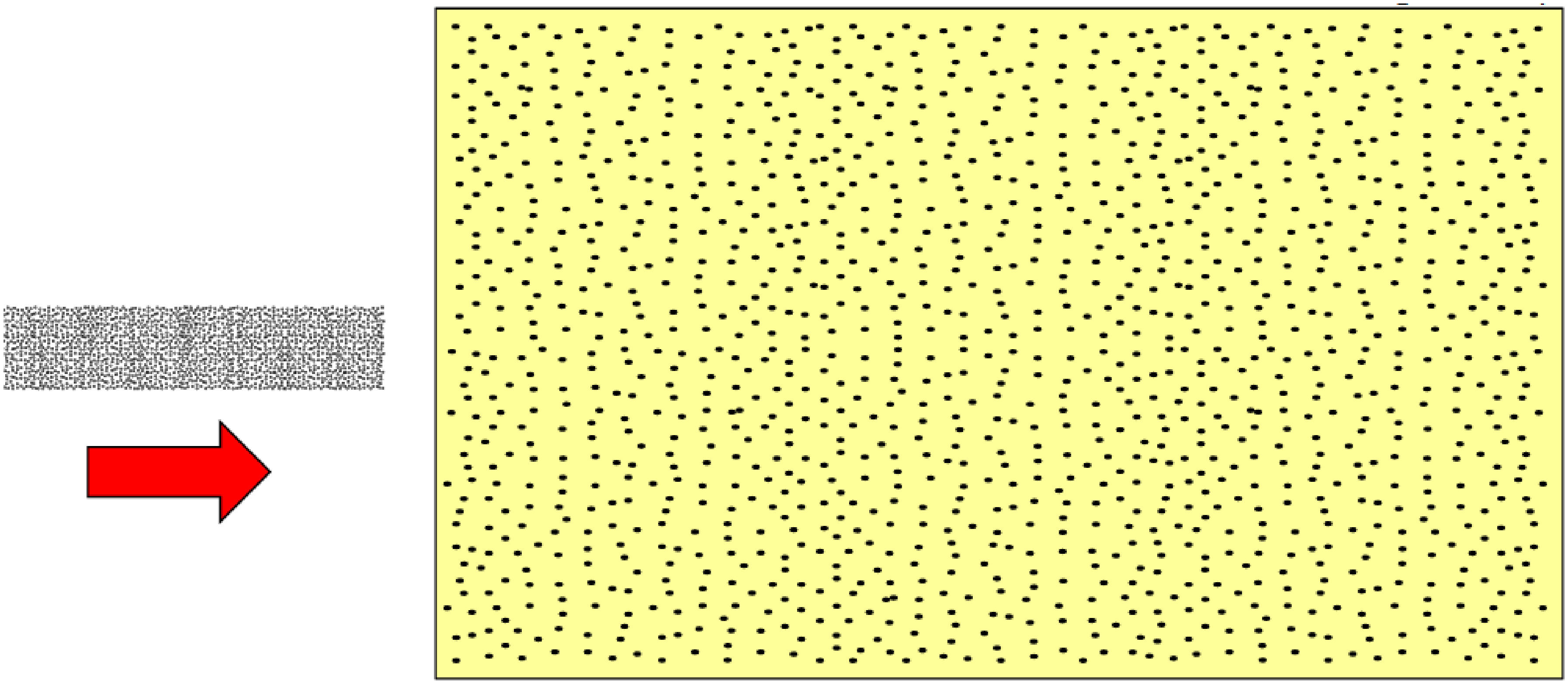
$$E_{z,max} = 240(MV\ m^{-1})\left(\frac{N}{4x10^{10}}\right)\left(\frac{0.6}{\boxed{\sigma_z}(mm)}\right)^2$$

- High accelerating gradient requires **short** bunches (σ_z less than 100µm)
- Existing proton machines produce **long** bunches (10cm)

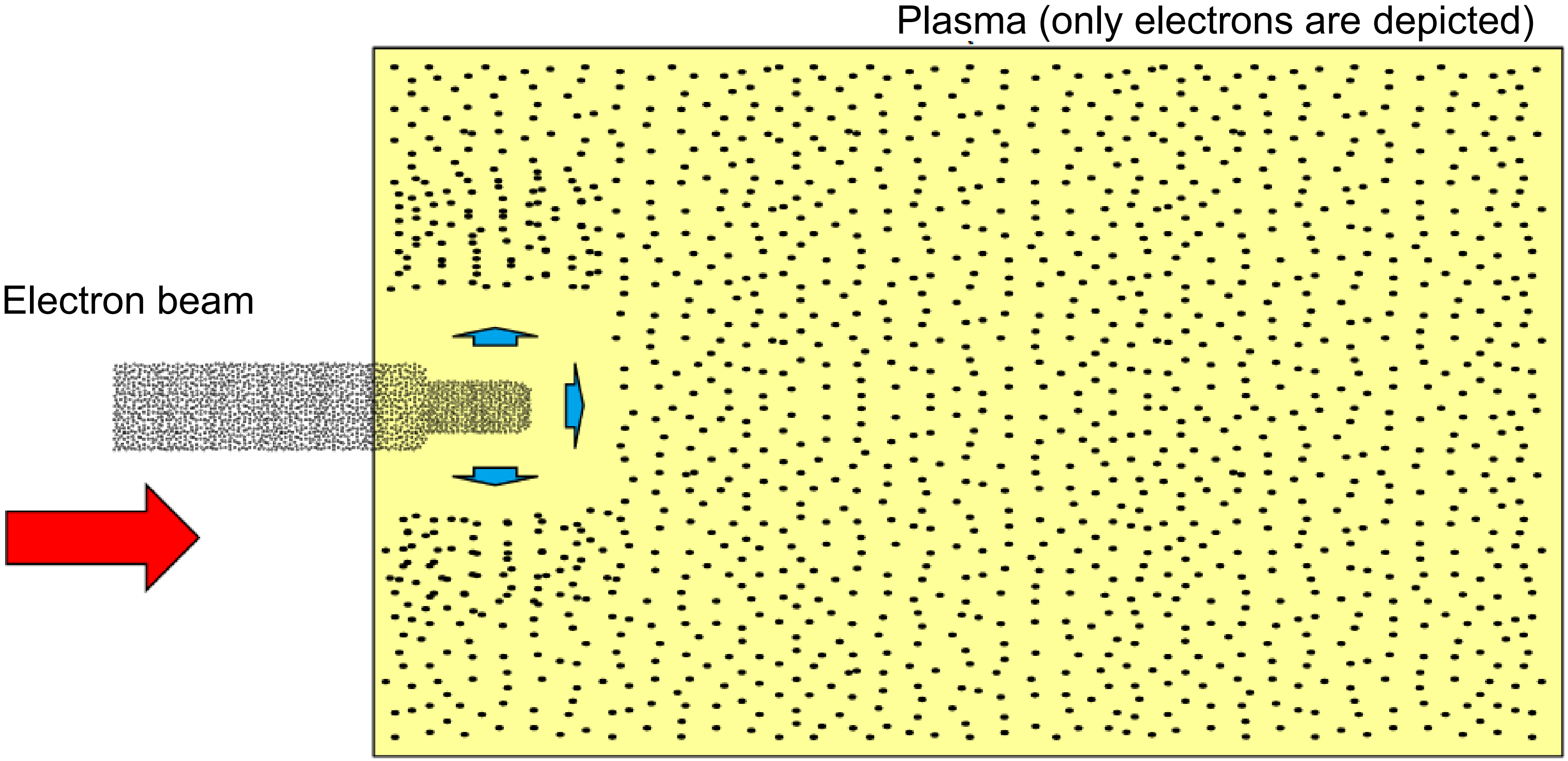
Self-modulation!

Courtesy:
Patric Muggli, Erdem Öz

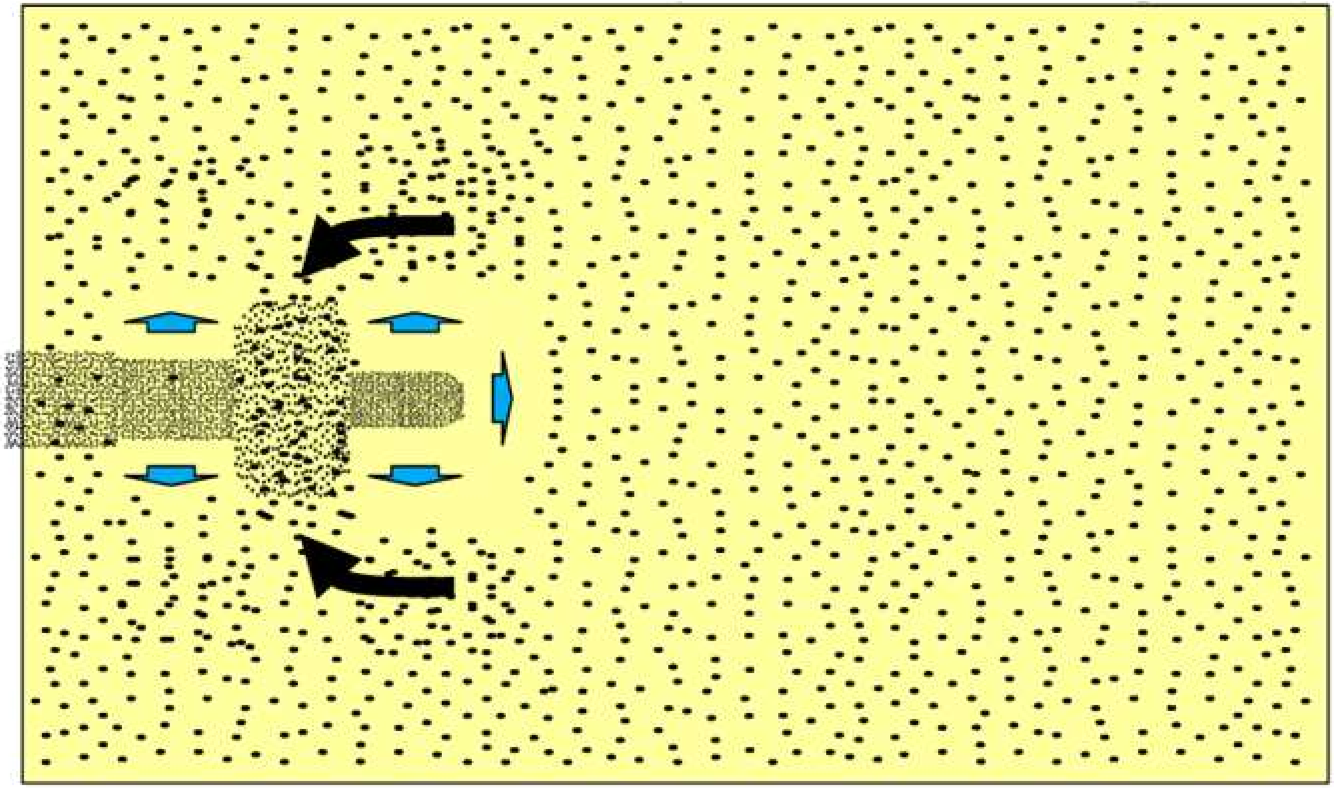
Self-Modulation instability development



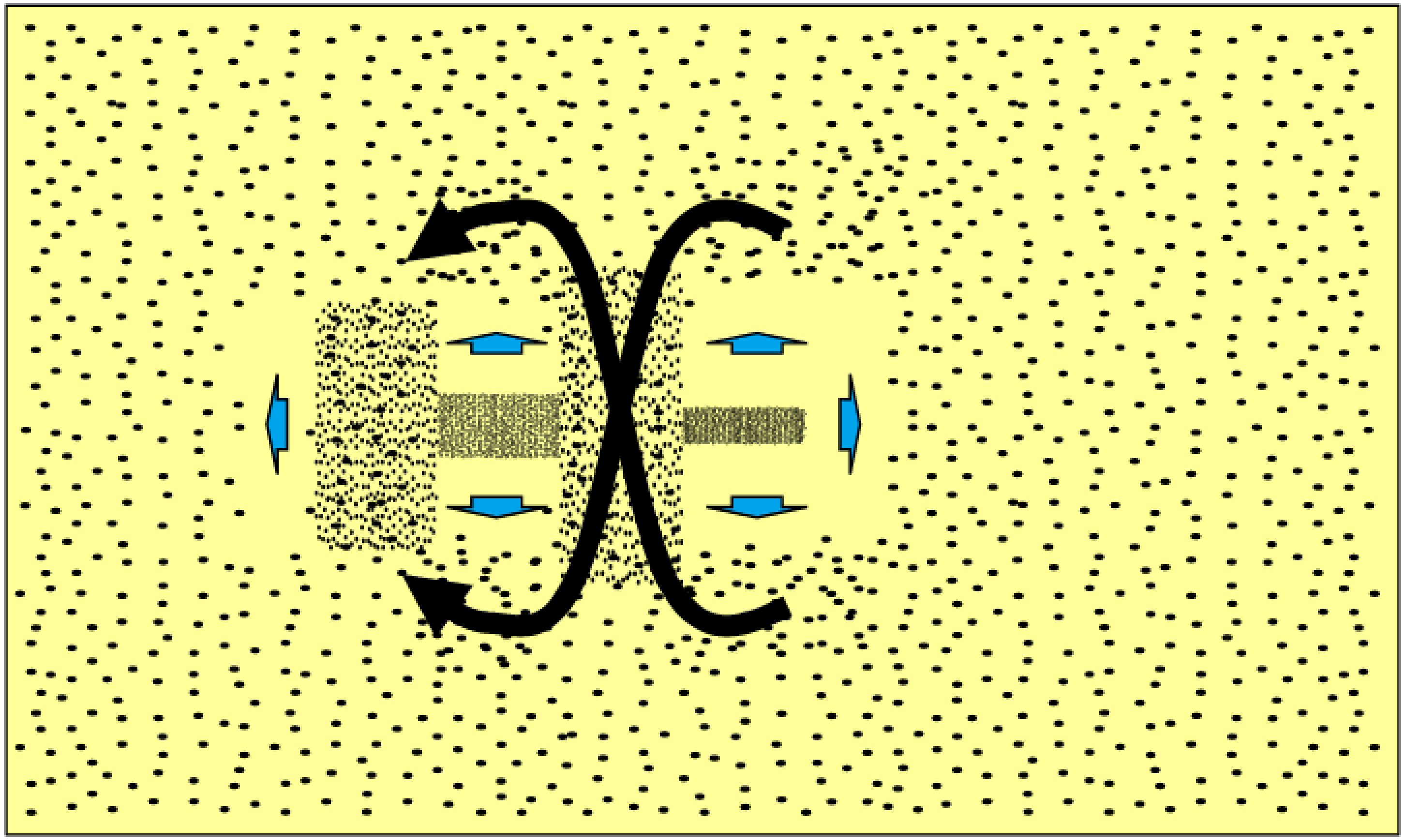
Self-Modulation instability development



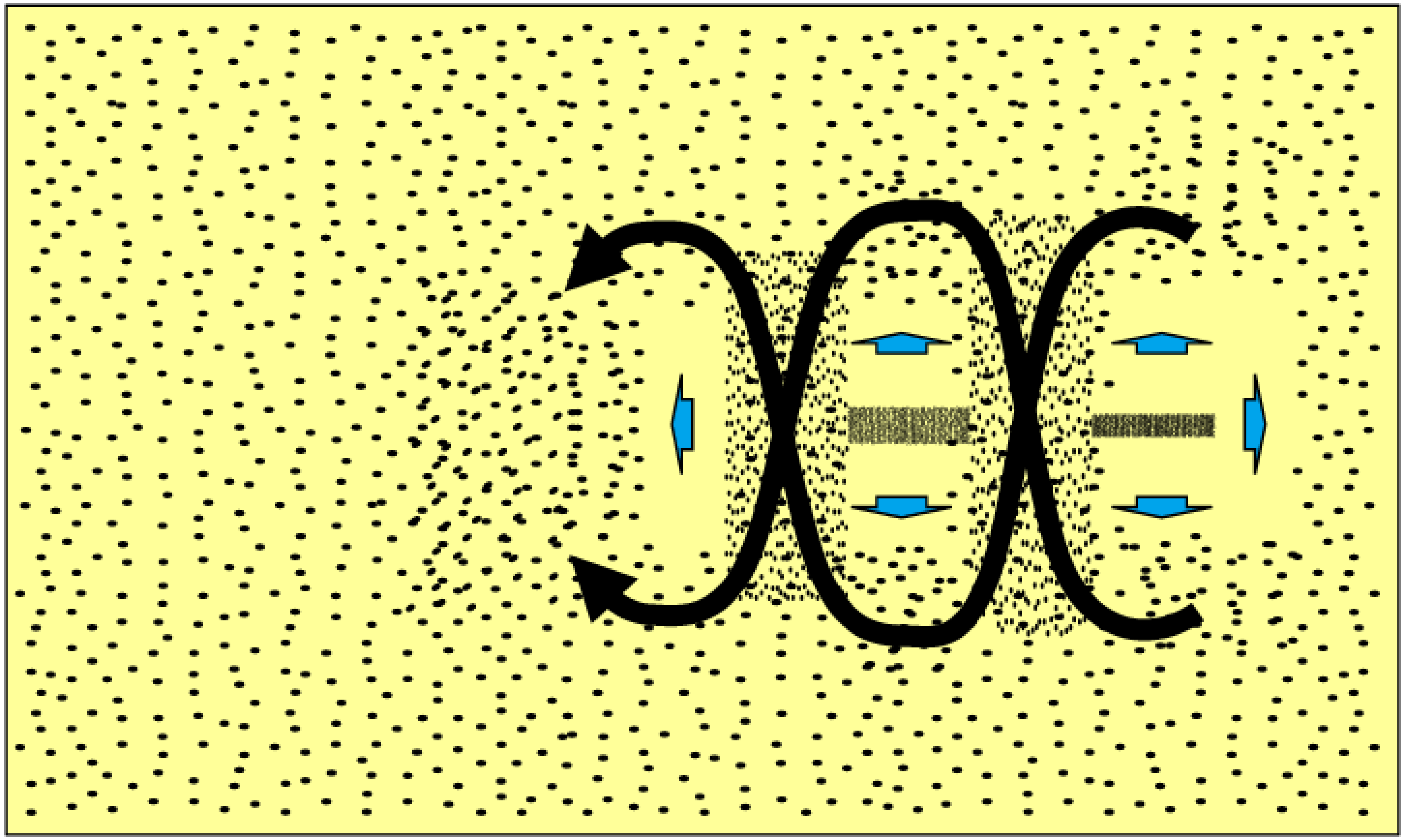
Self-Modulation instability development



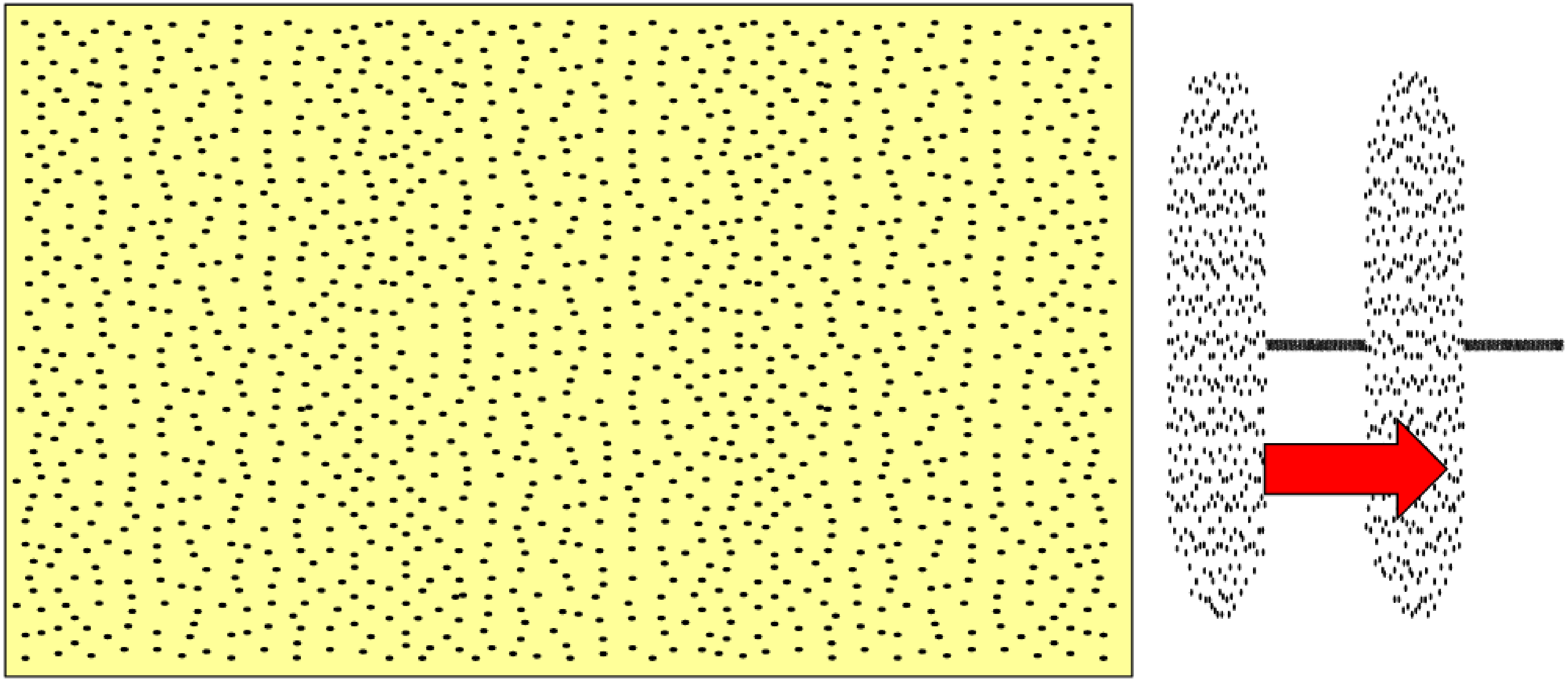
Self-Modulation instability development



Self-Modulation instability development



Self-Modulation instability development



Modulated electron beam

Simulated Self-modulation Experiment

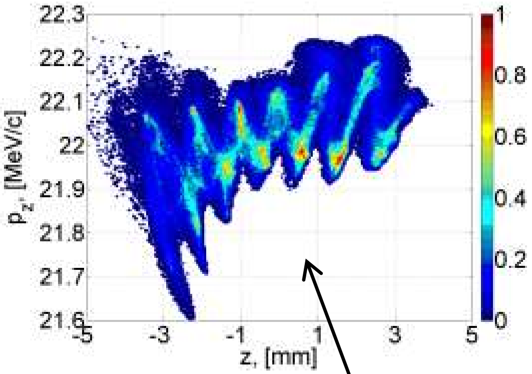
Not fully optimized

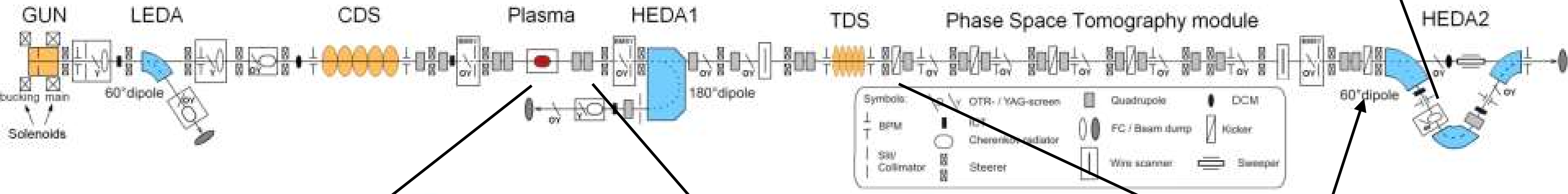
Longitudinal Phase-space studies

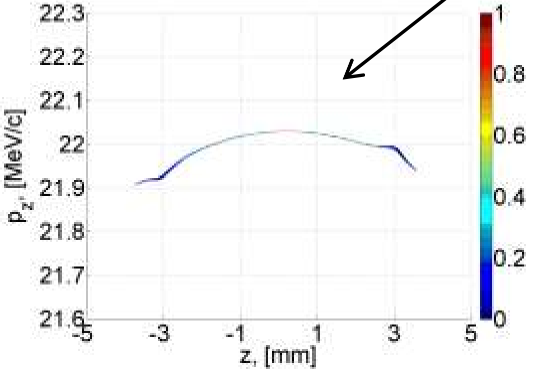
Simulations:
Martin Khojoyan /
Dmitriy Malyutin

Plasma density: 10^{15} cm^{-3} $\rightarrow \lambda_p \approx$ 1mm

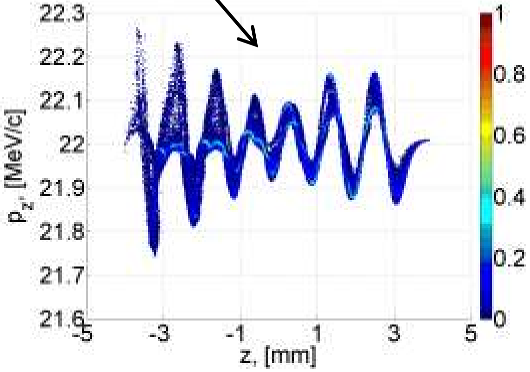
Expected phase space ←





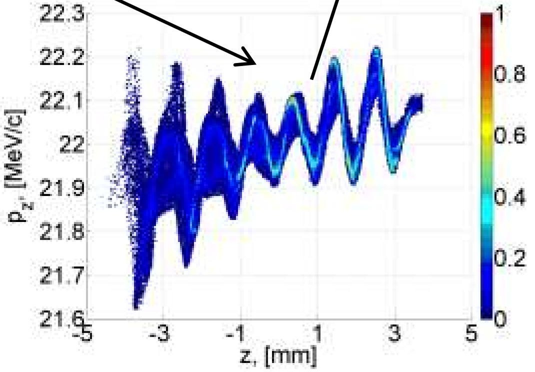


In front of plasma cell



After plasma cell

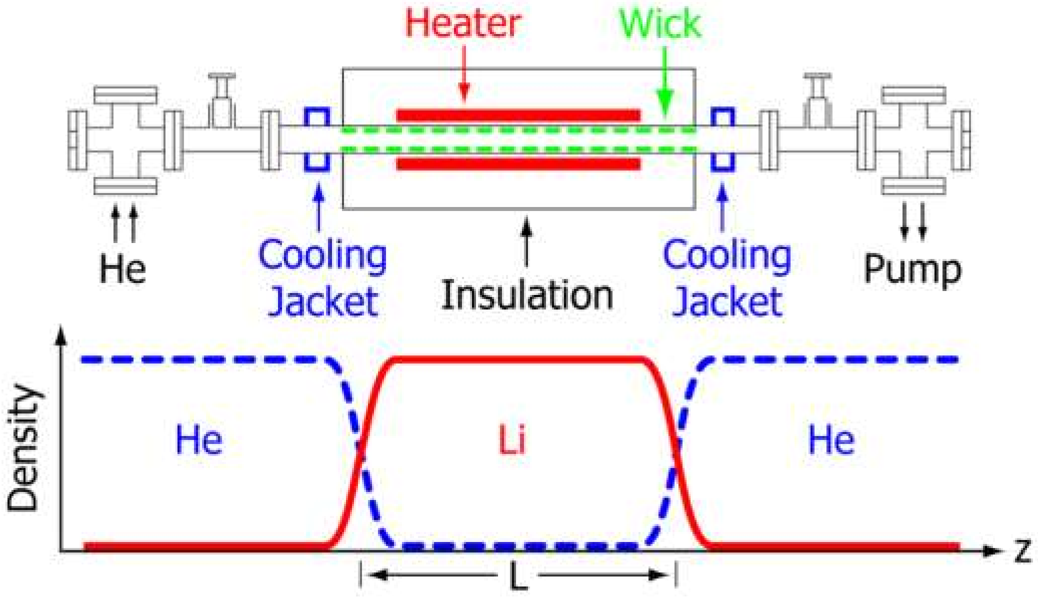
(assuming zero initial energy spread)



In front of dipole

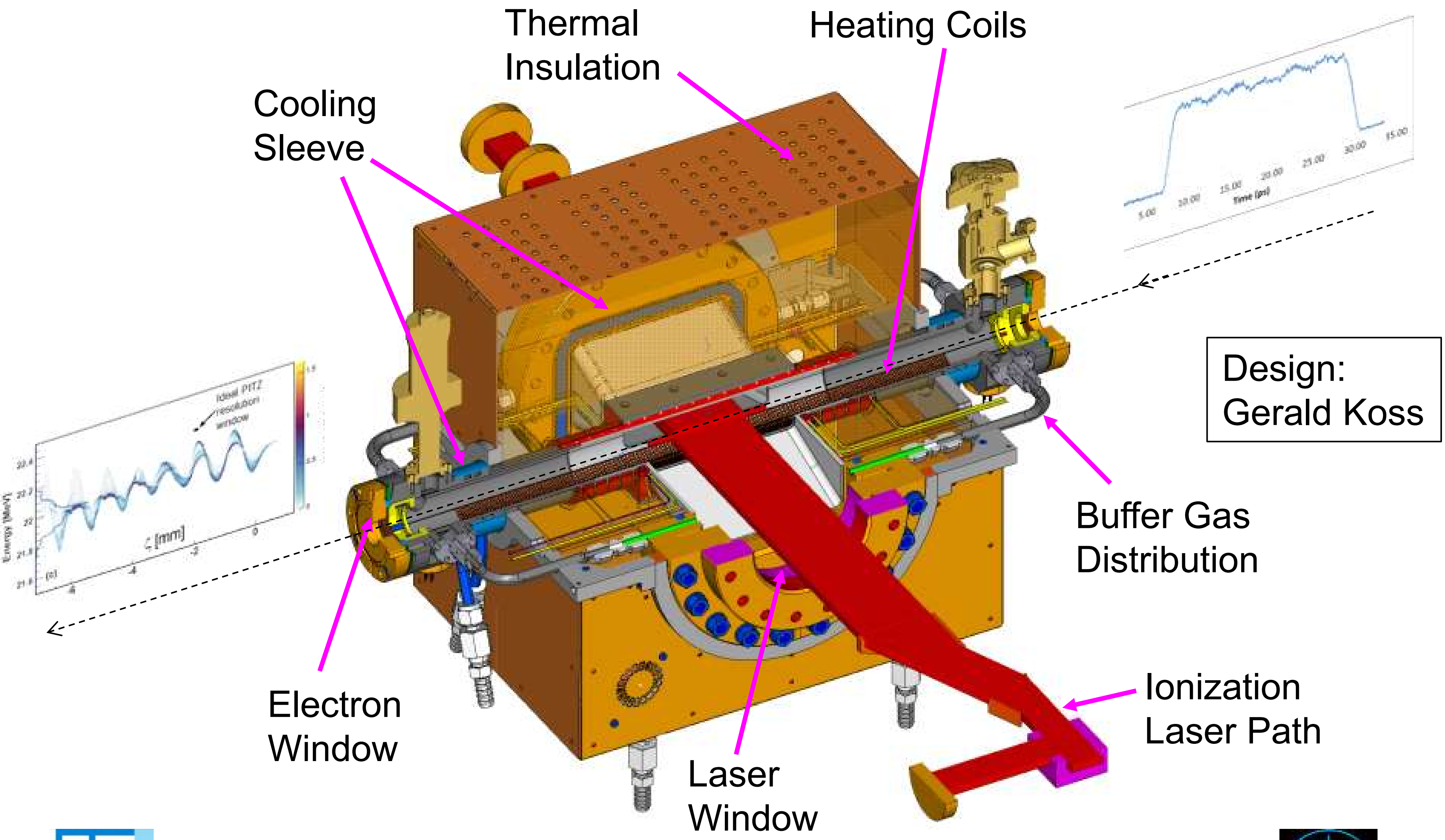
Plasma source

- Li is heated and evaporated in central zone
- Li vapor particles interact with buffer gas and condense
- Liquid Lithium flows back to the center thanks to the wick
- Buffer gas pressure defines vapor density and power input defines vapor column length



P. Muggli et al. **"Photo-Ionized Lithium Source for Plasma Accelerator Applications"**, *IEEE Trans. Plasma Science 27(1999), pp. 791-799*

Plasma cell design



Thermal Insulation

Heating Coils

Cooling Sleeve

Buffer Gas Distribution

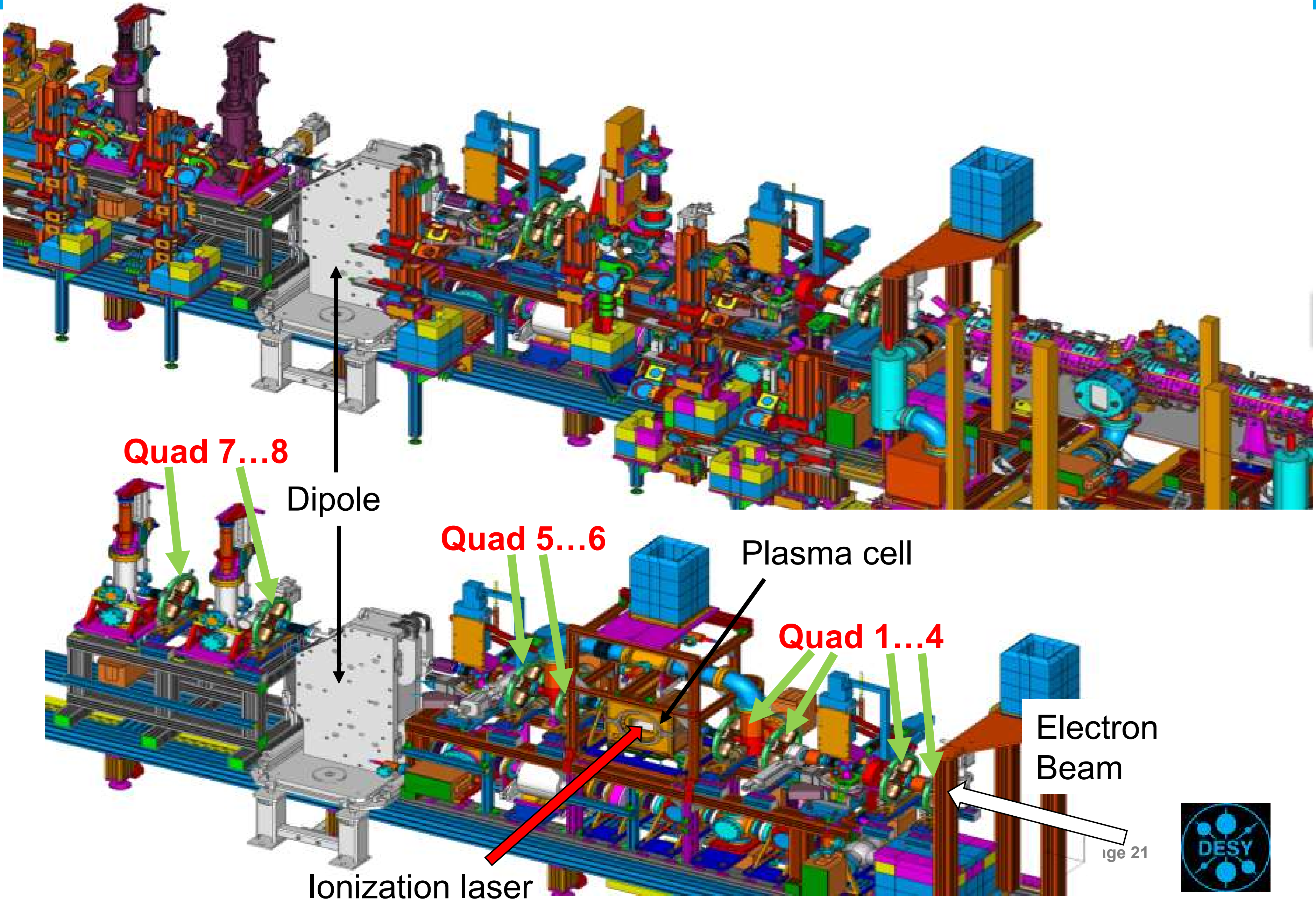
Electron Window

Laser Window

Ionization Laser Path

Design:
Gerald Koss

Beam Line Remodeling

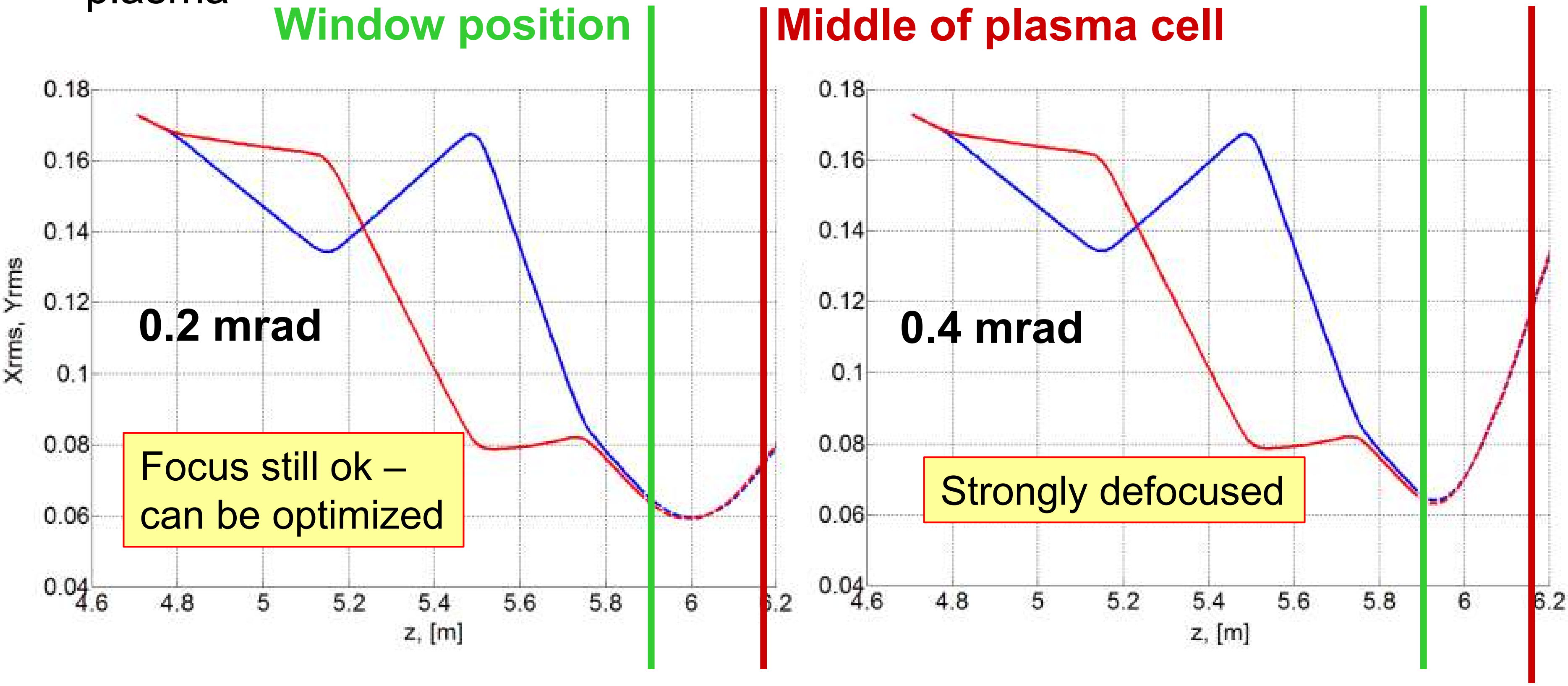


Electron windows: experiments in the beamline

- Two experimental runs with:
  - KW30: 62.5 hours of operation, interrupted by blockade of the beam path
  - KW36-37: 131 hours of the operation, interrupted by run out of N_2 for the ionization laser beamline, loss of beam intensity and breakdown of the plasma cell heater
- Experimental conditions:
  - 8 µm Kapton windows
  - Gun: 6MW; on-crest; 250 µs pulse length
  - Photocathode laser running with flat top profile
  - Booster: 3.1MW; on-crest; 200 µs pulse length
  - 100 pc bunch charge; 22 MeV; 1-2 pulses
  - Ionization laser: 300 mJ, but big fraction of energy was lost due to laser beamline imperfections

Electron windows: maximum acceptable scattering

- ASTRA simulations: electron beam scattering impedes focusing into the plasma



Window position

Middle of plasma cell

0.2 mrad

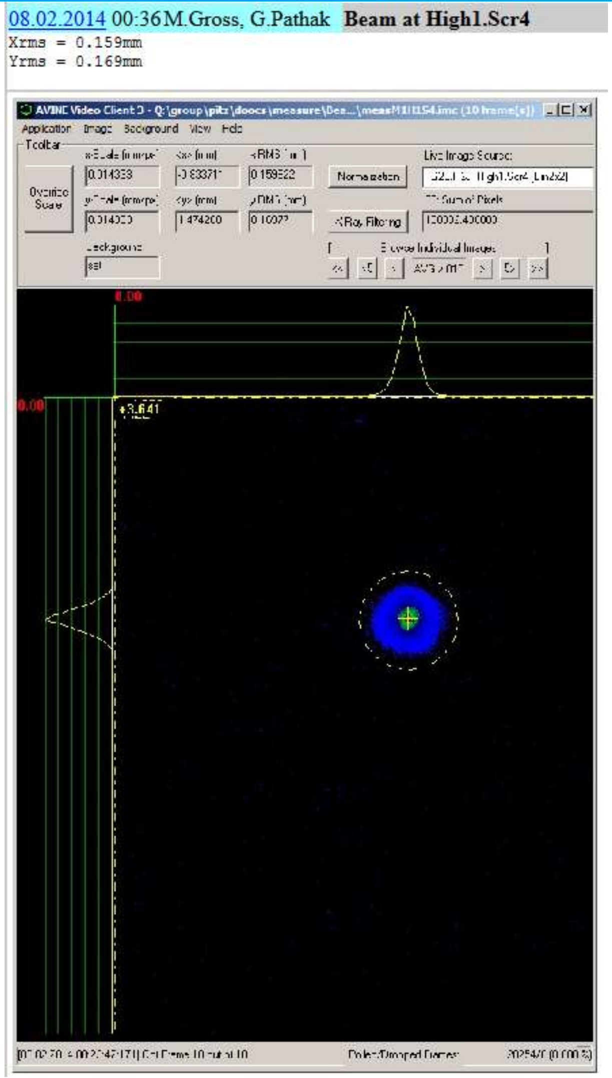
Focus still ok – can be optimized

0.4 mrad

Strongly defocused

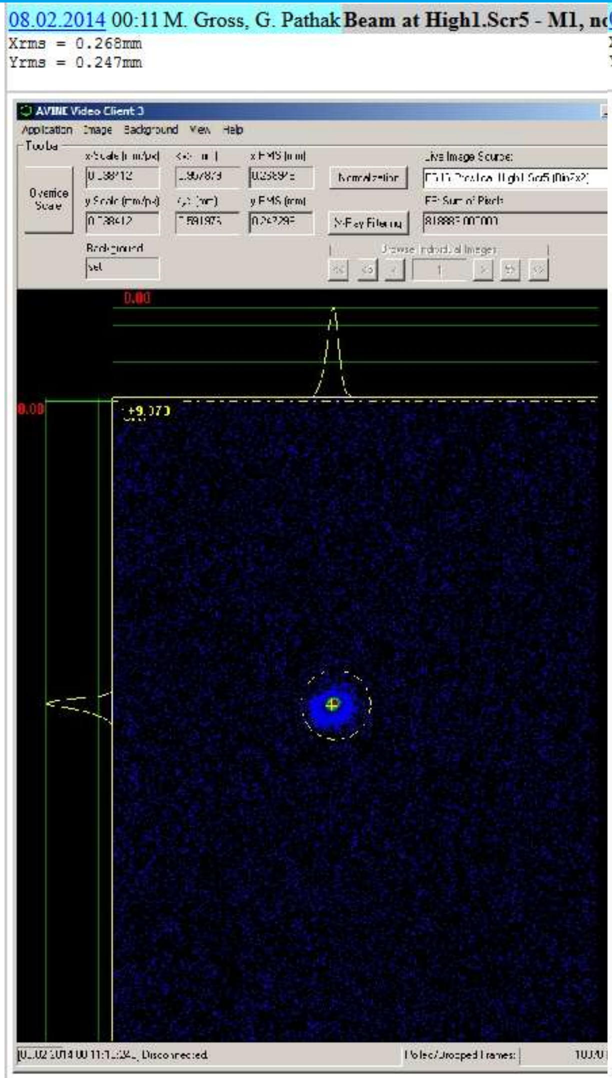
- Maximal agreeable scattering angle: 0.2 mrad

Electron windows: experiments in the beamline



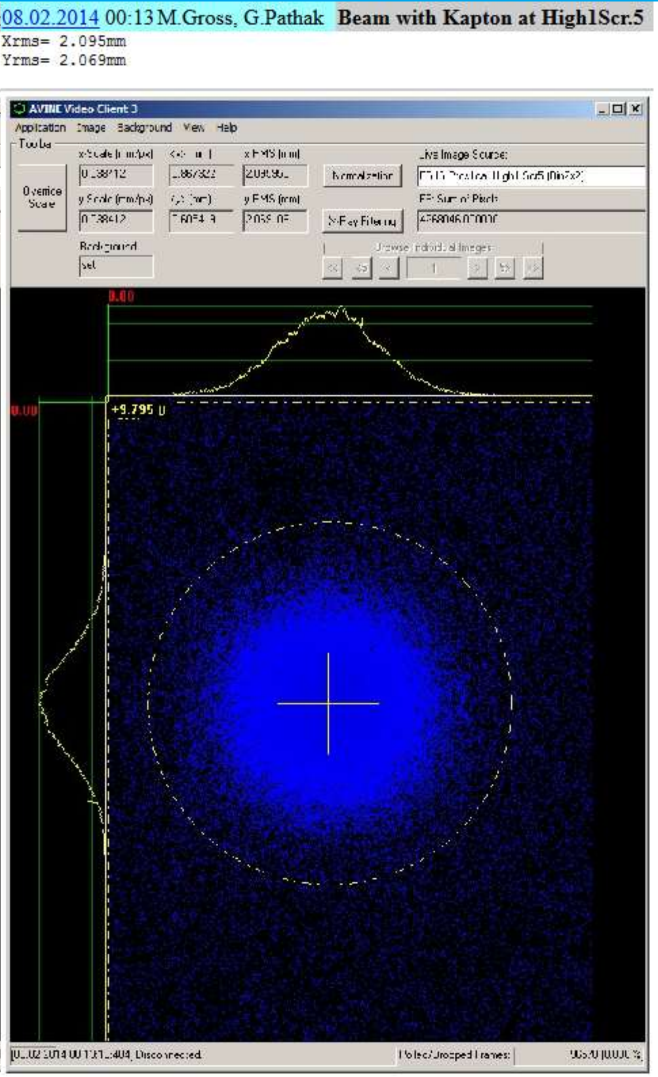
08.02.2014 00:36 M.Gross, G.Pathak **Beam at High1.Scr4**

```
Xrms = 0.159mm
Yrms = 0.169mm
```



08.02.2014 00:11 M. Gross, G. Pathak **Beam at High1.Scr5 - M1, no**

```
Xrms = 0.268mm
Yrms = 0.247mm
```



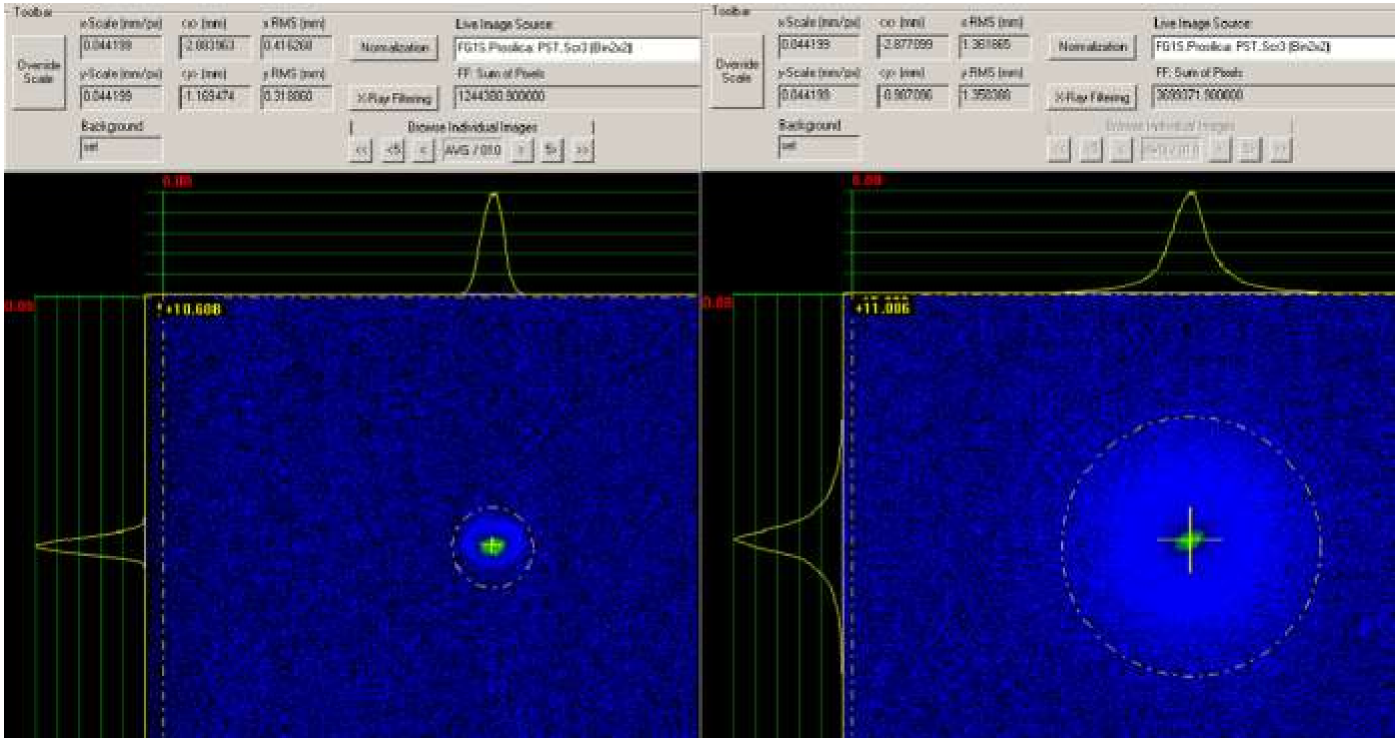
08.02.2014 00:13 M.Gross, G.Pathak **Beam with Kapton at High1Scr.5**

```
Xrms= 2.095mm
Yrms= 2.069mm
```

- 50 µm Kapton

Electron windows: experiments in the beamline

- 0.9 µm PET, coated with Al (37.5 nm) both sides
  - Experimental: less than 0.1 mrad beam divergence
  - Scattering values preliminary confirmed by FLUKA simulation
  - Gas permeability is acceptable
  - Mechanical/thermal stress test ongoing



xScale (mm/px): 0.044199
<x> (mm): -2.003963
x RMS (mm): 0.416260
yScale (mm/px): 0.044199
<y> (mm): -1.169474
y RMS (mm): 0.318860
Background: set
Live Image Source: FG1S Prosilica PST.Scr3 (Bin2x2)
FF: Sum of Pixels: 1244380.900000
Browse Individual Images: AVG / 050

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x RMS (mm): 1.361865
yScale (mm/px): 0.044199
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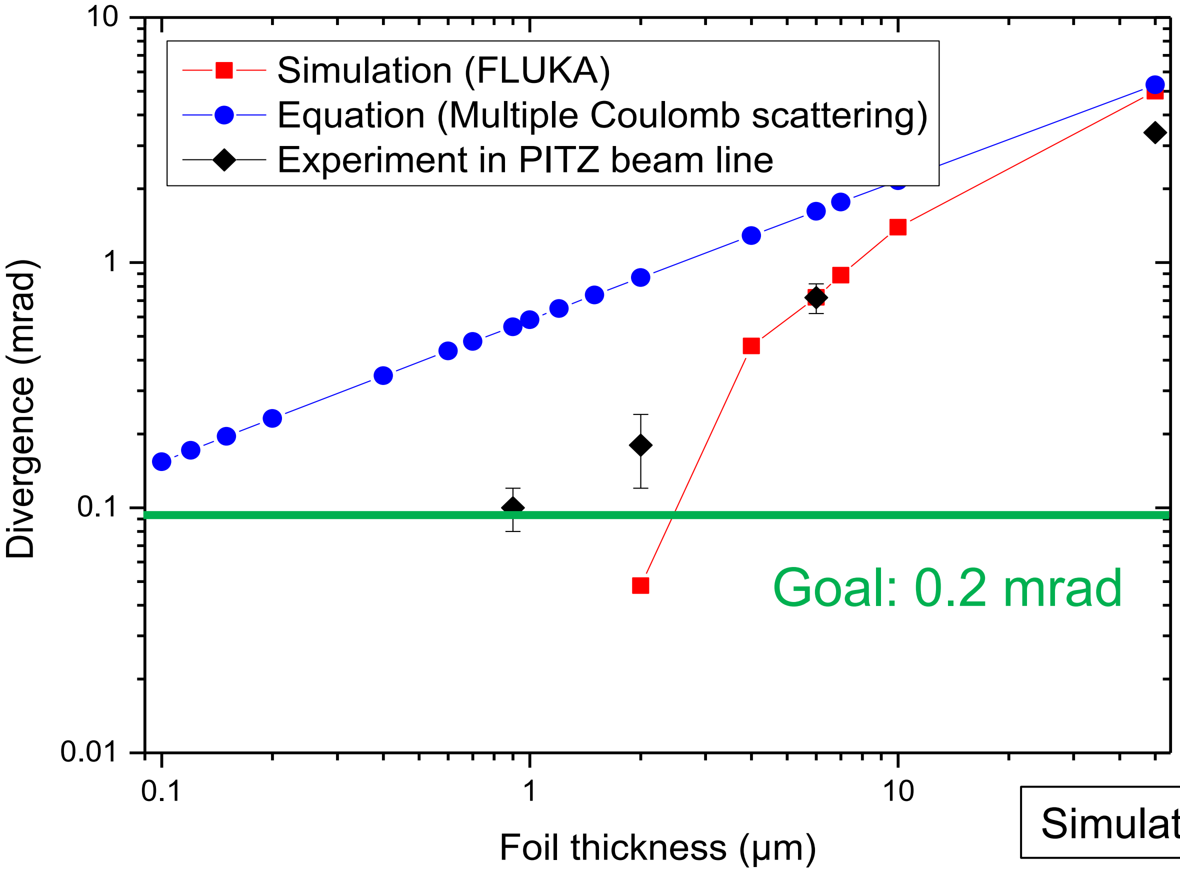
Electron windows: comparison



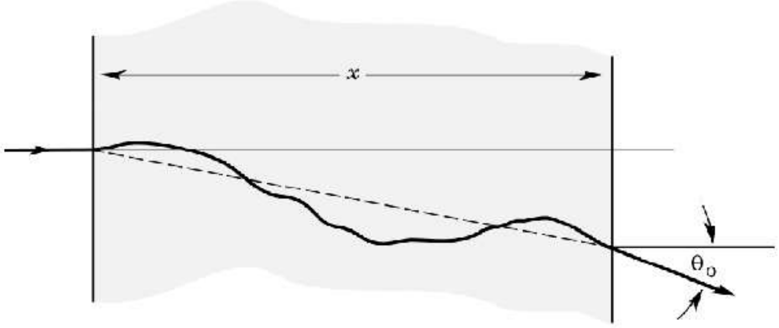
Simulations by Rico Schuetze

- 2014.02.07N – Kapton 50 μm + (?) Gold 5 nm
- 2014.05.15A – Mylar 6 μm + Gold coating of unknown thickness
- 2015.03.07M – Mylar 2 μm
- 2015.10.22M – PET (Mylar) 0.9 μm + 37.5 nm Al coating both sides

Electron windows: FLUKA simulations

Multiple scattering

- a particle undergoes a number of scatterings per each step, resulting a small deviation from initial trajectory
- Valid only if number of elementary scatterings per step is large enough

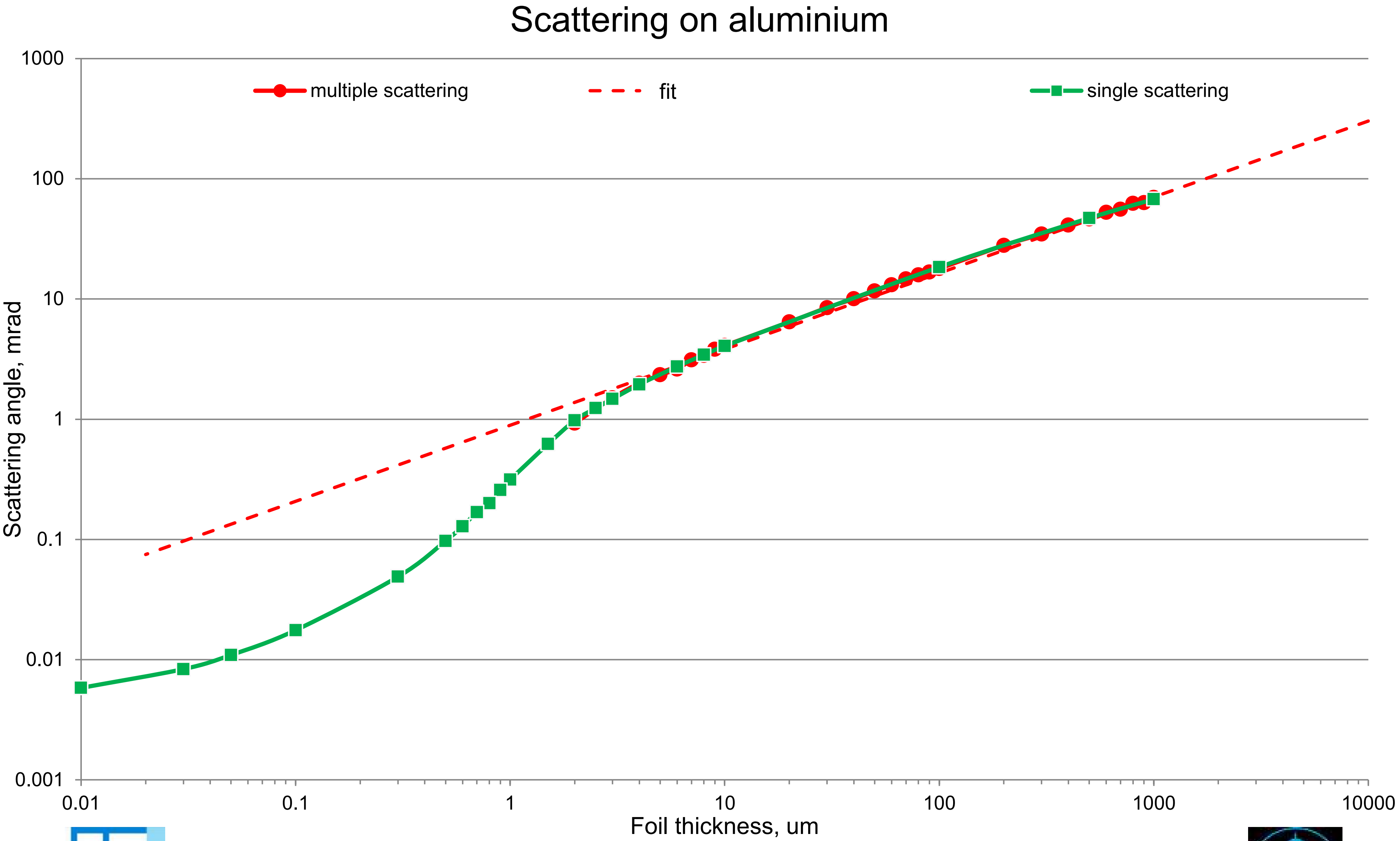


Single scattering

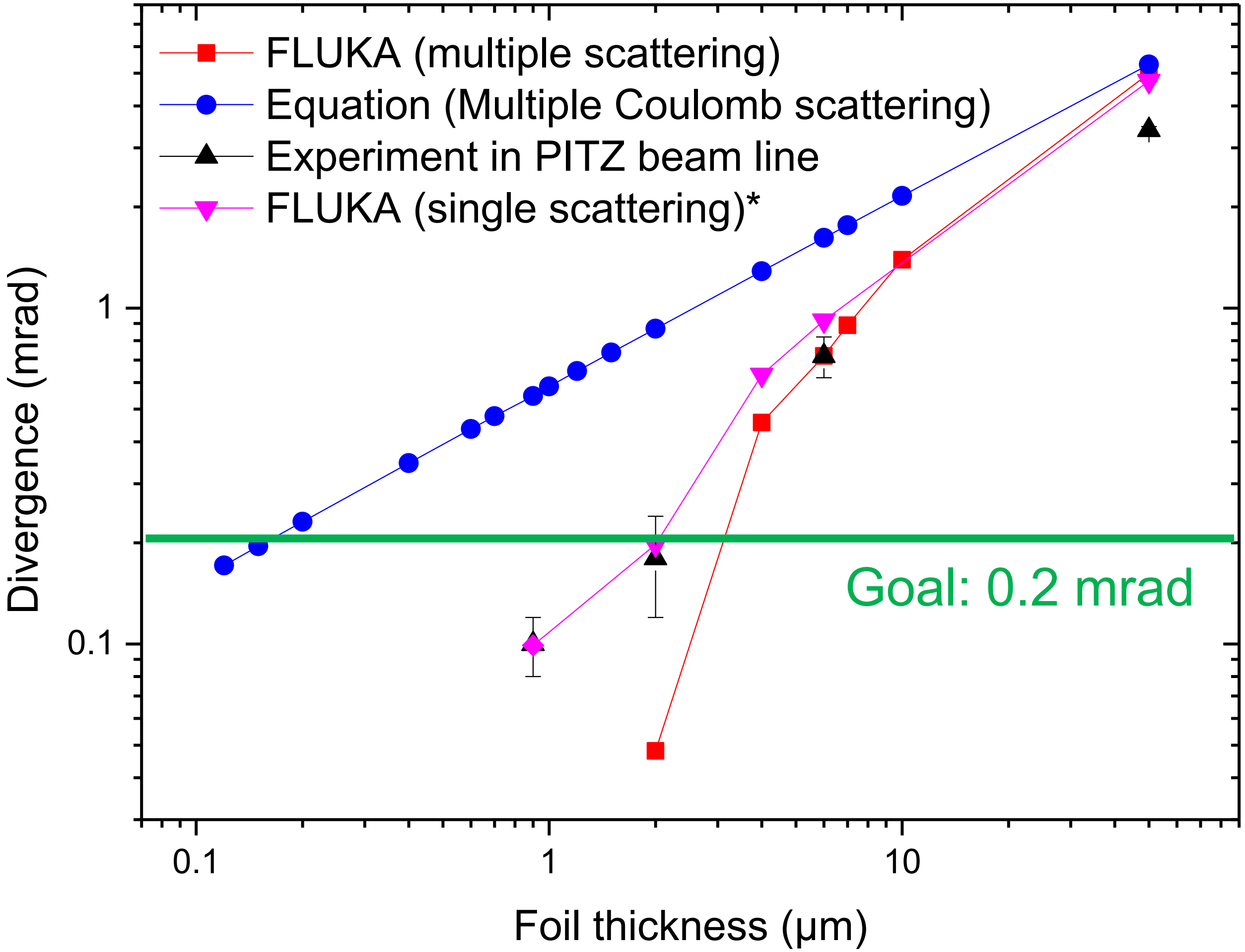
- based on the Rutherford formula
- Every interaction is a separate step ->demands **much more CPU time** compared to multiple scattering

"FLUKA: a multi-particle transport code"
A. Ferrari, P.R. Sala, A. Fasso`, and J. Ranft,
CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

Electron windows: multiple and single scattering in FLUKA



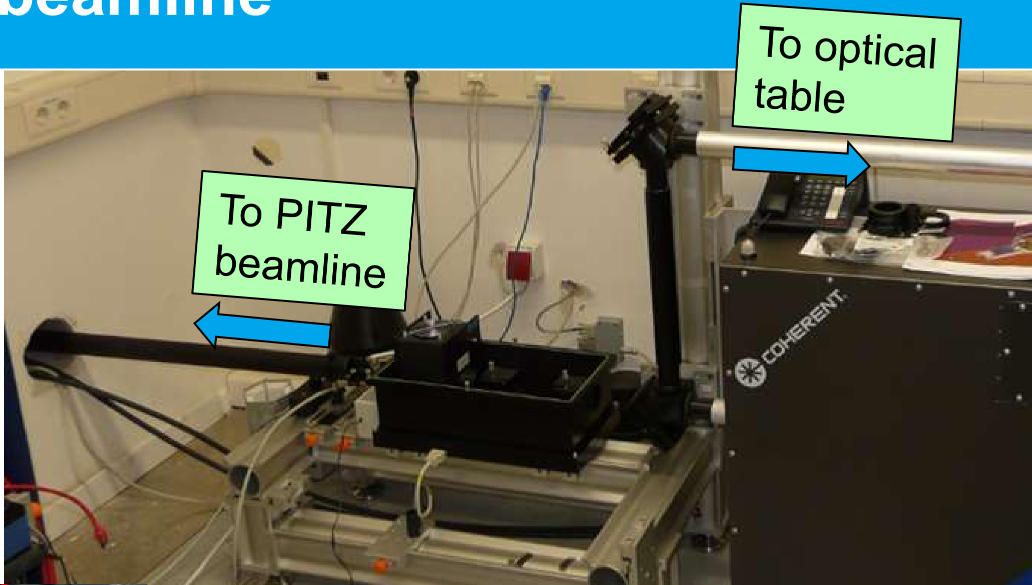
Electron windows: summary

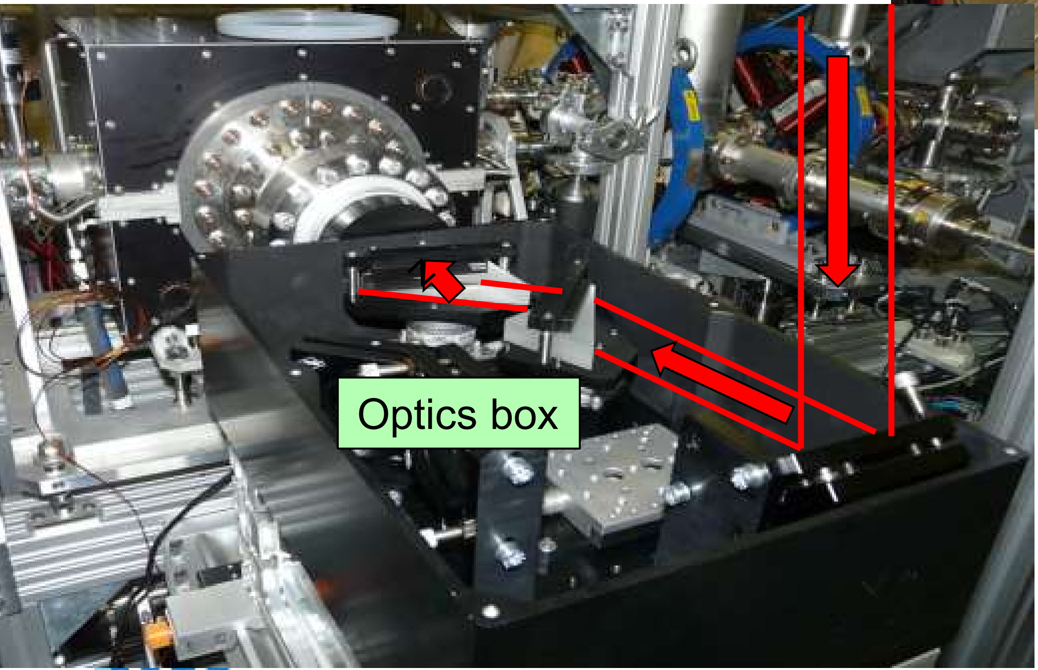


*for the last point (0.9 μm) a coated foil is simulated

Ionization Laser and laser beamline

- Coherent COMPexPro 201: ArF Excimer Laser, 193 nm, up to 400 mJ / pulse, 10 Hz



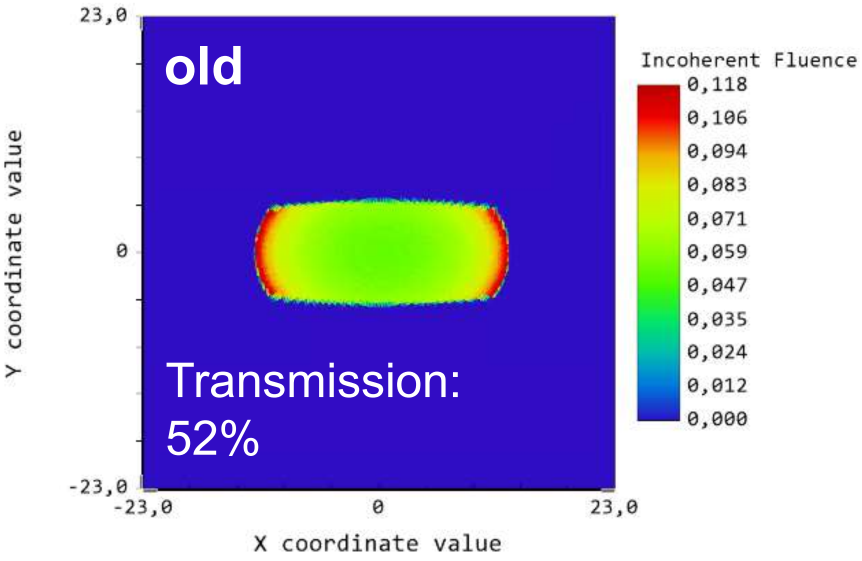


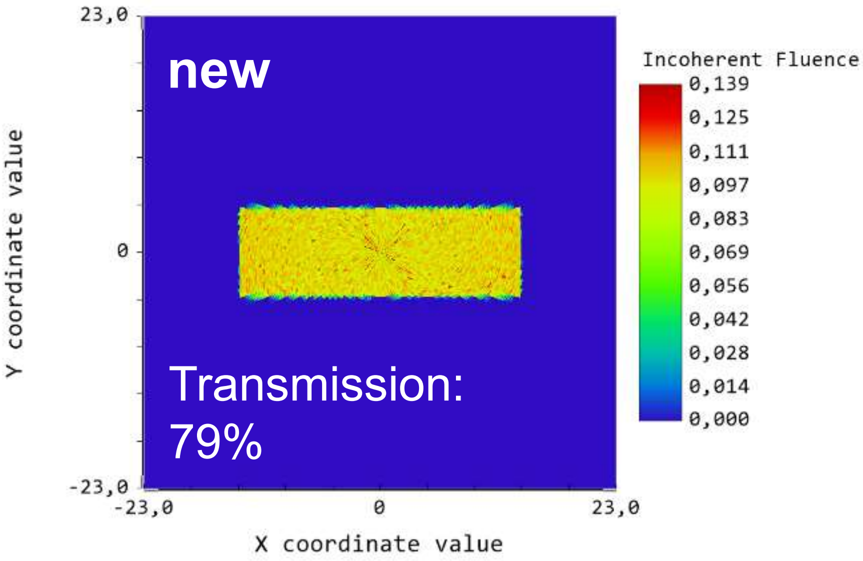
- Side coupling advantage: Well defined and adjustable plasma channel length
  - Option: Add filter to implement density ramps or other plasma profiles

Better Optics for ArF Laser Beam Line

Simulations by Matthias Gross

- Laser output: 24mm x 10mm with 3mrad x 1mrad divergence
  - Beam transport over ≈12m from laser aperture to plasma cell
  - Compensation of divergence done so far with spherical lenses → cutting at apertures
  - Now: 4 cylinder lenses (2 per axis) with AR coating for individual compensation

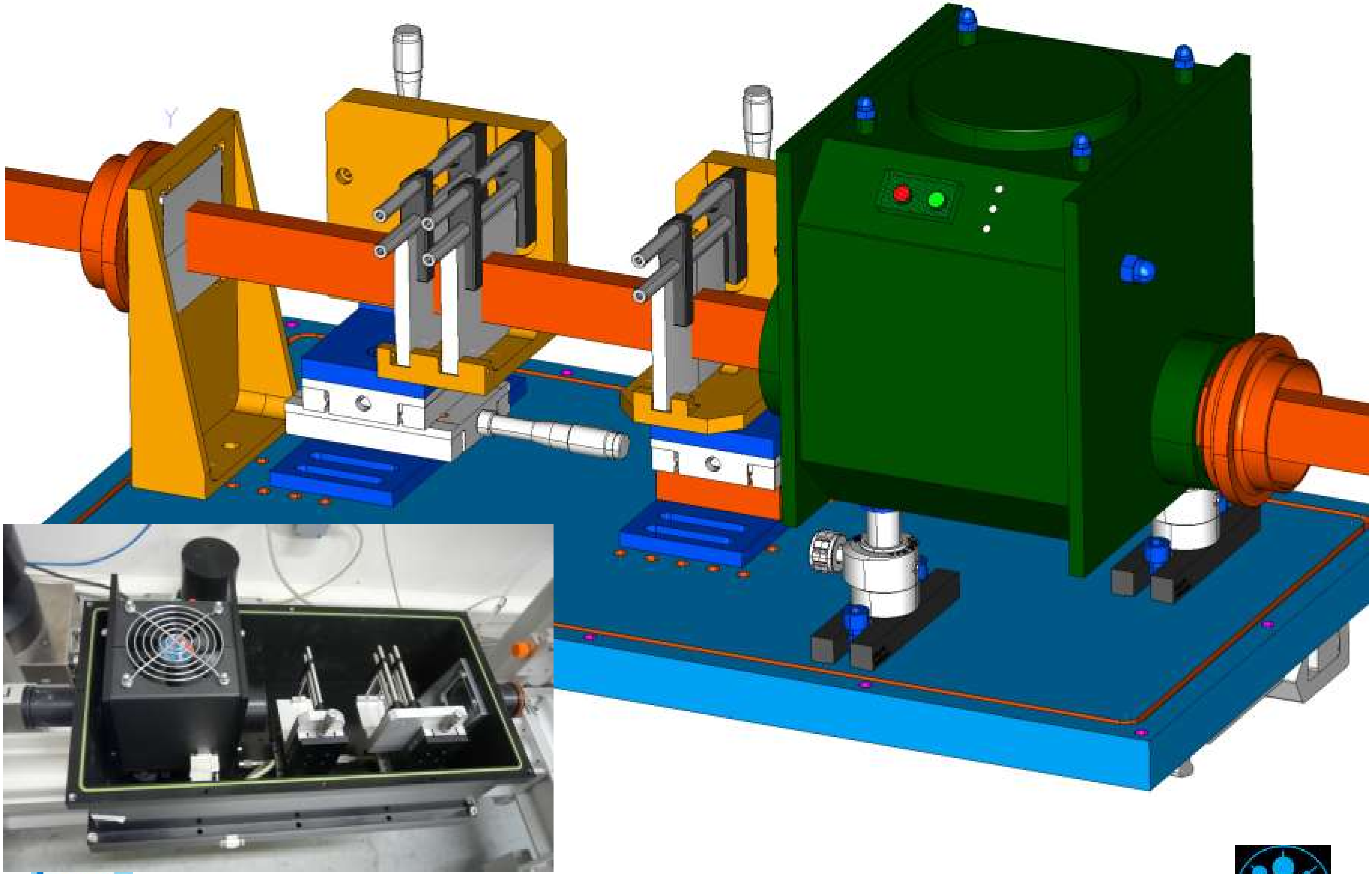




- ZEMAX simulated laser distribution at plasma cell position (before beam expander)

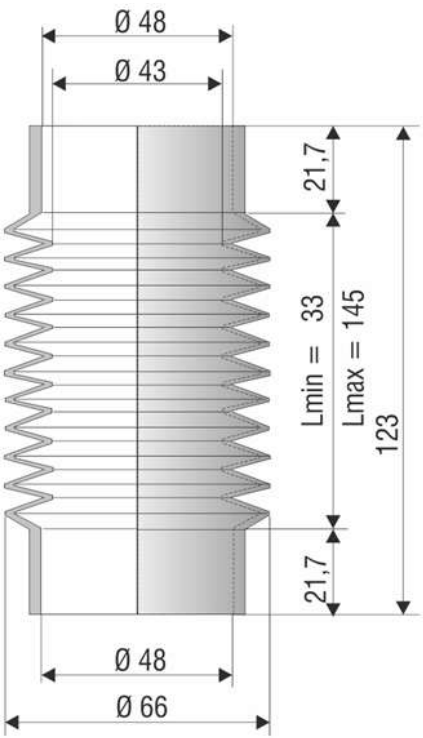
With cylinder lenses: rectangular, homogeneous

New Setup of Optics Box with Cylinder Lenses



Improved Beamline Setup

Bellows made from NBR rubber

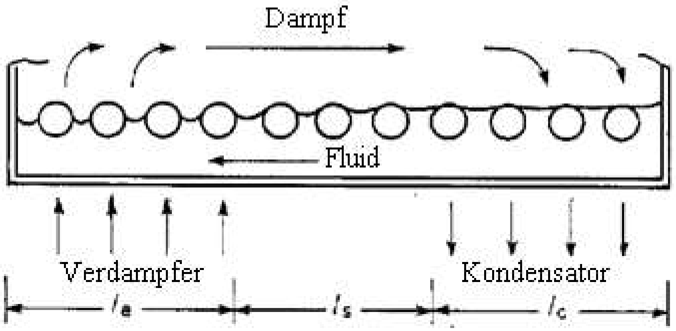


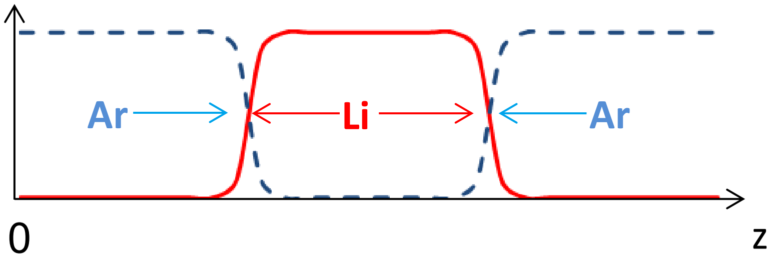
Improved setup with bellows and clamps for increased mechanical stability

- Result: No gas leakage measurable

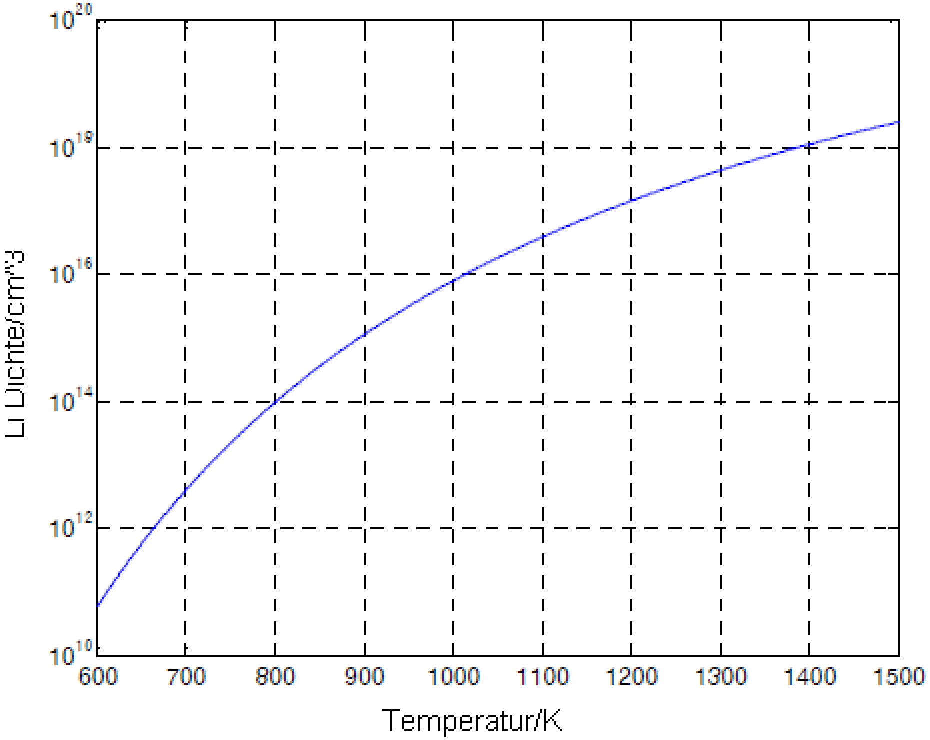
Plasma cell: Heat pipe oven

- The plasma cell is designed as a heat pipe with a metal mesh inside the oven acting like a wick.

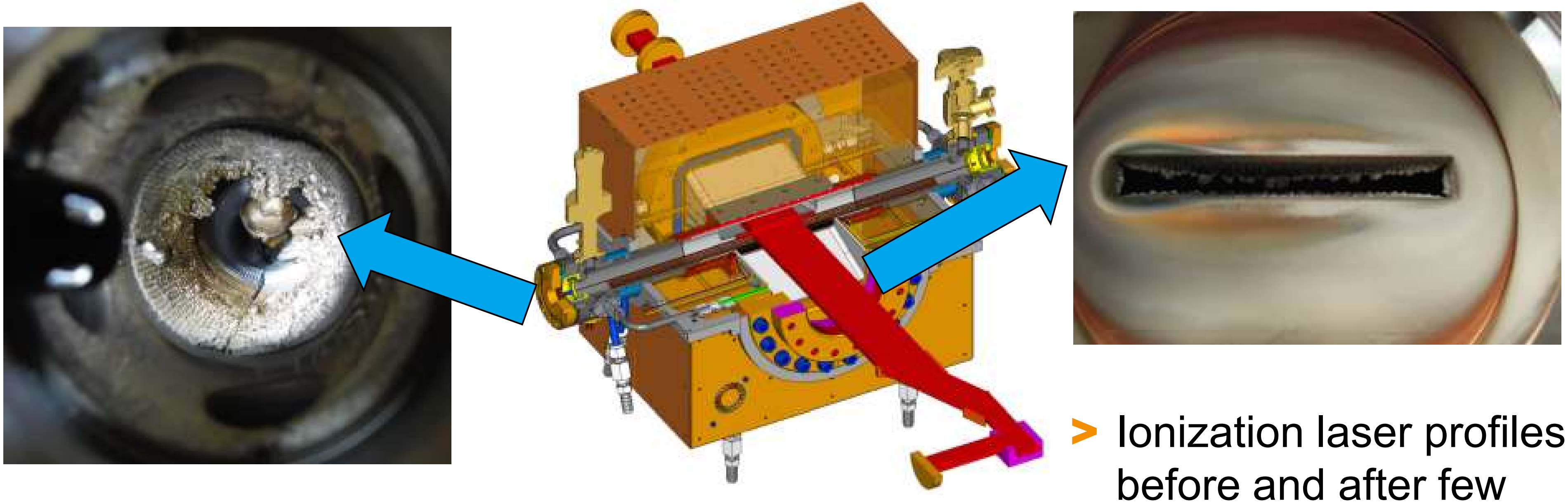




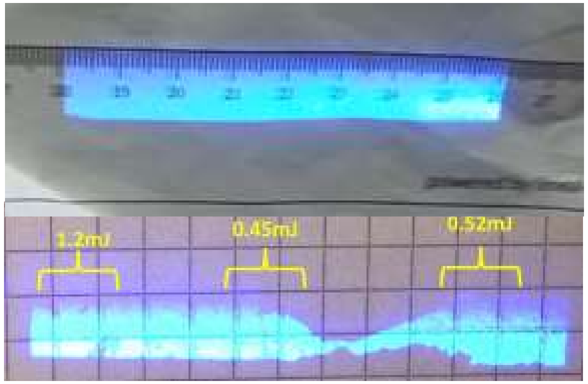
- Desired vapor density of 10^{16} cm^{-3} corresponds to 1000 K



Plasma cell status after extraction from the tunnel in 2015



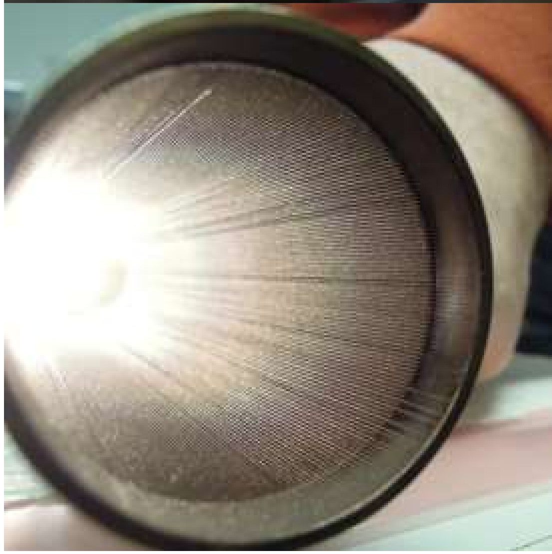
- Ionization laser profiles before and after few days of operation:

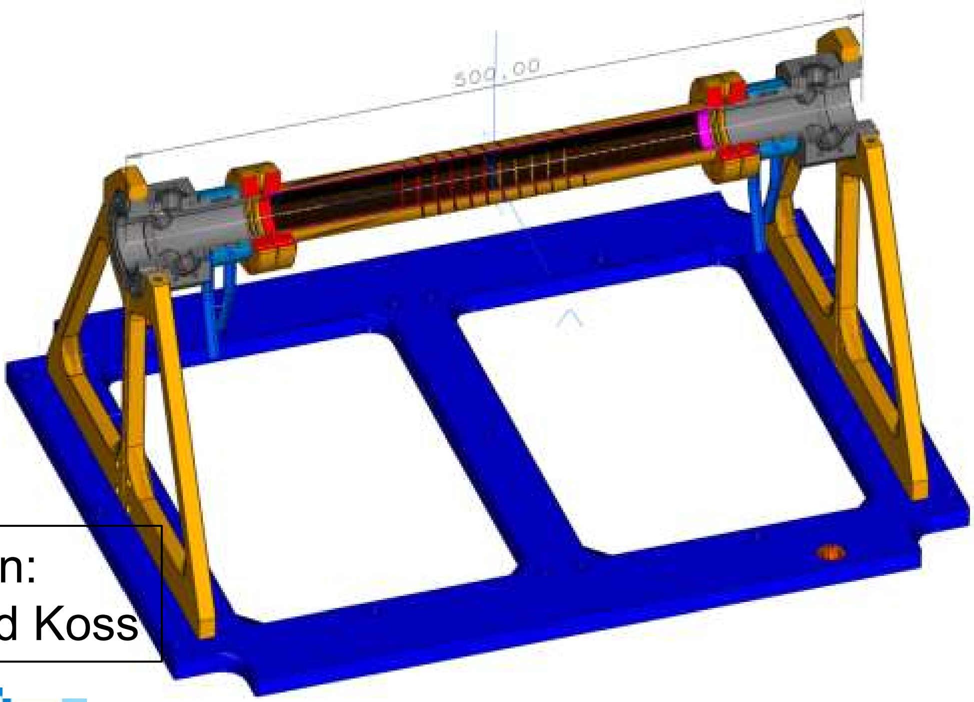


- The problem of lithium condensation was partially solved by adjusting the buffer gas pressure and extending side arms.

Plasma cell: mesh->grooves

- Mesh did not provide a stable lithium transport last year
- A small heat pipe setup was manufactured to study the lithium transport in grooves and optimal parameters of the heat pipe operation

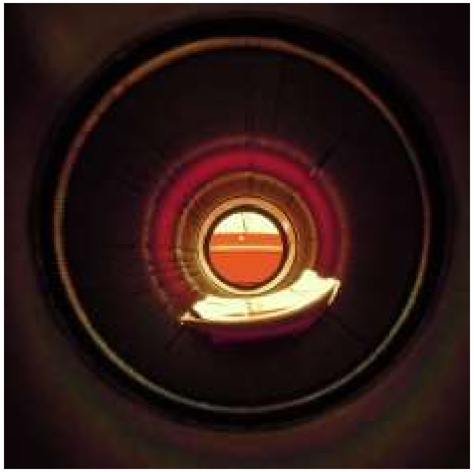




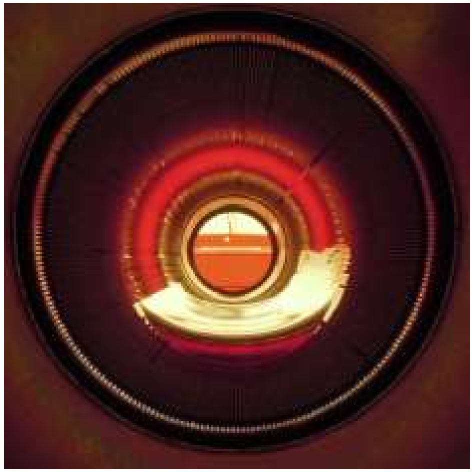
Design:
Gerald Koss

Lithium transport works well (March 2016)

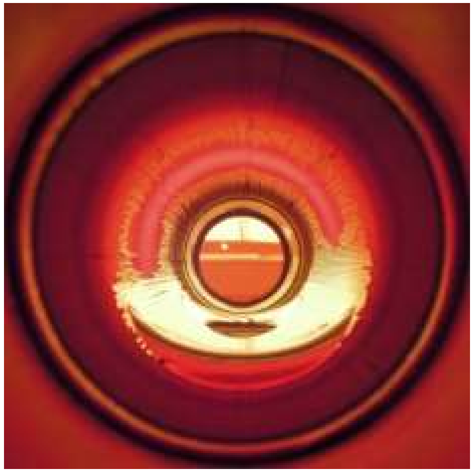
560 °C



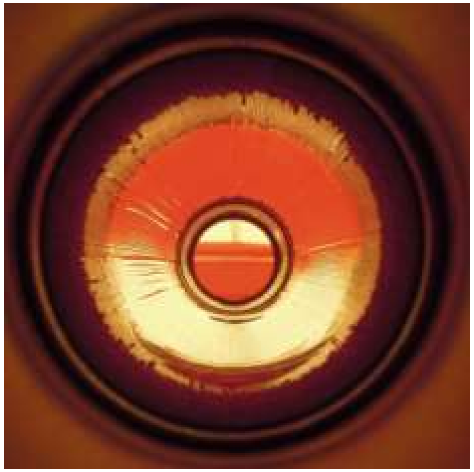
605 °C



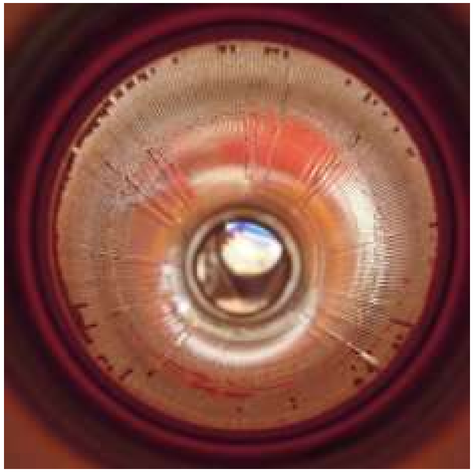
650 °C



700 °C



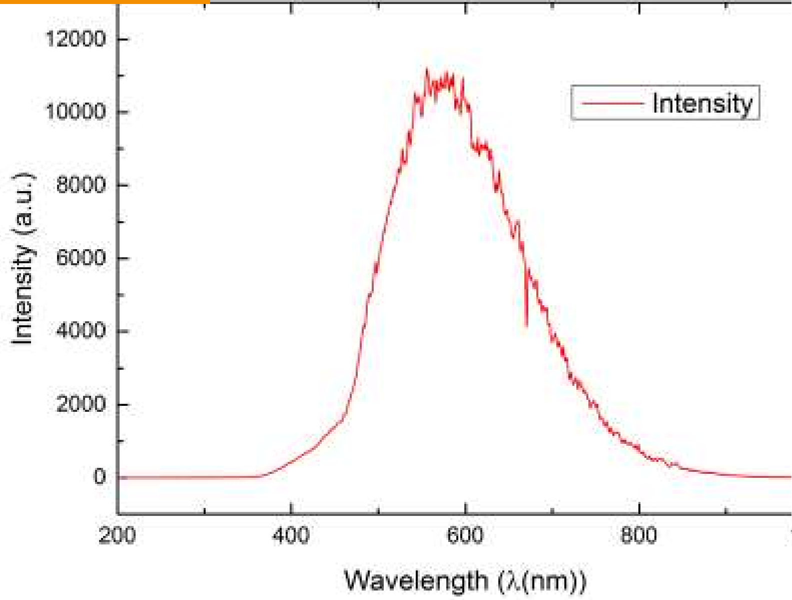
1 day at 700 °C



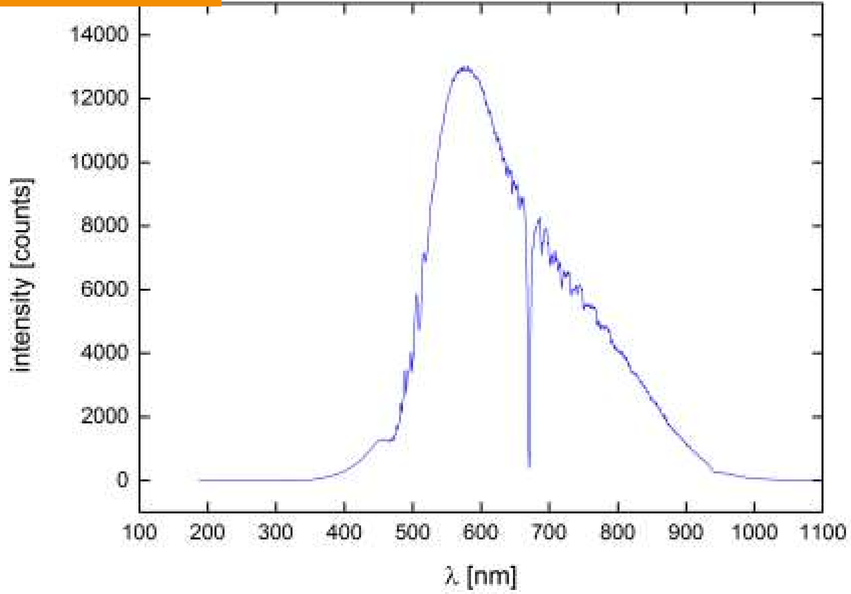
1 week at 700 °C

White Light absorption

Sep. 2015

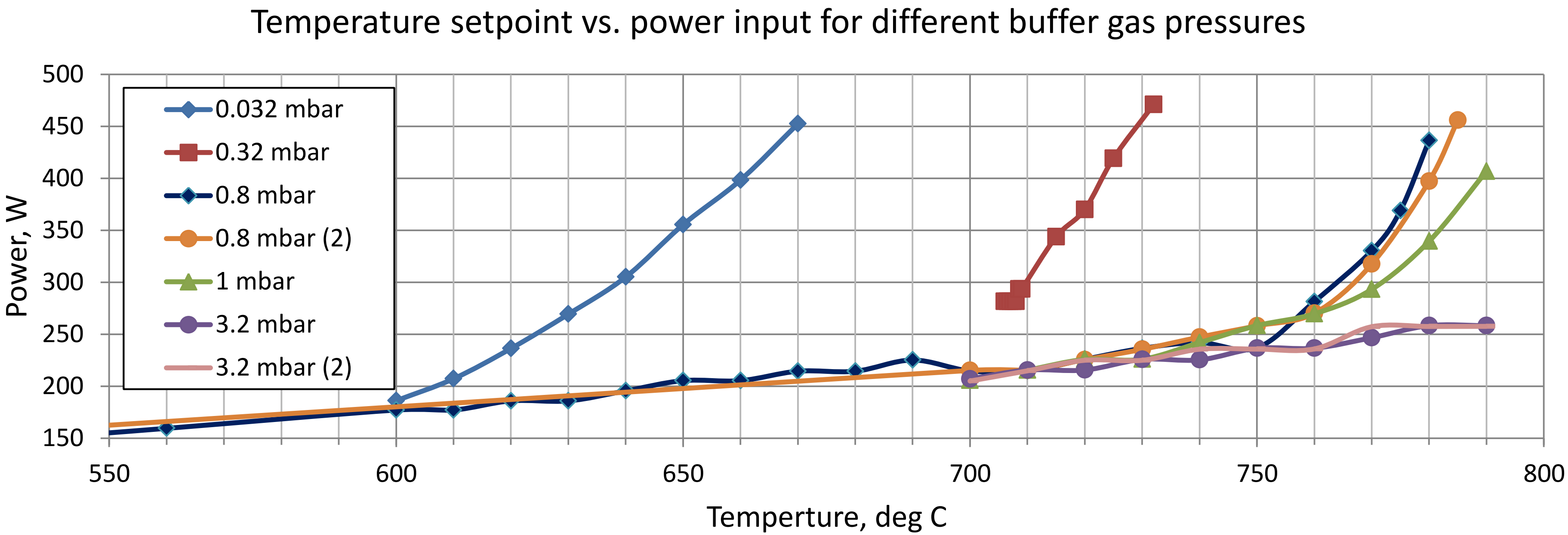


Apr. 2016

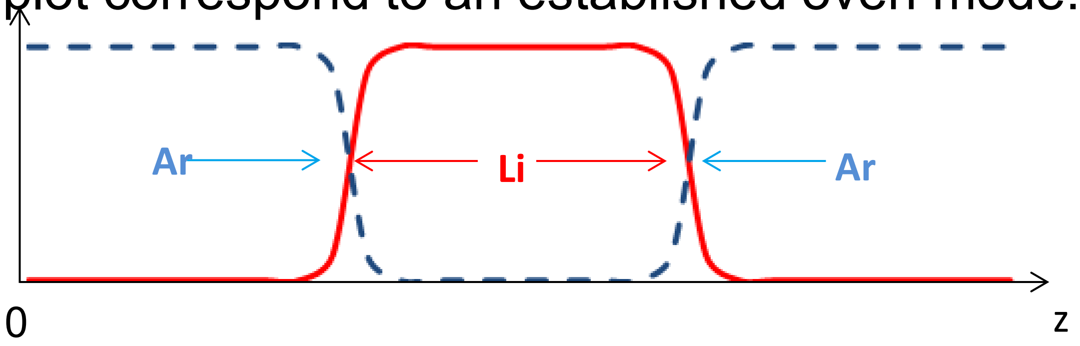


- The white light absorption shows an increase of vapor density compared to the previous setup

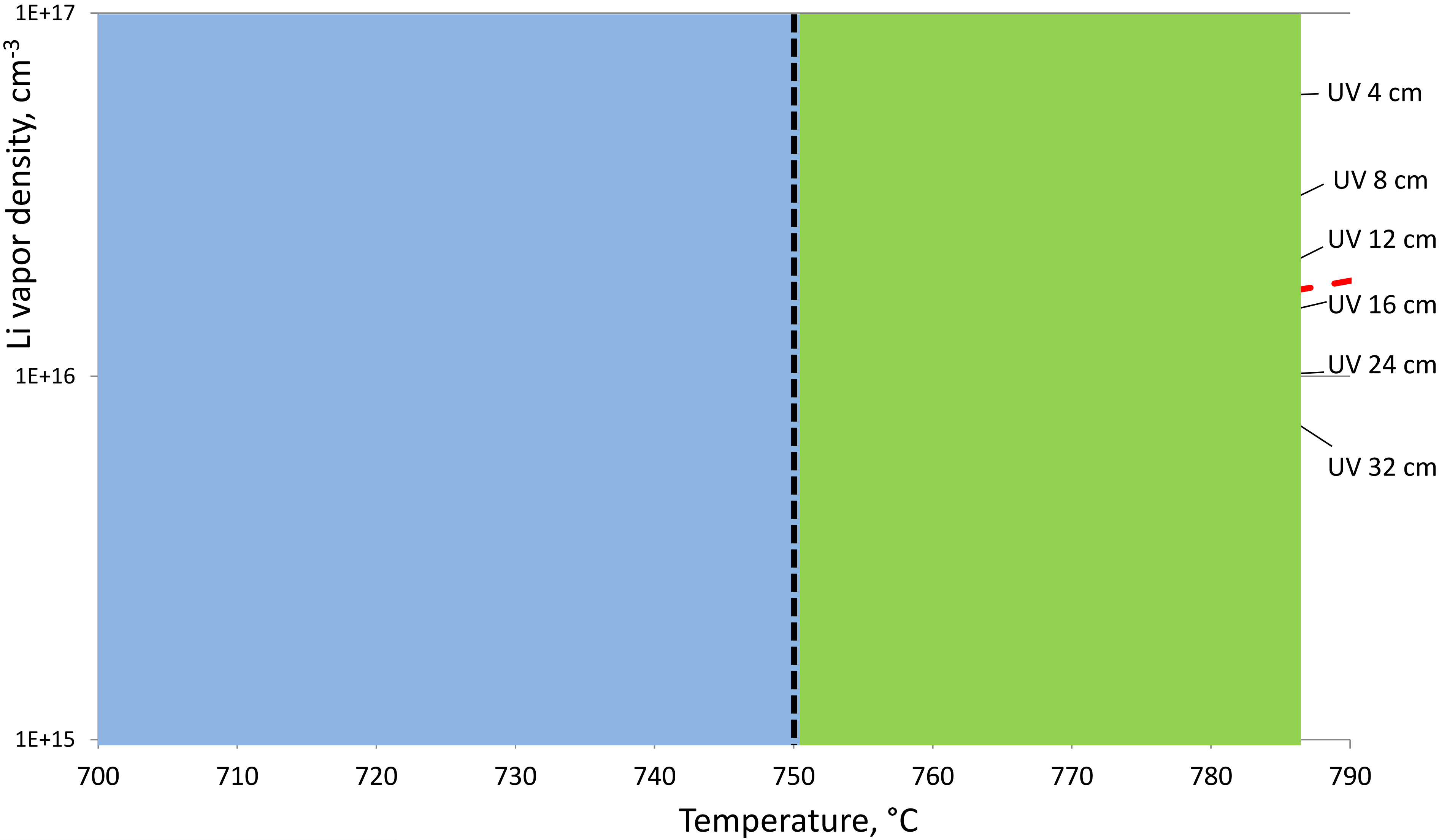
Heat pipe regimes



- 0.8 mbar was selected as an optimal pressure
- Kinks on the plot correspond to an established oven mode:

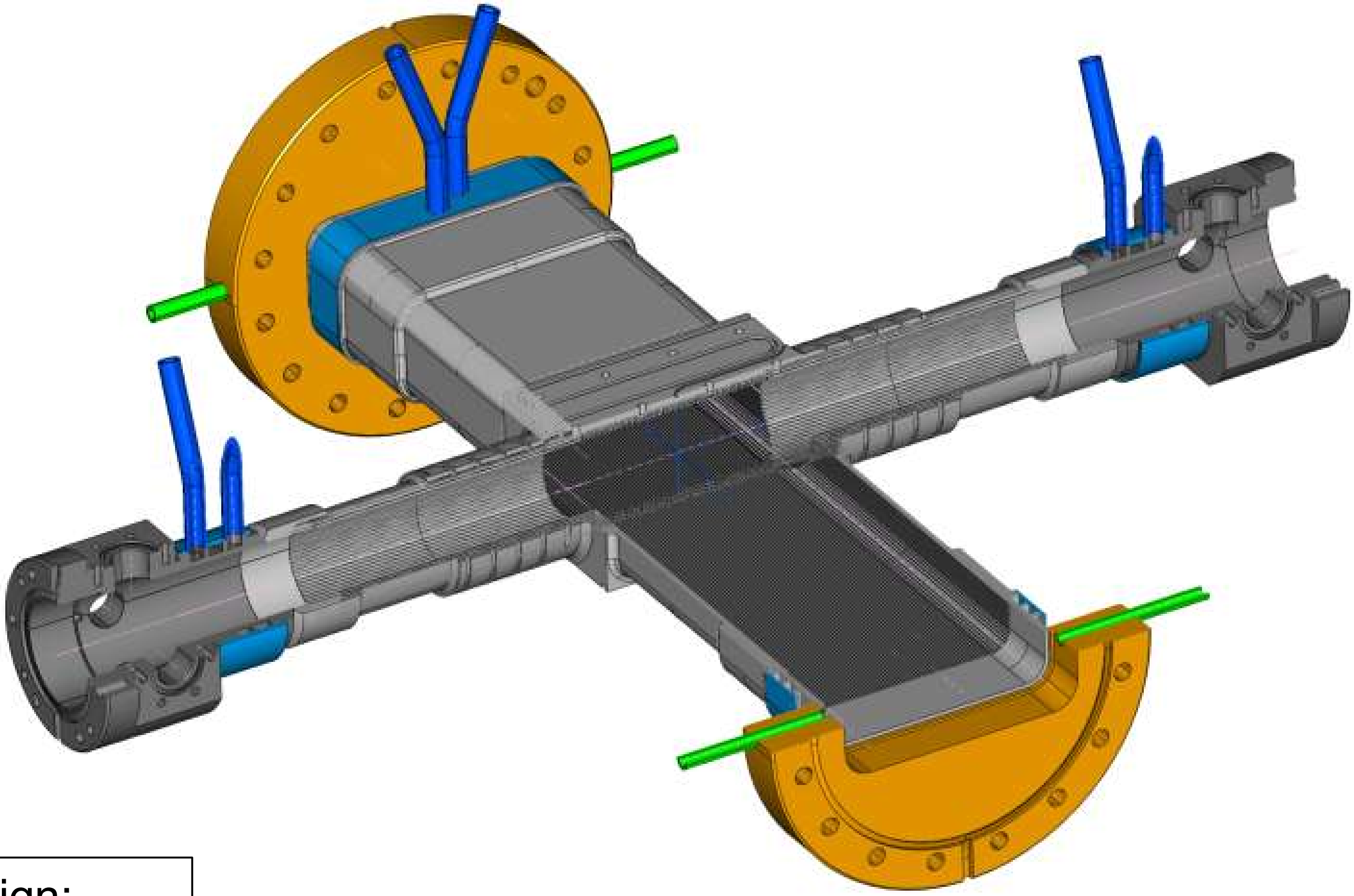


UV absorption (0.8 mbar)



$$n_oL = -\frac{1}{\sigma}\left(\frac{E_{\text{transmitted}}}{E_{\text{incident}}}\right)$$

New plasma cell



Design:
Gerald Koss

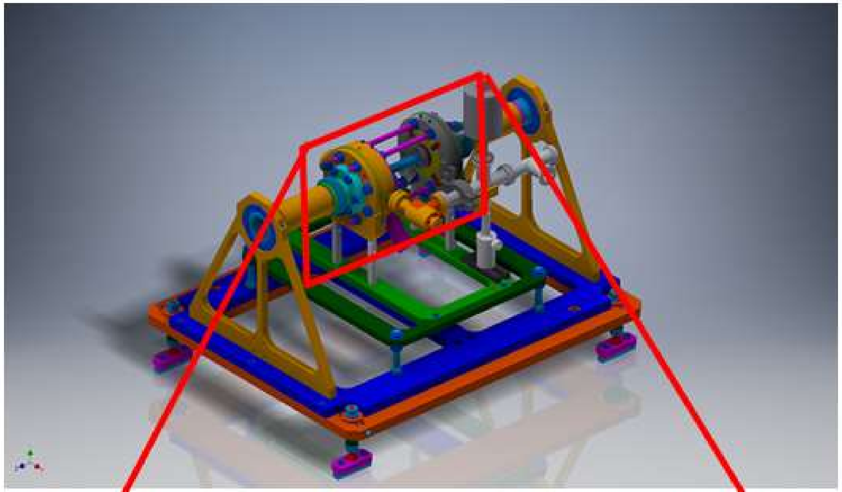
- Is being manufactured, first experiments this summer

Summary

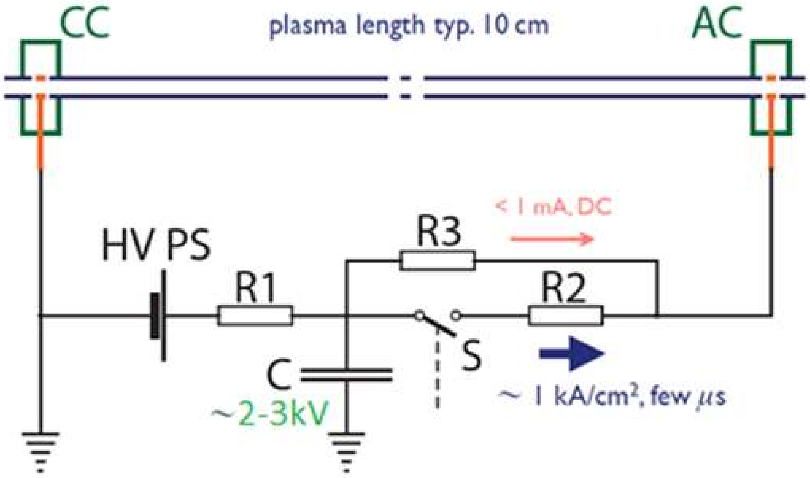
Problems	Solutions
Heating wires overpowered	• Stronger heater / better heat insulation
Lithium accumulation in cooling zones	• Axial grooves or finer mesh→ better lithium transport • Longer side arms
Insufficient density of lithium vapor	• Stronger heater / better heat insulation • Fine adjustment of buffer gas pressure
Only 10% laser pulse energy delivered to plasma cell	• Better optics (e.g. cylinder lenses; antireflection coating) • Better beamline sealing
Electron windows increase achievable focus size	• Thinner electron window foils

> Continue plasma experiments in summer 2016 with improved hardware

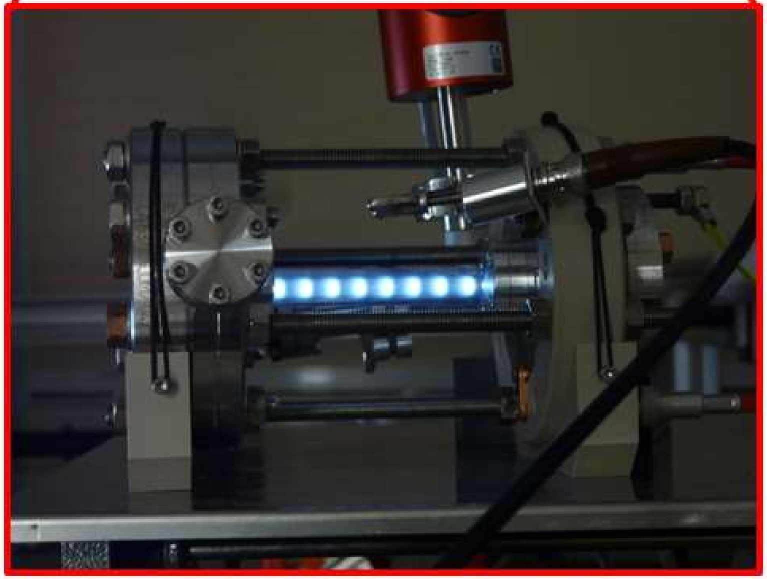
Gas discharge plasma cell



Design of the discharge plasma cell



Layout of the discharge circuit

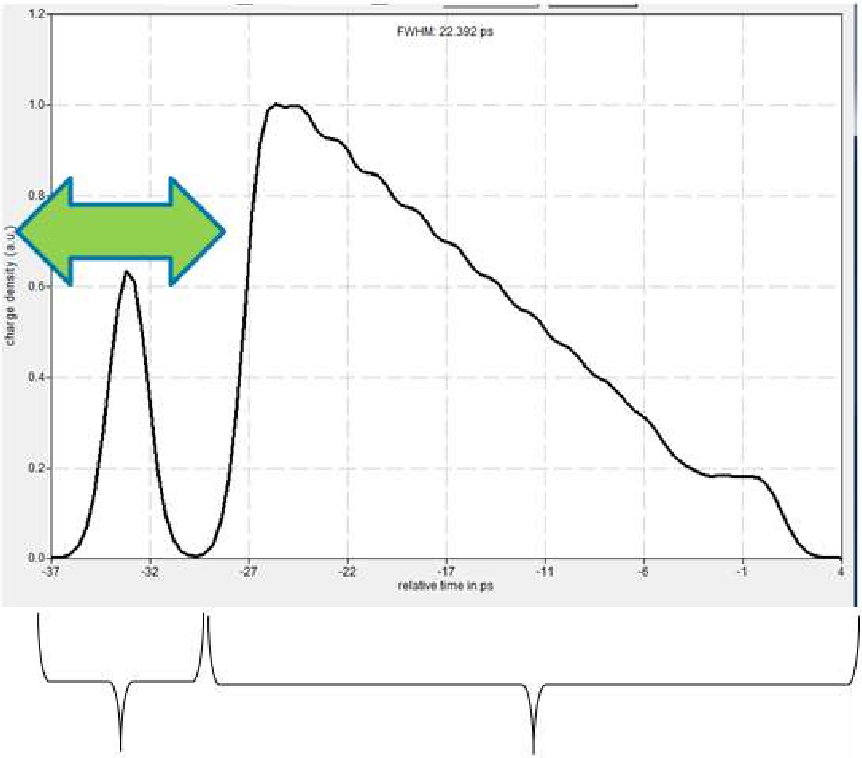


- Cell was manufactured
- Electronics and vacuum parts taken into operation

- "Paschen"-insulation works
- Electronics tested until 2 kV, 550 A (max. 3 kV, 600 A)
- No major problems observed

Upgrade of the MBI photocathode laser system

- Adding a witness pulse with variable delay to each laser pulse
  - → Higher flexibility
  - → Preliminary studies, e.g. measurement of plasma wavelength
- Adjustable driver/witness ratio
- Keep possibilities of existing system

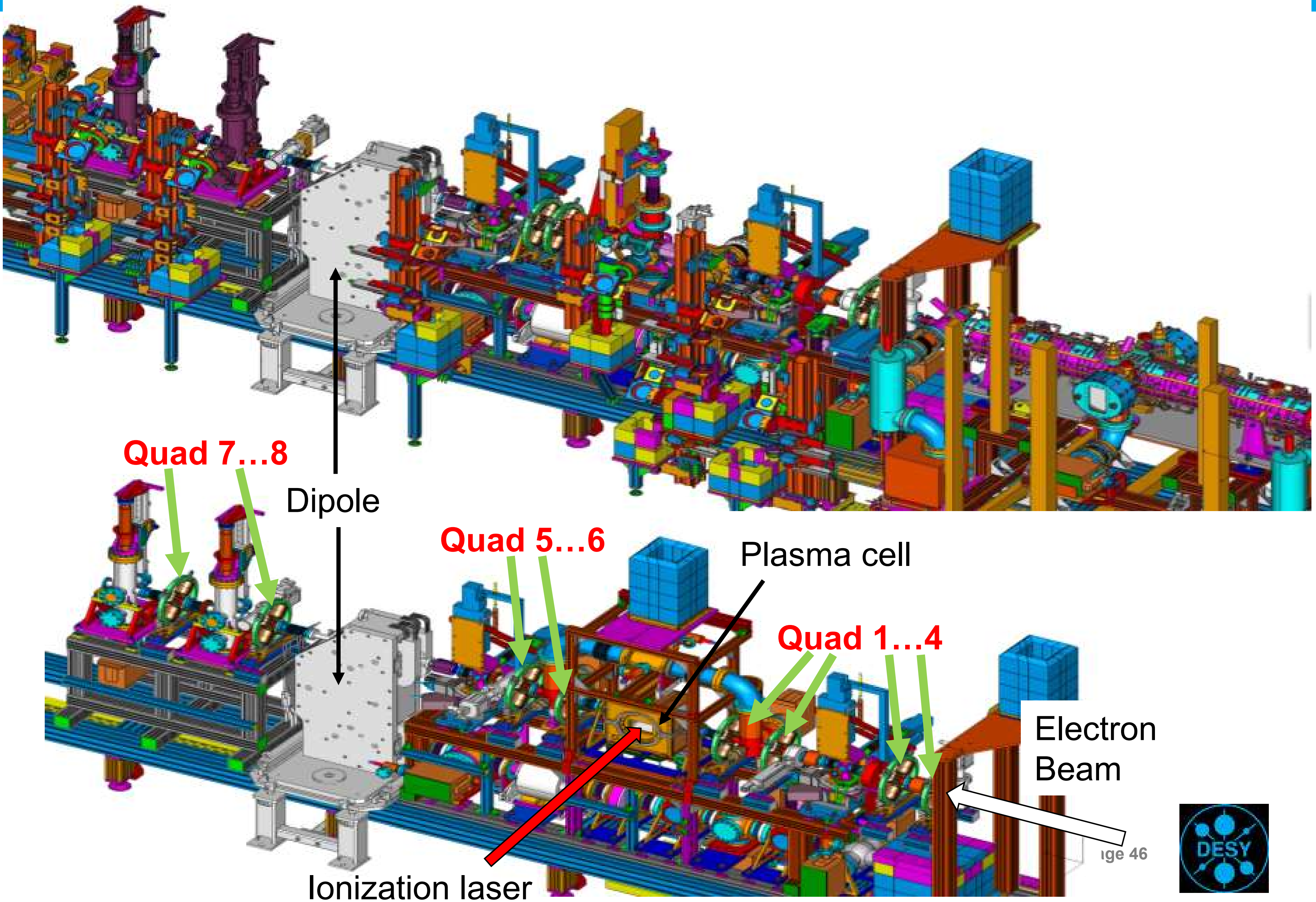


Variable delay witness bunch

Shaped drive bunch

Backup

Beam Line Remodeling



Quad 7…8

Dipole

Quad 5…6

Plasma cell

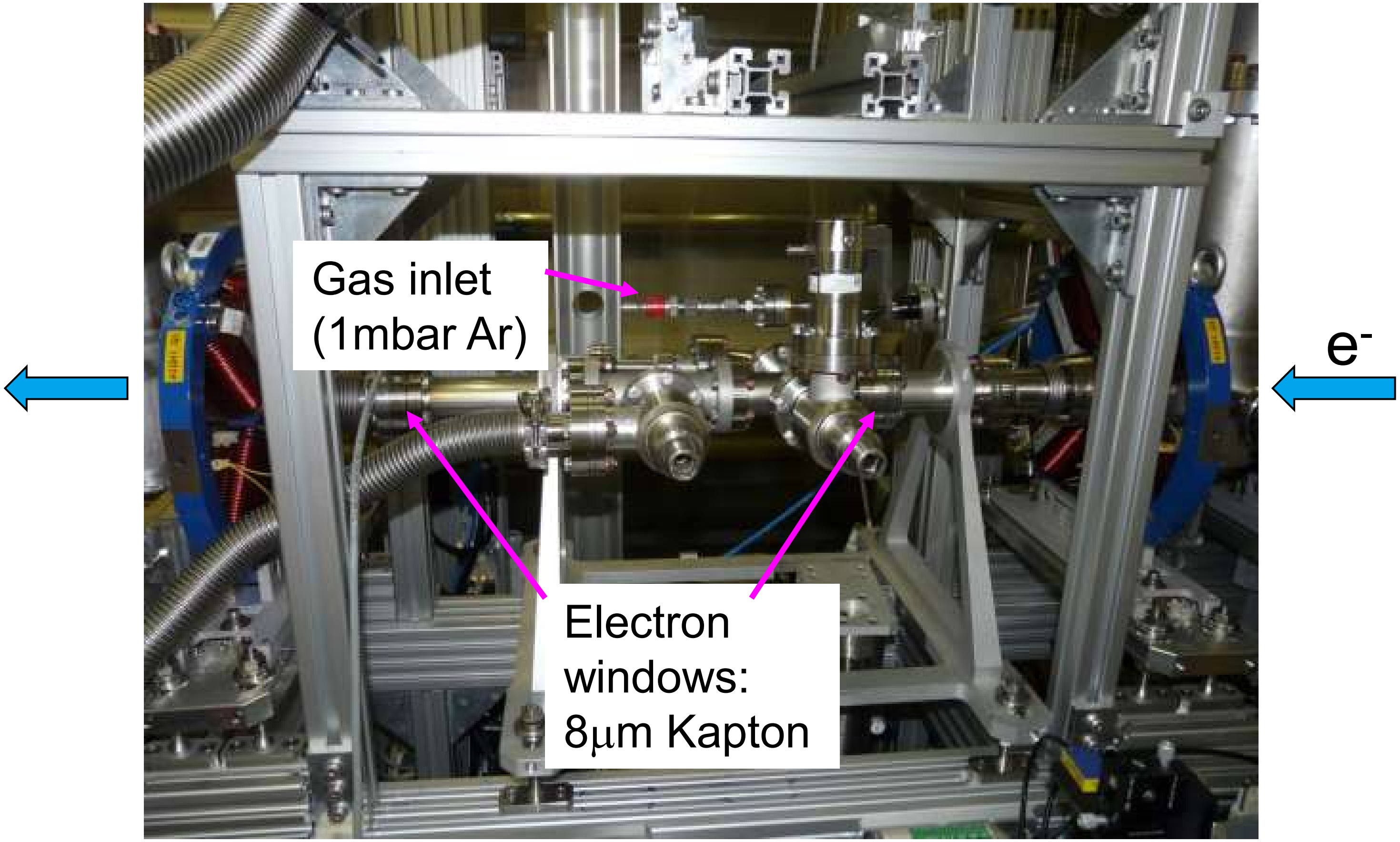
Quad 1…4

Electron Beam

Ionization laser

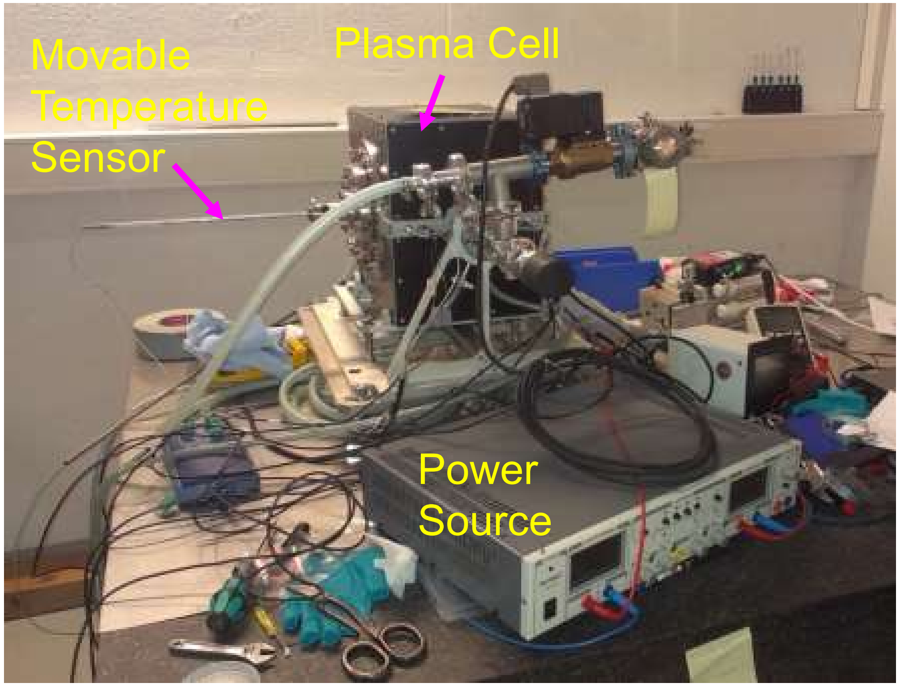
Pre-experiment #2: Dummy Plasma Cell

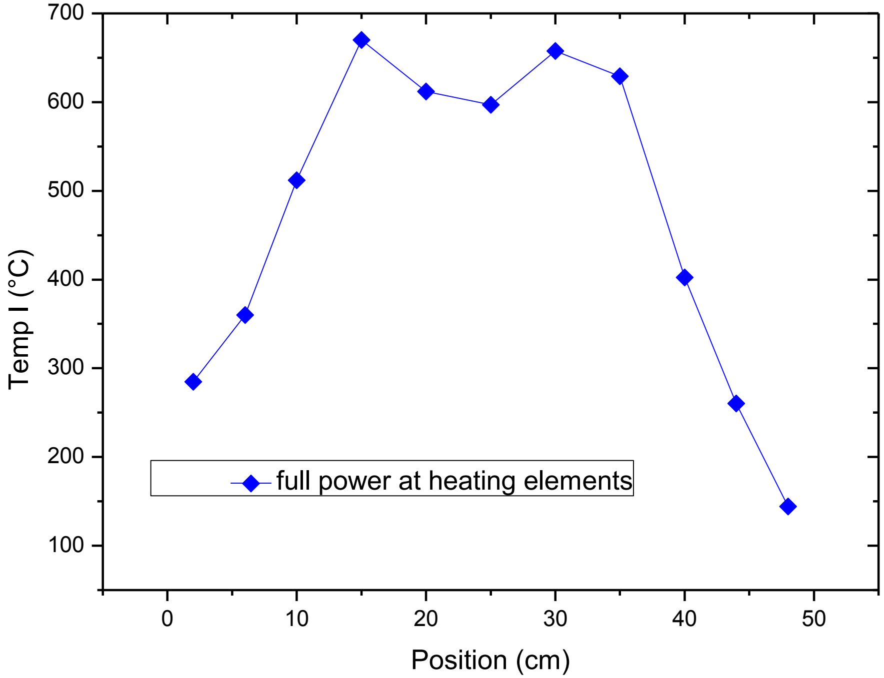
- Purpose: test of interaction electron beam ↔ electron window foils



Commissioning of PITZ Plasma Cell

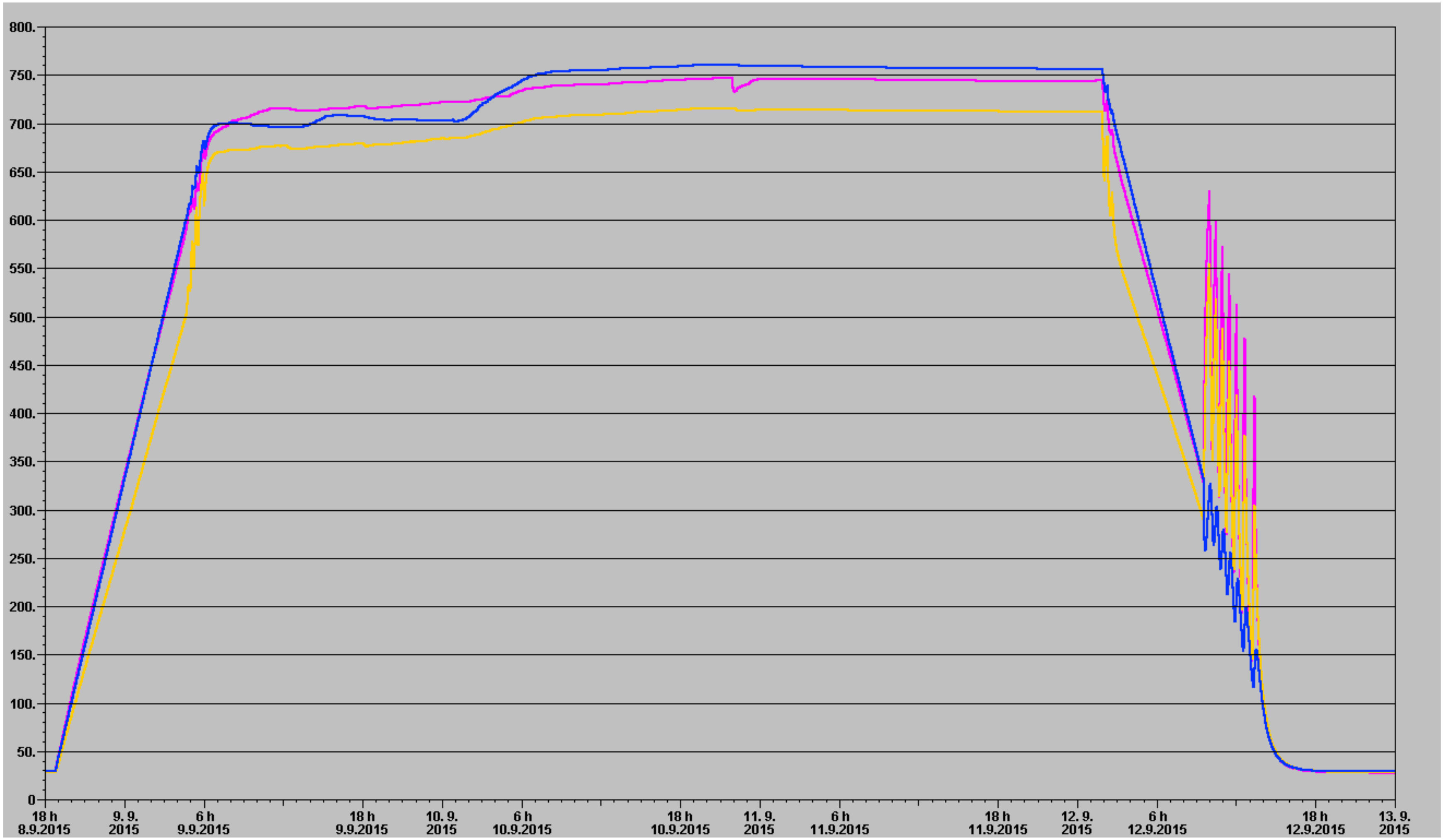
- Measurement of longitudinal temperature profile
  - Preliminary results





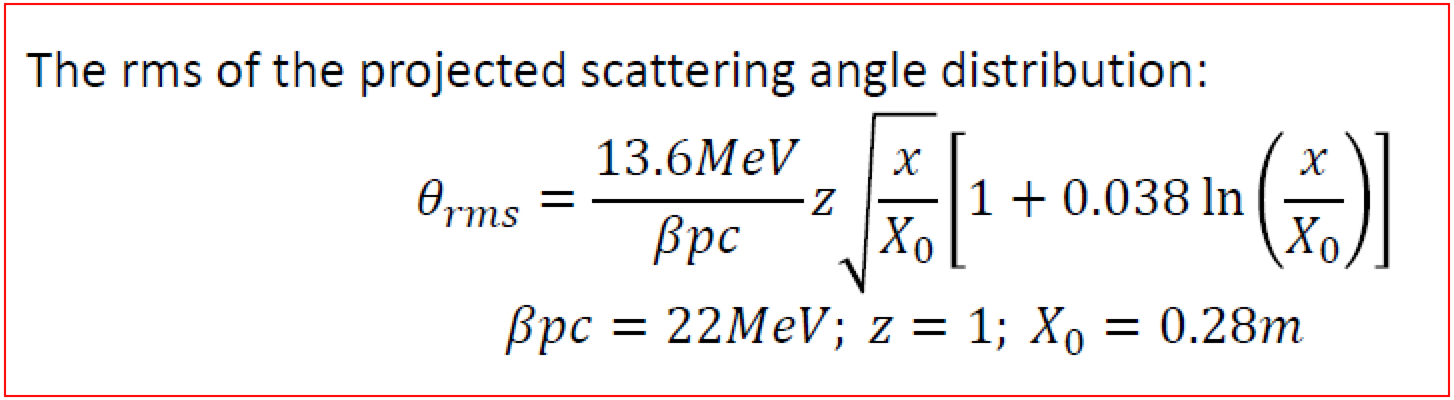
  - Maximal temperature ≈700°C → enough to reach Li gas density of ≈10^{16} cm^{-3}
  - Temperature dip: influence of cross-shaped plasma cell

Plasma cell temperature history



Theory: Multiple Coulomb Scattering

- From: Claus Grupen “Teilchendetektoren”: Multiple Coulomb Scattering



The rms of the projected scattering angle distribution:

$$\theta_{rms} = \frac{13.6MeV}{\beta pc} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

$$\beta pc = 22MeV;\ z = 1;\ X_0 = 0.28m$$

- Important: Radiation length X_0
  - Gold: 0.3 cm
  - Kapton (Polyimide): 28.6 cm
  - Beryllium: 35.3 cm
  - Polyethylene: 50.3 cm

Heat pipe: transport limitations

Table 3: Heat pipe transport limitations

Limitation	Mesh screen	Axial grooves
Capillary limitation	$1282.1\,\mathrm{Pa} > 172.1598\,\mathrm{Pa}$	$4230.7\,\mathrm{Pa} > 41.8974\,\mathrm{Pa}$
Sonic Limit	$635.25\,\mathrm{J/s}$	$676.66\,\mathrm{J/s}$
Entrainment Limit	$2457\,\mathrm{J/s}$	$5422\,\mathrm{J/s}$
Boiling Limit	$4.387 \times 10^6\,\mathrm{J/s}$	$5.7295 \times 10^7\,\mathrm{J/s}$
Viscous Limit	$1043\,\mathrm{J/s}$	$1198.7\,\mathrm{J/s}$